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Carbon Sequestration in Dryland Ecosystems

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ABSTRACT / Drylands occupy 6.15 billion hectares (Bha) or 47.2% of the world's land area. Of this, 3.5 to 4.0 Bha (57%–65%) are either desertified or prone to desertification. Despite the low soil organic carbon (SOC) concentration, total SOC pool of soils of the drylands is 241 Pg (1 Pg = petagram = 10^{15} g = 1 billion metric ton) or 15.5% of the world's total of 1550 Pg to 1-meter depth. Desertification has caused historic C loss of 20 to 30 Pg. Assuming that two-thirds of the historic loss can be resequestered, the total potential of SOC sequestration is 12 to 20 Pg C over a 50-year period. Land use and management practices to sequester SOC include afforestation with appropriate species, soil management on cropland, pasture management on grazing land, and restoration of degraded soils and ecosystems through afforestation and conversion to other restorative land uses. Tree species suitable for afforestation in dryland ecosystems include *Mesquite, Acacia, Neem* and others. Recommended soil management practices include application of biosolids (e.g., manure, sludge), which enhance activity of soil macrofauna (e.g., termites), use of vegetative mulches, water harvesting, and judicious irrigation systems. Recommended practices of managing grazing lands include controlled grazing at an optimal stocking rate, fire management, and growing improved species. The estimated potential of SOC sequestration is about 1 Pg C/y for the world and 50 Tg C/y for the U.S. This potential of dryland soils is relevant to both the Kyoto Protocol under UNFCCC and the U.S. Farm Bill 2002.

Dryland ecosystems are defined as regions in which the ratio of total annual precipitation to potential evapotranspiration (P:ET or the Aridity Index, AI) ranges from 0.05 to 0.65, and include dry sub-humid regions (AI = 0.50–0.65) covering 9.9%; semi-arid regions (AI = 0.20–0.50) covering 17.7%; arid regions (AI = 0.05–0.20) covering 12.0%; and hyperarid regions (AI = < 0.05) covering 7.5% of the earth's land area (Dregne 1983, Glenn and others 1993, Reynolds and Smith 2002). These regions cover about 47.2% of the earth's land area or about 6.15 billion hectares (Bha) (Table 1), predominantly in northern and southwestern Africa, southwestern and central Asia, northwestern India and Pakistan, southwestern United States and Mexico, western South America, and Australia (Hillel and Rosenzweig 2002, WRI 2000, Middleton and Thomas 1992, Noin and Clarke 1997).

The world's dryland soils contain 241 Pg of soil organic carbon (SOC) (Eswaran and others 2000), which is about 40 times more than what was added into the atmosphere through anthropogenic activities, estimated at 6.3 Pg C/y during the 1990s (Schimel and others 2001, IPCC 2001). In addition, dryland soils contain at least as much as or more soil inorganic carbon (SIC) than SOC pool (Batjes 1998, Eswaran and others 2000). Management of both SOC and SIC pools in dryland ecosystems can play a major role in reducing the rate of enrichment of atmospheric CO_2 (Lal 2002). Because of the vast areas and the importance of these soil C pools, drylands have a strong impact on the global C cycle. However, land degradation and desertification are pervasive in these regions, often resulting in emission of CO_2 into the atmosphere as well as other environmental degradation. The objective of this paper is to describe the potential of soils of the dryland ecosystems to sequester C and mitigate the accelerated greenhouse effect, and to outline land use and soil/vegetation management options to achieve this potential. Results are discussed in terms of the U.S. Farm Bill 2002 and the Kyoto Protocol.

Soils and Soil Characteristics

Principal soils of dryland ecosystems are Aridisols, Entisols, Alfisols, and Vertisols (Dregne 1976, Table 2). Whereas drought stress is the principal constraint to biomass production, deficiency of N and low SOC concentration are other important causes of low net primary productivity (NPP). Livestock production and ranching, based on extensive grazing, is the predominant land use. Arable land use is restricted only to semi-arid and dry sub-humid regions or where irrigation is available.

Physical and chemical properties of these soils also vary widely in accord with the major soil types (Table 2). Most soils are coarse-textured, low in SOC concentration, and have low water and nutrient retention ca-

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Table 1. Global distribution of drylands of the world (modified from Middleton and Thomas 1992, Noin and Clarke 1997, Reynolds and Smith 2002).

Region	Hyper-arid (< 0.05)[a]	Arid (0.05–0.20)	Semi-arid (0.20–0.50)	Dry sub-humid (0.50–0.65)	Total	% of Earth's land area
			Billion hectares			
Africa	67	0.5	0.51	0.27	1.96	15.0
Asia	0.28	0.63	0.69	0.35	1.95	14.9
Australia	0	0.30	0.31	0.05	0.66	5.1
Europe	0	0.01	0.11	0.18	0.30	2.3
N. America	0.003	0.08	0.42	0.23	0.74	5.6
S. America	0.03	0.05	0.27	0.21	0.54	4.2
Total	0.98	1.57	2.31	1.29	6.15	
% of Earth's land area	7.5	12.1	17.7	9.9	47.2	

[a]Aridity Index = P/PET.

Table 2. Principal soils of the dryland ecosystems (modified from Dregne 1976, Noin and Clarke 1997).

Region	Alfisols	Aridisols	Entisols	Mollisols	Vertisols
			Billion hectares		
Africa	0.235	0.5485	1.1362	0.0196	0.0169
Asia	—	0.7991	0.6627	0.3898	0.0975
Australia	0.0464	0.2917	0.2453	—	*0.0796*
N. America	0.0294	0.3312	0.0589	0.3018	0.0147
S. America	*0.0706*	*0.1520*	*0.2281*	*0.0923*	–
Total	0.3814	2.1225	2.3312	0.8035	0.2087

pacities and low inherent soil fertility. Entisols and Aridisols comprise 75% of all soils. Desert pavement, predominance of coarse fragments on the soil surface, is a common feature of most soils of hyper-arid and arid regions. In some soils, coarse fragments are abundant both in the surface and sub-soil horizons. Some gravelly soils also have concretionary materials (carbonates), and lower sides of pebbles may be coated with secondary carbonates. Because of the low SOC concentration and predominantly coarse texture, the A horizons of most soils of arid regions are light-colored and often less than 10 cm thick. Winds are pervasive in dryland ecoregions. Thus, dryland soils are also strongly affected by continuous wind sifting and sorting of soil materials. There are varying degrees of expression of this, the extreme case being dune fields. This results in a variation of SOC in the soils and also entrapment by surface vegetation. The wind action, irregularity of rainfall, and variation of surface temperatures are the common denominators of dryland soils.

The SOC concentration in dryland soils is usually less than 0.5% by weight. Perkins and Thomas (1993) reported that SOC concentration of the soils of the Kalahari Desert of Botswana ranges from 0.2 to 0.6%. For Vertisols in Central India, Balpande and others (1996) observed that SOC concentration ranges from 0.1 to 0.4%, but this generally increases in proportion to the amount of clay. The distribution of SOC with depth and the total SOC density (kg/m^2) are affected by vegetation, soil texture, landscape position, soil truncation, and the effect of runon and runoff or wind erosion/deposition. Gile and Grossman (1979) reported that SOC density to 1-meter depth ranged from 0.9 to 11 kg/m^2 from 86 pedons from the southwestern U.S. (Table 3). They also observed a linear relationship between SOC and clay concentrations (SOC in kg/m^2 to 1-m depth = $-0.06 + 0.15\%$ clay, $r = 0.73$). In China, Feng and others (2002) reported SOC density to 1-meter depth from 0.02 to 12.52 kg/m^2 from 340 profiles in 17 locations in different types of desert. In Africa, Branchu and others (1993) reported SOC density of 0 to 13 kg/m^2.

The vegetation cover in dryland ecosystems is highly variable with large patches of bare ground between small shrubs, resulting in large variations in SOC density vis-à-vis barren soil, grass strips, or under a shrub. In addition to drought stress, the vegetative cover is influenced by a range of temperatures throughout the year as well as during the growing season. Variations in temperatures across dryland regions make a considerable difference in water use efficiency. Evapotranspiration is lower in cooler regions, and soil water use efficiency is higher even though the region may get the same amount of precipitation. Differences in soil water use efficiency strongly impact biomass production and level of SOC. There are also wide variations in the length of the growing season, which normally varies with the availability of soil water, except in boreal and cooler regions and sometimes in temperate regions. The length of the growing season controls the amount and kind of biomass, and has significant impact on SOC concentration.

Grass strips, ranging from a few to several meters wide, normally occur in soils with fine- textured hori-

Table 3. Texture and soil organic carbon contents of two soil profiles in southwestern U.S. (adapted from Gile and Grossman 1979).

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	SOC (%)
Profile I				
0–33	86	5	9	0.18
33–102	86	6	8	0.21
SOC density to 102 cm = 2.7 kg/m^2				
Profile II				
0–28	94	3	3	0.15
28–58	92	4	4	0.15
58–84	89	6	5	0.13
84–109	89	6	5	0.10
SOC density to 109 cm = 2.1 kg/m^2				

zons (e.g., loam, clay loam, and silt loam). In Sahelian soils in Niger, Guillaume and others (1999) observed that tigerbush soils had high capacity to store SOC despite moderate primary production. Herrick and others (1999) observed differences in structural stability and infiltration rate in relation to vegetative cover in drylands of New Mexico, USA. The SOC concentration under the tigerbush vegetation was 0.93% compared with 0.45% within the bare area. Vegetation cover drastically affected both SOC density and its vertical distribution (Jobbagy and Jackson 2000).

In addition to SOC, dryland soils are also characterized by a relatively high concentration of SIC, namely, primary and secondary or pedogenic SIC (Lal and Kimble 2000). A predominant carbonate accumulation, called "caliche," is essentially a precipitate from aqueous solutions rising from below or from carbonate-rich moisture that moved from the surface downward. Most soils of dryland regions contain some forms of pedogenic carbonates, but not all contain caliche.

Drylands, especially in hyper-arid and arid regions, are also characterized by sand dunes, and these strongly affect variability in soil properties. Lei (1998) reported that SOC, N, and P concentrations were significantly lower on dunes relative to adjacent non-dune areas in the Mojave Desert of the U.S. Southwest.

Soil-Related Constraints to Biomass Production

Whereas lack of adequate water or drought stress during the growing season is the most obvious factor affecting net primary productivity (NPP), deficiency of N and other essential nutrients, as well as low SOC concentration may also limit biomass production (Breman and Kessler 1997, Felker 1998, Geesing and others 2000). In addition, an adequate level of SOC concentration is crucial to sustaining soil fertility, but it can also be a significant factor to increasing soil moisture storage and mitigate drought (Tiessen and others 1994). Over and above the elemental balance, there are severe problems due to extremes of soil and ambient temperatures. Therefore, enhancing biomass production in these ecosystems is very difficult and must first be approached through restoration of degraded soils and through sequestering SOC and SIC. These are important strategies with far-reaching economic and environmental impacts.

Desertification

Desertification has traditionally been defined as land degradation in arid, semi-arid, and dry sub-humid areas resulting from climatic variations and human activities (Le Hoúerou 1975, Warren 1996, UNEP 1992), but it has also been observed in cool, humid climates such as iceland (Arnalds 2000). The land area prone to desertification has been estimated at 3.5–4.0 Bha or 57%–65% of the total land area of dryland ecosystems (UNEP 1991). Of this, the land area affected by soil degradation alone (excluding vegetation degradation) ranges from 1.02 (UNEP 1991) to 1.14 Bha (Oldeman and Van Lynden 1998). The estimates of current rate of desertification also vary widely. Mainguet (1991) estimated the annual rate of desertification at about 5.8 million hectares (Mha), with 55% occurring in rangeland and 45% on rainfed cropland.

In accord with the low potential for NPP and the prevalent land degradation, desertification also leads to reduction in the ecosystem C pool and attendant decline in SOC. Lal and others (1999) estimated that soil erosion in drylands leads to emission of 0.21–0.26 Pg C/y, with an additional 0.02–0.03 Pg C/y due to exposure of carbonaccous material to climatic elements caused by surface soil erosion. Therefore, total annual emission of C due to erosion- induced land degradation in dryland ecosystems may be 0.23–0.29 Pg C/y (Lal and others 1999).

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Lal and others (1999) estimated historic loss of ecosystem C due to desertification at 9–14 Pg of SOC pool, with losses from the biotic/vegetation pool at 10–15 Pg. Similarly, Ojima and others (1995) estimated that grasslands and drylands of the world have lost 13–24 Pg C due to desertification. Although all estimates of ecosys-

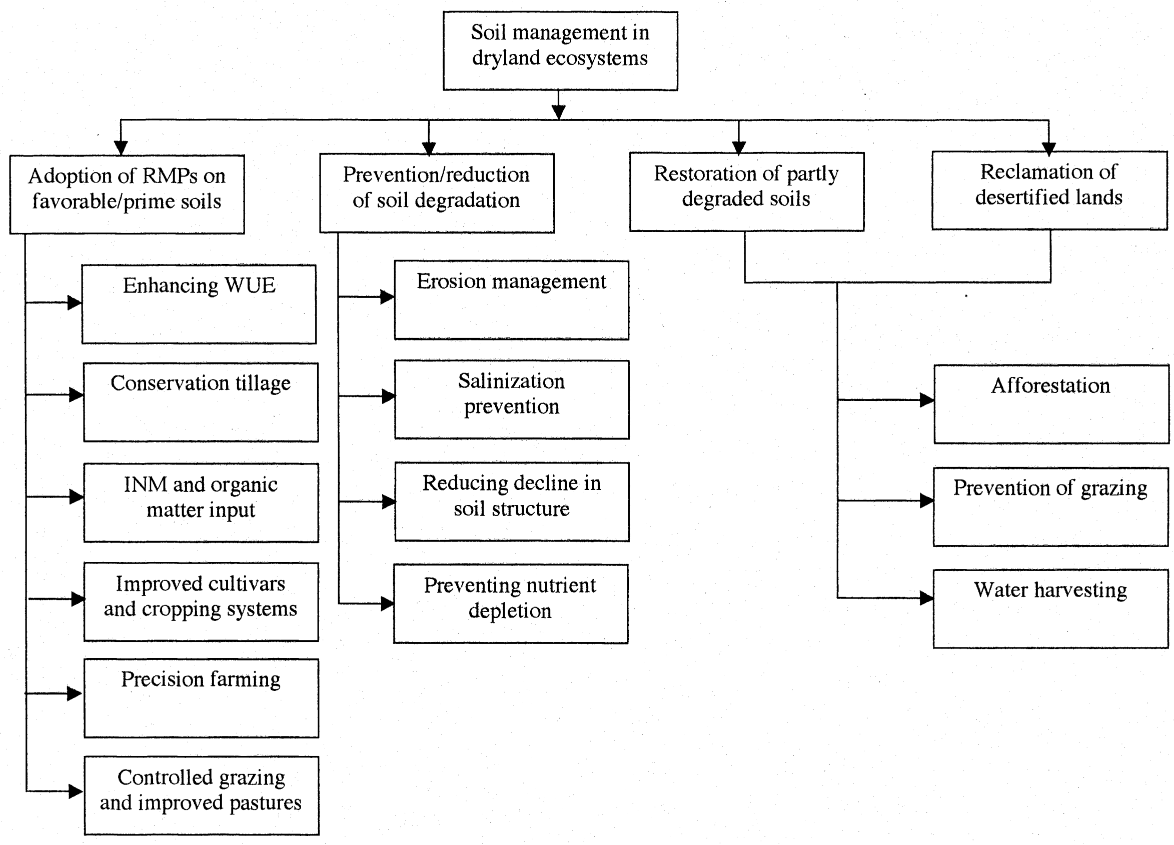

Figure 1. Soil management options for enhancing terrestrial carbon pool in dryland ecosystems.

tem C loss due to desertification are speculative, the numbers are large (20–30 Pg). If only 2/3 of this would be sequestered (Cole 1995) through desertification control and adoption of recommended land use and soil management practices, this would amount to 12–20 Pg over a 50-year period.

The schematics in Fig. 1 outline management options for enhancing SOC concentration. Technological options differ among soil type and land use systems (Hinman and Hinman 1992).

Agricultural Intensification and Soil Management

Adoption of recommended management practices (RMPs) on favorable soils with good soil moisture regime and the possibility of supplemental irrigation can increase SOC concentration. Enhancing water use efficiency (WUE), by reducing losses due to surface runoff and evaporation and decreasing soil temperature by residue mulching, is important. An objective of soil management practices is to increase the input of biosolids to the soil while enhancing soil quality including soil structure, and improving the soil moisture regime and the overall productivity.

Conservation tillage and residue management: Conversion from plow till to no-till or conservation tillage can increase WUE, reduce risks of soil degradation, and over time improve soil quality and SOC concentration. In Bushland, Texas, sweep-tilled delayed fallow contained 11.8 g/kg SOC compared with 9.3 g/kg in a plowed clean fallow treatment after 24 years (1943 to 1966) of cultivation (Jones and others 1997). The data reported by Eck and others (1967) indicated the potential of C sequestration on various soils in southern Great Plains. Unger (1991) measured SOC concentration to 20-cm depth 8 years after no-till and stubble mulch treatments were initiated on paired watersheds cultivated to wheat-sorghum-fallow rotation. Average SOC concentration to 10-cm depth was 16.3 and 15.8 g/kg for no-till and stubble mulch treatments, indicating a trend towards gain in SOC in no-till treatment. A significant increase in SOC concentration occurred in the top 2-cm depth. Stewart and Robinson (2000) stated that one of the gratifying consequences of the no-till system is increase in SOC concentration in soil, which may range from 60 to over 600 kg C/ha/y. The highest rates are usually associated with leguminous winter cover crops where residues are left on the soil surface. In northern Colorado, Potter and others (1997) reported 560 kg C/ha/y accumulation during 10 years of no-till continuous cropping wheat system. In Queensland, Australia, Dalal (1989) observed higher SOC concentration in Vertisols under no-till with crop residue retention than under conventional till. Significant increases in SOC were observed in the top 2.5- to 5.0-cm layers after 18 years of no- till practice (Dalal and others 1991, 1995, Dalal and Carter 2000). In India, Kihani and More (1984) conducted soil analyses on a 45-year old tillage experiment and reported that incorporation of biosolids improved SOC concentration. In the West African Sahel, Bationo and others (2000) observed that an annual addition of 4 Mg/ha of crop residue resulted in the maintenance of SOC at the same level as in the fallow in the top 20-cm layer. In southern Spain, Murillo and others (1998) reported that SOC concentration in 0- to 5-cm depth was 0.84% in traditional tillage and 1.1% in conservation tillage after 2 years, and 0.89% in traditional tillage compared with 1.34% in conservation tillage after 4 years. The increase in SOC concentration increased the overall soil quality. Indeed, widespread adoption of no-till farming can lead to SOC sequestration in dryland ecosystems.

Rotations and cover crops: The beneficial effects of using conservation tillage for enhancing SOC concentration are accentuated when used in conjunction with rotations based on appropriate cover crops or pastures (Ryan and others 1997). In Saudi Arabia, Shahin and others (1998) observed that introducing alfalfa in rotation with wheat grown on a sandy soil increased SOC concentration threefold as compared with continuous wheat. In Algeria, Arabi and Roose (1989) and Roose (1996) observed improvements in soil quality with legume-based rotations and sylvo-pastoral systems. In Syria, Ryan (1998) reported that incorporation of *Medicago* in rotation increased SOC concentration to 1-m depth. Jenkinson and others (1999) assessed the SOC pool under different rotations on a calcareous soil in Syria. The SOC pool in wheat-meadow rotation increased by 1.6 Mg/ha at a mean rate of 0.17 Mg C/ha/y in comparison with wheat-wheat rotation, and by 3.8 Mg/ha at the mean rate of 0.38 Mg C/ha/y in comparison with wheat-fallow rotation. In Australia, Whitehouse and Littler (1984) observed an increase in SOC concentration from 1.18% to 1.37% in 0- to 15-cm depth after 2–4 years of lucerne + prairie grass pasture. Dalal and others (1995) reported that the rate of increase in SOC concentration was 650 kg C/ha/y in a Vertisol under grass + legume pasture. Skjemstad and others (1994) reported an increase of 550 kg C/ha/y in a Vertisol under Rhodes grass. Holford (1990) and Chan (1997) observed similar effects of pasture on SOC concentrations in a Vertisol in New South Wales. In a Vertisol in central India, Mathan and others (1978) reported that continuous cropping and manuring increased SOC concentration by 20%–40% over 3 years. In northern India, Singh and others (1996) observed that incorporation of legumes in a rice-wheat rotation increased SOC concentration. Growing crops with a deep and prolific root system generally has a favorable impact on SOC concentration in the sub-soil. In semiarid regions of Argentina, Galantini and Rosell (1997) reported that rotations of mixed pastures (5 1/2 years) and annual crops (4 1/2 years) maintained the SOC pool at 17.3 Mg C/ha compared with 11.2 Mg C/ha in continuous cultivation with a wheat–sunflower rotation. Miglierina and others (1993, 1996) also reported that SOC concentration was high in wheat–grassland and wheat–alfalfa rotations, especially with conservation tillage.

Integrated nutrient management: Soil fertility enhancement is crucial to improving SOC concentration. Application of nitrogen fertilizer is important to obtaining high yields, but may have little impact on SOC concentration unless used in conjunction with no-till and residue management (Russell 1981, Dalal 1992, Skjemstad and others 1994, Dalal and others 1995). In semi-arid conditions, the SOC sequestration is limited by the input of biomass carbon. Although, crop yields are sufficiently increased by N application, the residue input is not sufficient enough to balance the mineralization rate. In Syria, Ryan (1998) reported a significant increase in SOC concentration by application of recommended rates of fertilizers. Dalal (1989) observed a positive effect on SOC concentration after 13 years of no-till, residue retained and N application (34.5 Mg C/ha vs. 35.8 Mg C/ha). In India, Gupta and Venkateswarlu (1994) observed that application of manure at 10 Mg/ha increased SOC concentration. Applications of farmyard manure, green manure, compost and other biosolids have a positive impact on SOC concentration. Use of high-lignin amendments, recalcitrant to decomposition, increases SOC concentration.

Irrigation management: Irrigation management is crucial to enhancing biomass production in dryland ecosystems. Some 40% of the world's food now comes from 17% of the cropland that is irrigated (Postel 1999). There is a large scope of enhancing SOC concentration in irrigated soils. In Mexico, Follett and others (2003) reported that adoption of conservation tillage on irrigated Vertisols sequestered soil C at the rate of 1.8 Mg/ha/y. Furthermore, the SOC sequestration efficiency was 8–10%, similar to that observed in the northern Great Plains (Follett and others 1997). This is an

Table 4. Strategies of soil management in dryland ecosystems for carbon sequestration

Strategy	Practice	Location/region	Reference
1. Erosion control/water conservation	a) No-till farming	Bushland, TX, USA	Jones and others 1997
		Northern CO, USA	Potter and others 1997
		Queensland, Australia	Dalal and others 2000
		West Africa Sahel	Bationo and others 2000
		Southern Spain	Murillo and others 1998
	b) Mulching		
	—stone cover	Negev Desert	Lahav and Steinberger 2001
	—residue mulch	Chihuahuan Desert	Rostagno and Sosebal 2001
	—mulch	Suriname	Breeman and Protz 1988
2. Crop diversification	a) Rotations	Saudi Arabia, West Asia	Shahin and others 1998
		Algeria, North Africa	Arabi and Roose 1989
	b) Legumes	Syria, West Asia	Jenkinson and others 1999
		Australia	Whitehouse and Littler 1984
		Northern India	Singh and others 1996
		Argentina	Galantini and Rosell 1997
3. Integrated nutrient management and recycling	a) Manuring	Maiduguri, Nigeria	Aweto and Ayub 1993
	b) Organic by-products	Spain	Pascual and others 1998
	c) Soil fauna	Chihuahuan Desert	Nash and Whitford 1995
	d) Sewage sludge	Spain	Pedreno and others 1996
4. Water management	a) Irrigation and conservation tillage	Mexico	Follett and others 2003
	b) Irrigation with sewage	Israel	Hillel 1998
	c) Irrigation with silt-laden water	Ningxia, China	Fullen and others 1995
	d) Saline aquaculture	Drylands	Glenn and others 1993
	e) Water harvesting		

exceptionally high rate of SOC sequestration and indicative of the potential of irrigated soils in carbon sequestration. A judicious use of irrigation water is crucial to sustainable use of soil and water resources in dry areas. Rather than flood irrigation using drip, furrow or subirrigation can enhance WUE and improve soil quality in irrigated croplands.

Use of wastewater for irrigation requires a special mention, especially in dryland ecosystems. Land application of sewage may be an important strategy to minimize pollution of rivers and improve soil quality. In Israel, well over two-thirds of domestic sewage is currently being recycled for use in agriculture, and the plan is to reuse up to 80% (Hillel 1998). Wastewater irrigation enhances soil fertility and improves SOC concentration. However, there are health hazards with regards to heavy metals and contamination of groundwater, which must be addressed. In Ningxia, China, Fullen and others (1995) observed that irrigating desert soils with silt-laden irrigation water from the Yellow River enhanced soil quality and biomass production. Increase in biomass returned can improve SOC concentration of irrigated soils.

In addition to cropland, irrigation with saline water may enhance production of halomorphic plants (Lal and others 1999). Halomorphic plants, grown by irrigation with brackish/seawater, can produce 17–35 Mg/ha/y of biomass (Glenn and others 1993). Growing suitable species with saline–water irrigation can lead to production of high-grade fodder, forage, oil, food, and industrial raw material.

Some examples of soil management practices that may lead to SOC sequestration are listed in Table 4. Surface application of biosolids, manuring, use of sewage sludge and organic by-products can enhance the SOC pool. Activity of soil fauna, especially termites, improves soil structure and enhances the SOC pool in the long run. An appropriate use of stone cover and gravel mulch can also improve soil moisture regime and enhance the SOC pool.

Pasture and Rangeland Management

Grazing is the predominant land use in dryland ecosystems, and adoption of improved grazing practices can improve C sequestration through conservation and better management of surface residue. Conversion

Table 5. Strategies of pasture and range land management for soil carbon sequestration.

Strategy	Practice	Location/region	Reference
1. Improved species	a) Sowing legumes	Vertisols, Australia	Chan and others 1997
		Northern Colorado	Havlin and others 1990
		Sadore, Niger	Hiernaux and others 1999
	b) Agroforestry	West African Sahel	Breeman and Kessler 1997
2. Fire management	Prescribed burning	Wyoming, USA	Schuman and others 2002
	a) Stocking rate	Negev, Israel	Zaady and others 2001
3. Grazing management	b) Controlled grazing	Kawas, USA	Rice and Owensby 2001
4. Improving grasslands	Integrated management	World's drylands	Conant and others 2001
5. Erosion management	Integrated management	World's drylands	Lal 2001

of degraded cropland soils to pasture and improving the pasture management enhance SOC concentration in dryland ecosystems. Some examples of improved practices with positive impact on the SOC pool are listed in Table 5 Important among these are grazing management through controlled stocking and rotational grazing, fire management, and agroforestry practices involving legume species (Conant and others 2001).

In Australian semi-arid tropics, Chan and others (1997) reported that SOC concentration in degraded Vertisols increased from 1.3% to 1.6% in 0- to 5-cm depth in 4 years by restoration of pasture with barrel medic (*Medicago truncatula*) and Mitchell grass (*Astrebla lappacea*). Increase in SOC concentration by incorporation of legumes is partly due to biological nitrogen fixation (BNF). Thus, application of nitrogenous fertilizers to degraded pastures may also improve SOC concentration. In addition to growing improved pasture species, incorporation of perennial woody legumes into the grazing system may also enhance SOC concentration by transferring the carbon to sub-soil at lower depths. Stewart and Robinson (2000) compared the SOC pool for four sites on Pullman silty clay loam in west Texas, USA. One site was cultivated to dryland wheat for more than 50 years, and the other three sites were grassland—one native grassland, one previous cropland converted to grassland 37 years prior to sampling, and one field returned to grassland 7 years prior to sampling. The data showed a substantial gain in SOC concentration even under semi-arid conditions. Similar results have been reported from northeastern Colorado by Ibori and others (1995), Havlin and others (1990), and Potter and others (1997).

Prescribed burning and controlled stocking rate are also important to maintaining and improving SOC concentration. Modification of fire regimen and grazing at the right intensity may influence SOC concentrations both directly and indirectly. In addition to the impact on charcoal carbon, reduction in fire frequency may lead to a shift in favor of woody vegetation, which produces lignified litter.

Preventing Soil Degradation and Restoring Degraded Soils

Preventing or minimizing risks of soil degradation is important to decreasing losses of terrestrial C from the ecosystem. The global rate of soil degradation may be as much as 10 Mha/y, most of which is occurring in dryland ecosystems. Reducing risks of environmental degradation implies controlling soil erosion by water and wind, decreasing risks of secondary salinization, and reducing decline in soil structure and nutrient pool. There are several options of soil quality restoration by combating desertification (Squires and others 1995, Lal 2001). Erosion control through establishment of vegetation cover and afforestation, soil fertility management through BNF and application of biosolids, and reclamation of salt-affected soils are important strategies (Fig. 1). There are also numerous practices of water harvesting and runoff management, which are essential to enhancing biomass production. There are approximately 3.6 Bha of degraded and desertified lands in dryland ecosystems. A coordinated effort at their restoration would be a win–win strategy.

Fallowing: Taking land out of agricultural uses and permitting natural vegetation to grow prevents degradation and restores degraded soils. Bush fallowing, permitting natural vegetation to grow without grazing or biomass removal, can restore soil quality and enhance SOC concentration. In northern Nigeria, Abubakar (1996) monitored the impact of duration of fallowing on changes in SOC concentration. The mean SOC concentration of the surface soil was 0.94% for 2-year fallow, 1.13% for 5-year fallow, 1.42% for 10-year fallow, and 1.44% for 15-year fallow. The data from a 30-year fallowing experiment conducted in eastern Spain showed that SOC concentration in the top 10-cm layer increased after 20 years of fallowing (Ruecker and others 1998).

Table 6. Soil management options for C sequestration in soils of dryland ecosystems.

Strategy/technique	Location/region	Reference
Surface application of biosolids	Chihuahuan Desert	Rostagno and Sosebal 2001
Stone cover	Negev Desert	Lahav and Steinberger 2001
Enhancing termites activity	Chihuahuan Desert	Nash and Whitford 1995
Manuring	Maiduguri, Nigeria	Aweto and Ayub 1993
Desert soil macrofauna (termites/ants)	Chihuahuan Desert	Whitford 1996
Sewage sludge	Spain	Pedreno and others 1996
Organic by-products	Spain	Pascual and others 1998

Afforestation: Afforestation is an important strategy of restoring degraded soils and ecosystems. With 47.2% of the earth's land area covered by dryland ecosystems, conversion to an appropriate land use, restoration of desertified and degraded soils, and adoption of RMPs can enhance the terrestrial C pool leading to increase in both biomass C and SOC pools. Establishing a vigorous vegetation cover is an effective strategy for C sequestration in soil and vegetation. However, not all trees can be grown everywhere. Soil water, temperature, and tolerance to frost differ among species. For arid and semi-arid regions with rainfall of 400–800 mm/y, there are numerous seasonal, perennial, and xerophytic plants, which are naturally adapted to dryland ecosystems. In regions with low rainfall (200–400 mm), valleys that receive run-on and have a favorable soil moisture regimen need to be developed for afforestation with appropriate tree species. Some promising species are listed in Table 6

Establishing appropriate tree species enhances soil fertility and sequesters C in soil and biomass. There are numerous tree species adapted to dryland ecosystems (Stiles 1988). Important among these are Tamarisk (*Tamarix* spp.), gum tree (*Eucalyptus* spp.), leucaena (*Leucaena* spp.), cypress (*Cupressus* spp.), casuarinas (*Casuarina* spp.), mesquite (*Prosopis* spp.), neem (*Azadirachta* spp), acacia (*Acacia* spp.), teak (*Tectone grandis*), cassia (*Casia* spp.) and others. In Sahel and sub-Saharan Africa, *Acacia albida* enhances the SOC pool (Charreau and Vidal 1965, Dancette and Poulain 1969, Pieri 1991). Similarly, *Prosopis* sp has been useful in SOC sequestration, and especially in reclamation of salt-affected soils (Singh and others 1994, Gupta 1995, Garg 1998, Felker and others 1981, Rhodes and Felker 1988, Baker and others 1995, Ahmad and others 1994). Some *Prosopis* species are multipurpose trees producing food and valuable timber (Felker 2000). Other tree species suitable for salt-affected soils are *Acacias* (Craig and others 1990), *Casurinas* (El-Lakany and Luard 1982, Ng 1987), and other halomorphic species (Patil and others 1996). The usefulness of establishing *Acacia* and *Prosopis* sp in SOC sequestration has also been demonstrated in the western U.S. (Connin and others 1997, East and Felker 1993). Geesing and others (2000) estimated that SOC sequestration potential of growing *Prosopis* and *Acacia* spp in 3.12 Bha of drylands is 6.2 Pg C/yr. In eastern Spain, Ruecker and others (1998) observed that tree establishment on degraded soils significantly increased SOC concentration in 0–10 cm layer after 30 years of growth. In northeastern Sudan, Alstad and Vetass (1994) reported improvements in soil quality following afforestation with *Acacia tortillis.* Whereas these species also store C in the above-ground biomass, which may be prone to leakage when harvested, the buildup of SOC pool is a long-term increase provided that subsequent soil degradation is prevented (Swisher 1997, Batjes 1998). Further, the residence time of C in drylands is much longer because of the slower decomposition rate than that in the humid environments (Gifford and others 1992).

Secondary Carbonates

In addition to SOC, there is potential of SIC sequestration in soils of dryland ecosystems through formation of secondary carbonates, which depends on land use and soil/crop management systems (Fig. 2). Upon dissolution, CO_2 in soil air forms carbonic acid that precipitates as carbonate of Ca^{+2} or Mg^{+2} (Eqs. 1, 2 and 3).

$$CO_2 + H_2O \rightleftarrows H^+ + HCO_3^- \rightleftarrows H_2CO_3 \ldots\ldots\ldots \quad (1)$$

$$Ca^{+2} + 2HCO_3^- \rightleftarrows CaCO_3 + H_2CO_3 \ldots\ldots\ldots\ldots \quad (2)$$

$$Ca^{+2} + HCO_3^- \rightleftarrows CaCO_3 + H \ldots\ldots\ldots\ldots\ldots \quad (3)$$

The SIC sequestration happens if cations (Ca^{+2} and Mg^{+2}) are supplied from outside the ecosystem (Nordt and others 2000). Some external sources of cations include eolian dust, Ca^{+2} dissolved in rainwater, sea salts and sprays, use of fertilizers, application of biosolids and amendments. Thus, formation of secondary carbonates depends upon the dynamics of several pe-

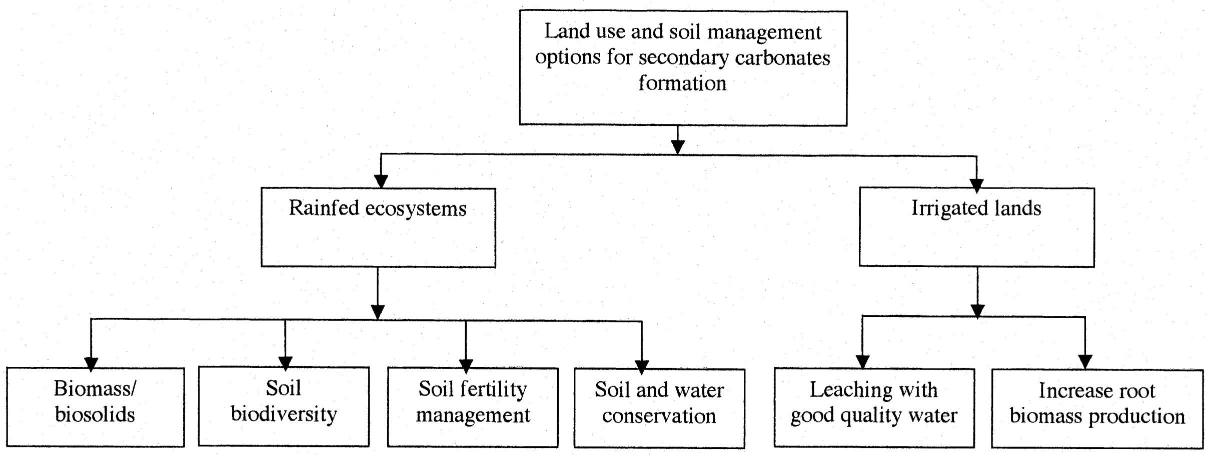

Figure 2. Technological options leading to formation of secondary carbonates in soils of dryland ecosystems.

dospheric processes including solubilization, leaching, and precipitation of carbonates, and availability of cations (Ca^{+2}, Mg^{+2} Ka^{+}, Na^{+} etc.).

The partial pressure of CO_2 in soil air is governed by the availability of biosolids, microbial activity, and soil temperature and moisture regimens. There is a strong synergistic interaction between SOC and secondary carbonates; the latter increases with an increase in SOC concentration or increase in rate of application of biosolids to the soil. The addition of biomass, both above- and below-ground, is critical to the formation of secondary carbonates. Decomposition of biomass increases the partial pressure of CO_2 in the soil air. Breeman and Protz (1988) reported that the rate of formation of secondary carbonates was 6.8 g $C/m^2/y$ with biomass addition of 5 Mg/ha/y and 13.9 g $C/m^2/y$ with biomass addition of 20 Mg/ha/y. The addition of biomass also enhances biotic activity of soil fauna (e.g., termites). Secondary carbonates are formed in the vicinity of the foci of such activities (Monger and Gallegos 2000). Humus-eating termites (Brune and Kuhl 1996) and those that generate CH_4 and CO_2 (Sanderson 1996) may enhance formation of biogenic carbonates. Root activity is also important to carbonate dynamics. Relatively high concentration of carbonates in the vicinity of plant roots may be due to excretion of Ca^{+2}, HCO_3^- and some acid exudates. Rhizospheric processes enhance precipitation of $CaCO_3$ both within and outside the roots. Along with biosolids, techniques that enhance soil fertility may also lead to formation of secondary carbonates. Improvements in soil fertility increase production of shoot and root biomass, which upon decomposition accentuate the production of CO_2 in soil air. Further, the addition of Ca^{+2} with fertilizers and other soil amendments increases the formation of secondary carbonates.

Water management is crucial to enhancing biomass. Water harvesting and trapping of sediments can bring in the cations (Ca^{+2}, Mg^{+2} etc.) from outside the ecosystems. Adoption of conservation effective measures also enhances the biomass production. Irrigation leads to a drastic increase in biomass production. Irrigation with good quality water (not saturated with carbonates) can dissolve carbonates and leach these into the ground water (Nordt and others 2000). Thus, quality of irrigation water, with regards to concentration and nature of salts, plays an important role in the dynamics of carbonates.

Some researchers argue that the rate of SIC sequestration is low at 0.03–0.05 Mg C/ha/y (Schlesinger 1990, 1997). In contrast, others have shown that the rate of formation of secondary carbonates may be 0.11–0.15 Mg C/ha/y (Monger and Gallegos 2000). The flux of secondary carbonates with the atmosphere is estimated at about 0.023 Pg C/y (Schlesinger 1997). Thus, the turnover time of C in secondary carbonates may be 30,000 to 90,000 years. With adoption of RMPs, it is evident that the formation of secondary carbonates and leaching of carbonates in ground water are important mechanisms of SIC sequestration in dryland soils.

Global Potential of Soil Carbon Sequestration in Drylands

Global potential of C sequestration in dryland ecosystems is large and has been estimated by several researchers. These estimates are crude and tentative at best and are merely indicative of what may be possible under ideal conditions. These potentials are calculated on the basis of the land area under a specific ecosystem that may be converted to a restorative land use, multiplied by the rate of SOC sequestration under improved land use and management system as reported in the literature, and multiplied by the number of years the land will be maintained under the improved system or for the duration over which the soil's SOC sink capacity may be filled. Lal and others (1998) computed the SOC sequestration potential, using the following equation: where A is the land area (ha), R is the rate of SOC sequestration (Mg C/ha/y), and D is the duration in years.

Squires and others (1995) estimated that a vigorous effort to control degradation in the drylands can result in a net sequestration of up to 1 Pg C/y. Lal and others (1999) reported that sequestration potential as a result of desertification control, fossil fuel offset through biofuel production, and erosion control is 0.9–1.9 Pg C/y. Geesing and others (2000) estimated that if an increase of 2 Mg/ha of soil C could be achieved by growing *Prosopis* and *Acacia* species, it would lead to sequestration of 6.2 Pg C/y. These and other data show that the potential of soil C sequestration in the dryland ecosystems is about 1 Pg C/y. Realization of this potential, however, requires a vigorous and a coordinated effort at a global scale towards desertification control, restoration of degraded ecosystems, conversion to appropriate land uses, and adoption of RMPs on cropland and grazing land.

Potential of Soil Carbon Sequestration in U.S. Drylands

Because of relatively low NPP and thus low quantity of biomass returned to the soil, rates of SOC sequestration in soils of the dryland ecosystems are generally lower than in more humid regions. Commonly observed rates of C sequestration in soil and biomass range from 40 to 400 kg/ha/y for SOC and 2000 to 4000 kg/ha/y for biomass (Table 7). The rate of formation of secondary bicarbonates is 100–120 kg/ha/y (Lal and Kimble 2000). With these assumptions, and on the basis of the data on land use in dryland soils of the U.S. (Table 8), the data in Table 9 show the potential of soil C sequestration through restoration and management of these ecosystems. The total potential of C sequestration in dryland soils of the U.S. is 38–56 Tg C/y (Tg = teragram = 10^{12} g = 1 million metric ton). This potential is rather small compared with the soil C sequestration potential in U.S. cropland of 75–208 Tg C/y (Lal and others 1998), grazing land of 18–91 Tg C/y (Follett and others 2001), and forest land soils of 49–186 Tg C/y (Kimble and others 2002).

Several assumptions are made in assessing the potential of soil C sequestration reported herein (Lal 2001).

Table 7. Rates of carbon sequestration through land use change and adoption of recommended management practices (adapted from Lal 2001a, Lal and others 2000, Lal 2002).

	C sequestration rate	
	Soil	Vegetation
Land use/management	(Mg C/ha/y)	
Erosion control	0.04–0.06	2–3
RMPs on agricultural land	0.08–0.10	–
Management of irrigated land	0.2–0.3	–
Restoration of degraded soils	0.04–0.06	–
Reclamation of salt-affected soils	0.2–0.4	3–4
Biofuel production for direct combustion	–	2–3
Secondary carbonates	0.10–0.12	–

(i) Restoration of degraded soils and ecosystems improve C pool in terrestrial dryland ecosystems.

(ii) Adoption of RMPs on agricultural soils improves soil quality and productivity over time.

(iii) The data on soil C sequestration from a few benchmarks oils and ecoregions can be extrapolated to other soils and ecoregions of the global drylands.

(iv) The hidden C costs are included in the RMPs package, whose adoption is inevitable to feed the rising world population.

(v) Carbon sequestered in the terrestrial ecosystems has a long residence time and is not re- emitted into the atmosphere.

(vi) Inputs required for adoption of RMPs on agricultural soils are available and at affordable prices especially to resource-poor farmers.

(vii) Adoption of RMPs and afforestation of degraded soils improve the economy of the region and augment farm income.

(viii) Soil/terrestrial C sequestration enhances positive feedbacks with numerous ancillary benefits.

An important assumption is that adoption of RMPs is driven by the overriding need for enhancing food production and augmenting farm income while sequestering C and improving the environment.

Nutrient Requirements for Soil Carbon Sequestration

Carbon is only one of the several constituents of humus. Other essential constituents include N, P, S, Zn, Cu, and several micronutrients (Jenkinson 1988). Whereas decomposition of humus leads to release of these nutrient elements, conversion of C from crop residues and other biosolids into humus requires their

Table 8. Land use and the risk of desertification in the U.S. (recalculated from Dregne and Chou 1992).

Land use	Total area	Area affected by desertification				
		Slight	Moderate	Severe	Very Severe	Moderate +
Mha						
Irrigated cropland	15.2	11.2	3.5	0.4	0.1	4.0
Rainfed cropland	30.1	26.5	3.5	0.09	0.02	3.6
Rangeland	325.1	49.1	98.0	173.0	5.0	276.0
Hyper-arid	1.3	–	–	–	–	–
Total	371.7	86.8	105.0	173.5	5.1	283.6

Table 9. Potential of soil carbon sequestration in U.S. drylands over a 50-year period.

Strategy	Land area (Mha)	Rate of C sequestration (kg/ha/y)	C sequestration potential (Tg C/y)
Desertification control	284	80–120	23–34
Recommended management practices[a]			
– Irrigated cropland	11	200–300	2–3
– Rainfed cropland	27	80–100	2–3
– Rangeland	49	80–100	4–5
Secondary carbonates	372	20–30	7–11
Total			38–56

[a]Land area used in these calculations is adjusted for that under desertification control to avoid duplication.

availability towards formation of humic substances. Therefore, increasing SOC concentration or sequestering carbon also involves immobilizing other elements (e.g., N, P, S etc.). Humus contains about 58% C (Stevenson 1982). Further, the ratio of C to other elements (weight basis) in humus is about 10 for N (Allison 1973), 50 for P (Jenkinson 1988), and 70 for S (Jenkinson 1988). Himes (1998) estimated that sequestration of 10,000 kg of carbon into humus will require 833 kg of N, 200 kg of P, and 143 kg of S. Therefore, sequestration of 1 Pg C/y in the dryland ecosystems would require 83 million tons of N, 20 million tons of P, and 14 million tons of K, amounting to a total of 117 million tons of fertilizer nutrients. In comparison, the global fertilizer use in 2000 was 136 million tons (IFDC 2002). These are large numbers, and these nutrients must be made available from a wide range of sources. Some nutrients are contained in crop residues (Lal 1995). One Mg of cereal straw, on average, contains 12–15 kg N, 1–4 kg P, and 1–2 kg S (Scott and Aldrich 1983, Aldrich and others 1986). Therefore, 10 Mg of carbon, synthesized in humus, is contained in 125 Mg of cereal residue such as wheat and corn (average C content of 40% and humification efficiency of 20%). This amount of residue contains 1500–1875 kg N, 125–500 kg P, and 125–250 kg S. Thus, nutrients supplied in crop residue are more than adequate for conversion of C into humus. In practical terms, therefore, the process of C sequestration is limited more by the availability of adequate amount of residue rather than that of nutrients. Besides residues, there are other sources of nutrients. In drylands, with limited leaching, there is some nitrate-nitrogen accumulated in the soil profile (Stewart and Robinson 2000), which can also be immobilized. Then, there is some addition of N from rainfall and BNF. There are numerous other sources of N applied to the soil on an annual basis. Globally, 350 million tons of N are returned to soil annually, of which 80 million tons are from fertilizer (Vitousek 1997). The fertilizer nitrogen use efficiency is generally 20% to 40% (Halvorson and others 2002), and even lower for P in soils of high P fixation capacity. A large fraction of unused N and P are pollutants of water and air. Thus, it may be advantageous to immobilize N in humus to minimize volatilization (as N_2O a greenhouse gas with 310 GWP) or leaching (as NO_3) into the ground water. Elemental recycling from sub-soil through establishment of deep-rooted species is also an important strategy to enhancing nutrient supply. Thus, the question of nutrient availability for SOC sequestration is a challenging but doable task that must be done through adoption of RMPs including precision farming.

Relevance to the Kyoto Protocol

Following the Kyoto summit of 1997 (UNFCCC 1997), there has been a strong international interest in identifying and harnessing terrestrial, geologic, and oceanic sinks for long-term storage of atmospheric CO_2*[1]. The data and review presented in this and other reports indicate a large potential of soil (terrestrial) C sequestration over the very extensive arid lands. The importance of soil C sequestration in dryland ecosystems cannot be overemphasized. If 1 Pg out of 3.2 Pg of the annual increase in atmospheric concentration of CO_2 can be sequestered in soil, it will be an important factor in stabilizing the concentration of greenhouse gases in the atmosphere. Furthermore, the sequestered C has economic value that can be realized through creation of certified carbon credits and traded on the international market under the Clean Development Mechanism, Joint Implementation etc. of the Kyoto Protocol. The Kyoto Protocol creates an enabling environment for creation of Certified Emission Credits (CERs), including those obtained by sequestration. There are also opportunities of trading carbon under the Bio-Carbon and Prototype Carbon Funds being developed by the World Bank. Such mechanisms also enhance opportunities to bring in corporate and public sector funds to finance C sequestration and improved land management.

Trading Certified Emission Credits necessitates "commodification" of carbon sequestered in soils. In other words, soil carbon must have an economic value similar to wheat, corn, milk, meat, or any other farm produce. Further, SOC must have value as a public good to mitigate climate change. The "commodity price" and the mechanism for promotion may be quite different. The price of SOC may be on the basis of cost/Mg, whereas the value of public good may be cost/ha. Both payment mechanisms can be operative within a geographic region.

There is also a strong need for establishing criteria for determining the societal value of soil carbon. In comparison with the market forces, the societal value of soil carbon may be determined by on-site and off-site benefits. The on-site benefits are due to long-term improvements in soil quality, productivity, and land value. The off-site benefits are due to reduction in erosion and sedimentation, improvement in water quality, and decrease in net emission of greenhouse gases into the atmosphere. Lal and others (1998) estimated the value of soil carbon at \$250/Mg, compared with the market value of \$4 to \$10/Mg.

In this regard, the importance of restoring degraded/desertified soils and ecosystems cannot be overemphasized. Establishing plantations of *Acacia, Prosopis,* Neem, and other species is an important strategy. A judicious management of irrigated lands and growing halomorphic plants by irrigation with saline water can also be implemented. Soil-specific RMPs must be adopted on croplands in dryland ecosystems. International agreements need to be implemented to protect terrestrial/soil C sinks, initiate long-term projects to enhance and restore SOC/SIC pools, discourage biomass burning, and restore degraded soils and ecosystems. In view of its strong relevance, there is a strong need to develop simple and economic techniques of validating/monitoring the SOC pool and its dynamics.

[1]Although not a signatory to the Kyoto Protocol, President Bush has also emphasized the importance of forest and soils in C sequestration on a voluntary basis.

Conclusions

Analyses of the available information support the following conclusions:

1. World dryland soils cover a vast area with diverse land uses and a wide range of soils and ecosystems.
2. There is a severe problem of desertification or degradation of drylands probably caused by land misuse, soil mismanagement, and harsh climate.
3. Historic loss of SOC due to desertification and degradation is estimated at 20–30 Pg for a total pool of 241 Pg. Of the historic loss, 12–20 Pg (about two-thirds) can be resequestered through restoration of desertified soils and ecosystems.
4. The mean potential of SOC sequestration is about 1 Pg C/y, through afforestation with *Mesquite, Acacia,* Neem etc., and adoption of RMPs on croplands and grazing lands.
5. The potential of SOC sequestration in dryland soils is highly relevant to the Kyoto Protocol and the U.S. Farm Bill 2002.

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