Chapter 6

Climate Change and Carbon Sequestration in Dryland Soils

Peeyush Sharma, Vikas Abrol, Shrdha Abrol and Ravinder Kumar

Additional information is available at the end of the chapter

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1. Introduction

Climate change is the biggest threat to humanity with implications for food production, natural ecosystems, health etc. The primary greenhouse gases are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Although carbon dioxide is the most prevalent greenhouse gas in the atmosphere, nitrous oxide and methane have longer durations in the atmosphere and absorb more long-wave radiations. Therefore, small quantities of methane and nitrous oxide can have significant effects on climate change. The mean global level of greenhouse gases in the atmosphere is increasing to a level that can generate serious climate changes in air temperature, aggressive weather cycles and greater frequency of storms (Osborn et al., 2000). The primary sources of greenhouse gases in agriculture are the production of nitrogen based fertilizers; the combustion of fossil fuels such as coal, gasoline, diesel fuel, natural gas; and waste management. Livestock enteric fermentation results in methane emissions. Increased levels of greenhouse gases enhance the naturally occurring greenhouse effect by trapping even more of the sun's heat, resulting in a global warming effect. The average surface temperature of the earth is likely to increase by 2 to 11.5°F (1.1-6.4°C) by the end of the 21st century, relative to 1980-1990, with a best estimate of 3.2 to 7.2°F (1.8-4.0°C) (Fig. 1). The average rate of warming over each inhabited continent is very likely to be at least twice as large as that experienced during the 20th century.

These changes in greenhouse gas emissions generally are linked to human activities. Scientists have concluded that warming of the climate system is "equivocal" and there is a "very high confidence that the globally averaged net effect of human activity since 1750 has been one of warming" (IPCC, 2007). The concentration of carbon dioxide (CO_2) in the atmosphere increased from 285 ppm at the end of the nineteenth century, before the industrial revolution, to about 366 ppm in 1998 (equivalent to a 28-percent increase) as a consequence of anthropogenic emissions of about 405 gigatonnes of carbon (C) (± 60 gigatonnes C) into the atmosphere (IPCC, 2001). This increase was the result of fossil-fuel combustion and cement production (67 percent) and land-use changes (33 percent). Acting as carbon sinks, the marine and terrestrial ecosystems have absorbed 60 percent of these emissions while the remaining 40 percent has resulted in the observed increase in atmospheric CO_2 concentration. Agricultural ecosystems represent 11% of the earth's land surface and include some of the most productive and carbon-rich soils. Agriculture accounts for approximately 13% of total global anthropogenic emissions and is responsible for about 47% and 58% of total anthropogenic emissions of methane (CH_4) and nitrous oxide (N_2O). Besides CH_4 from enteric fermentation (32%), N_2O emissions from soils due to fertilization constitute the largest sources (38%) from agriculture (US-EPA, 2006; IPCC, 2007; Stern, 2006). The annual greenhouse gas emissions from agriculture are expected to increase in coming decades due to increased demand for food and shifts in diet. Conservation tillage, nutrient management, cover cropping and crop rotation can drastically increase the amount of carbon stored in soils. Now scientists use carbon dioxide equivalents to calculate a universal measurement of greenhouse gas emissions as greenhouse gases have varying global warming potentials Table (1).

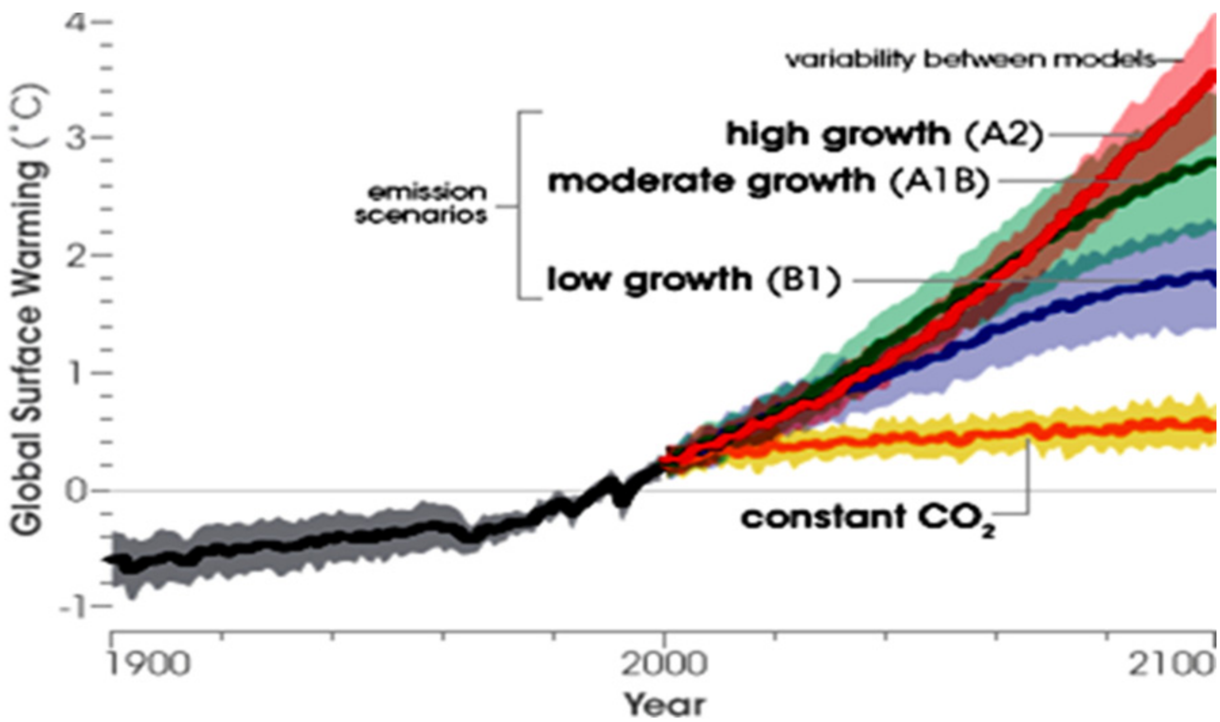

Figure 1. Temperature projections to the year 2100, based on a range of emission scenarios and global climate models. The orange line ("constant CO_2") projects global temperatures with greenhouse gas concentrations stabilized at year 2000 levels. Source: NASA Earth Observatory, based on IPCC Fourth Assessment Report (2007)

Sources	1990	1995	2000	2005	Avg. 2001-2005
	Million metric tons CO_2 equivalent ($MMTCO_2$- Eq)				
U. S. Agricultural Activities					
GHG Emissions (CH_4 and N_2O)					
Agriculture soil management[a]	366.9	353.4	376.8	365.1	370.9
Enteric fermentation[b]	115.7	120.6	113.5	112.1	115.0
Manure management	39.5	44.1	48.3	50.8	45.6
Rice cultivation	7.1	7.6	7.5	6.9	7.4
Agricultural residue burning	1.1	1.1	1.3	1.4	1.2
Subtotal	530.3	526.8	547.4	536.3	540.1
Carbon sinks					
Agricultural soils	(33.9)	(30.1)	(29.3)	(32.4)	(31.7)
Other	NA	NA	NA	NA	NA
Subtotal	(33.9)	(30.1)	(29.3)	(32.4)	(31.7)
Net emissions, Agriculture	496.4	496.7	518.1	503.9	508.4
Attributable CO_2 emissions[c] Fossil fuel/mobile combustion	46.8	57.3	50.9	45.5	52.6
% All emissions, Agriculture[d]	8.5%	8.0%	7.7%	7.4%	8.0%
% Total sinks, Agriculture	4.8%	3.6%	3.9%	3.9%	4.0%
% Total emissions, forestry	0.2%	0.2%	0.2%	0.3%	0.3%
% Total sinks, forestry[e]	94.3%	92.0%	94.8%	94.7%	95.0%
Total GHG emissions, All sectors	6,242.0	6,571.0	7,147.2	7,260.4	6,787.1
Total carbon sinks, All sectors	(712.8)	(828.8)	(756.7)	(828.5)	(801.0)
Net emissions, All sectors	5,529.2	5,742.2	6,390.5	6,431.9	5,986.1

Source: EPA, Inventory of U.S. Grenhouse Gas Emissions and Sinks: 1990-2005, April 2007, [http://epa.gov/climatechange/emissions/usinventoryreport.html].
a. N_2O emissions from soil management and nutrient/chemical applications on croplands.
b. CH_4 emissions from ruminant livestock.
c. Emissions from fossil fuel/mobile combustion associated with energy use in the U.S. agriculture sector (excluded from EPA's reported GHG emissions for agricultural activities).
d. Does not include attributable CO_2 emissions from fossil fuel/mobile combustion.
e. Change in forest stocks and carbon uptake from urban trees and land filled yard trimmings.

Table 1. Greenhouse gas emissions and carbon sinks in agricultural activities, 1990-2005 (CO_2 equivalent).

2. Soil as a source of carbon storage

Soils are the fundamental foundation of our food security, global economy and environmental quality, the degradation of soil conditions can affect the on-farm environment. The soil environment is a principal component of the global carbon (C) cycle where key interactions between biotic and abiotic components take place to regulate the flow of materials to and from the pedosphere, atmosphere and hydrosphere. There is general agreement that although soil is part of the climate change problem, it is also an integral part of the solution. Soils altogether contain an estimated 1,700 Gt (billion metric tons) to a depth of 1 m and as much as 2,400 Gt to a depth of 2 m (Fig.2). An estimated additional 560 Gt is contained in terrestrial biota (plants and animals). The carbon in the atmosphere is estimated to total 750 Gt. The amount of organic carbon in soils is more than four times the amount of carbon in terrestrial biota and three times that in the atmosphere. Lal et al., (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. Ojima et al., (1993) estimated that grasslands and drylands of the world have lost 13–24 Pg C due to desertification.

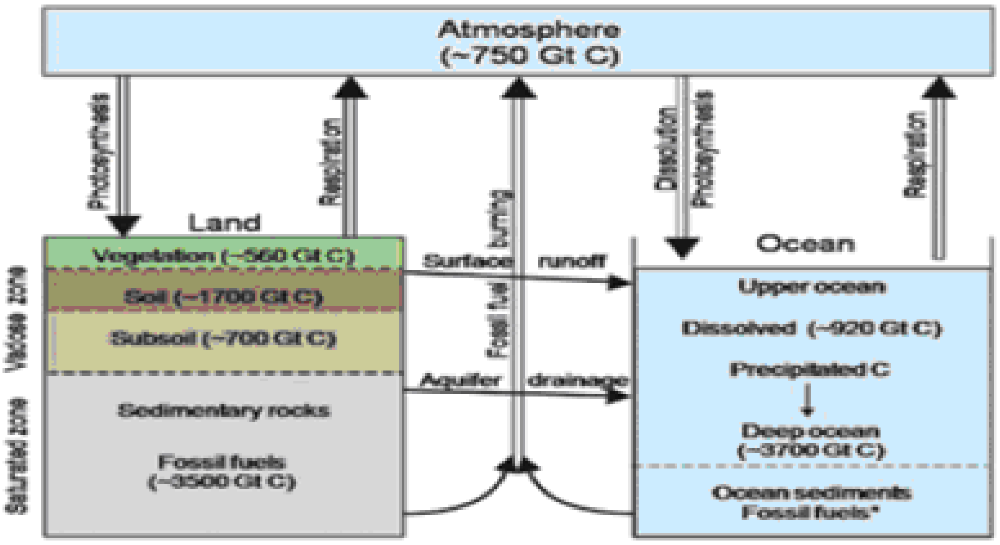

Figure 2. Carbon reserve and exchange in the land- ocean- atmosphere continuum (Quantitative estimates regarding fossil fuels in ocean sediments vary widely)

Carbon dioxide is removed from the atmosphere and converted to organic carbon through the process of photosynthesis. As organic carbon decomposes, it is converted back to carbon dioxide through the process of respiration. The quantity of organic carbon in soils is spatially and temporally variable, depending on the balance of inputs versus outputs. The inputs are due to the absorption of carbon dioxide from the atmosphere in the process of photosynthesis and its incorporation into the soil by the residues of plants and animals. Some of the dead plant matter is incorporated into the soil in humus, thereby enhancing the soil organic carbon pool. Decomposition of soil organic matter, releases carbon dioxide under aerobic conditions and methane under anaerobic conditions. In certain conditions, decomposition of organic matter may also cause the release of nitrous oxide, which is another powerful greenhouse gas. The content of organic carbon in soils in most cases constitutes less than 5% of the mass of soil material and is generally concentrated mainly in the upper 20 to 40 cm (the so-called topsoil). However, that content varies greatly, from less than 1% by mass in some arid-zone soils (Aridisols) to 50% or more in waterlogged organic soils such as Histosols (Table 2). Changes in agricultural activities and land use system during the past centuries have made soils act as net sources of atmospheric CO_2. Evidence from long-term experiments suggests that carbon losses due to oxidation and erosion can be reversed with soil management practices that minimize soil disturbance and optimize plant yield through fertilization. Appropriate land management practices can result in a significant increase in the rate of carbon into the soil. Because of the relatively long turnover time of some soil carbon fractions, this could result in storage of a sizable amount of carbon in the soil for several decades. Maintaining soil quality can reduce problems of land degradation, decreasing soil fertility and rapidly declining production levels that occur in large parts of the world which lack the basic principles of good farming practices. The loss of rain water that cannot infiltrate in the soils to replenish the ground water reserves might be the more serious long-term result of excessive tillage. Thus, the way soil is cultivated must be drastically changed.

Soil Order	Area 10^3 km^2	Organic C Gt
Alfisols	13,159	90.8
Andisols	975	29.8
Aridisols	15,464	54.1
Entisols	23,432	232.0
Gelisols	11,869	237.5
Histosols	1,526	312.1
Inceptisols	19,854	323.6
Mollisols	9,161	120.0
Oxisols	9,811	99.1
Spodosols	4,596	67.1
Ultisols	10,550	98.1
Vertisols	3,160	18.3
Other orders	7,110	17.1
Total	130,667	1,699.6

Source USDA

Table 2. Estimated mass of carbon in the worlds soils resources

3. Degradation of dryland

Degradation of soil is especially important in drylands of the world where desertification is a serious problem (UNEP, 1992). The world's drylands, 6.31 billion hectares (Bha) or 47% of the earth's land area, are found in a wide range of climates spanning from hot to cold.

According to FAO (1993), drylands comprise four ecoregions covering land area of 0.98 Bha in hyper-arid, 1.57 Bha in arid, 2.31 Bha in semi-arid and 1.29 Bha in dry sub-humid climates (Table 3). Soils of the drylands also vary widely, but are mostly Aridisols (2.12 Bha) and Entisols (2.33 Bha). Dryland soils also include Alfisols (0.38 Bha), Mollisols (0.80 Bha), Vertisols (0.21 Bha) and others (0.47 Bha) (Dregne, 1976; Noin and Clark, 1997). The arid zones cover about 15 percent of the land surface. The annual rainfall in these areas is up to 200 mm in winter-rainfall areas and 300 mm in summer rainfall areas. Interannual variability is 50–100 percent. Africa and Asia have the largest extension of arid zones (Table 4).

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
Africa	67	0.5	o.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	

* Aridity Index = P/PET

Table 3. Global distribution of drylands of the world (modified from Middleton and Thomas 1992, Noin and Clarke 1997, Reynolds and Smith 2002)

Continent	Extension			Percentage		
	Arid	Semi-arid	Dry subhumid	Arid	Semi-arid	Dry subhumid
	Million ha					
Africa	467.60	611.35	219.16	16.21	21.20	7.60
Asia	704.30	727.97	225.51	25.48	26.34	8.16
Oceanta	459.50	211.02	38.24	59.72	27.42	4.97
Europe	0.30	94.26	123.47	0.01	1.74	2.27
North/Central America	4.27	130.71	382.09	6.09	17.82	4.27
South America	5.97	122.43	250.21	7.11	14.54	5.97
Total	1641.95	1897.74	1238.68			

Source FAO (2002a)

Table 4. The global dryland areas by continent

Desertification is defined as destruction of the biological potential of land which can lead ultimately to desert-like conditions' (UNEP, 1977). In this context, the term 'land' includes whole ecosystems comprising soil, water, vegetation, crops and animals. The term 'degradation' implies reduction of resource potential by one or a combination of degradative processes including erosion by water and wind and the attendant sedimentation. The process of desertification is not confined to the drylands of the tropics it also occurs in developed countries (U.S.A.), high latitude humid ecoregions (Iceland) and even humid regions (tropical rainforest). Traditionally desertification has been defined as land degradation in arid, semi-arid, and dry sub-humid areas resulting from climatic variations and human activities (Le Hou´erou, 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. Desertification in humid areas results mainly from land misuse and soil mismanagement. Estimates of the extent of desertification range widely and are highly subjective. UNEP estimated 3.97 Bha in 1977, 3.48 Bha in 1984 and 3.59 Bha in 1992 (UNEP, 1992). Land area affected by desertification was estimated at 3.25 Bha by Dregne (1983) and 2.0 Bha by Mabbutt (1984). According to the GLASOD methodology (Oldeman and Van Lynden, 1998), land area affected by desertification due to soil degradation is estimated at 1.14 Bha (Table 5). As with the area affected, estimates of the current rates of desertification also vary widely. The annual rate of desertification is estimated at 5.8 million hectares (Mha) or 0.13% of the dryland in mid latitudes. Also desertification is considered as a biophysical process driven by socio-economic and political factors (Mortimore, 1994; Mainguet and Da Silva, 1998). Two principal biophysical processes leading to desertification are erosion and salinization. Accelerated soil erosion by wind and water are severe in semi-arid and arid regions (Balba 1995; Baird, 1997), especially those in the Mediterranean climates (Brandt and Thornes, 1996; Conacher and Sala, 1998a,b). Salinization is a major problem on irrigated lands. The irrigated land area in the world has increased 50 fold during the last three centuries which was 5 Mha in 1700, 8 Mha in 1800, 48 Mha in 1900, and 255 Mha in 2000. Risks of secondary salinization are exacerbated by use of poor quality water, poor drainage and excessive irrigation, leakage of water due to a defective delivery system, impeded or slow soil drainage and other causes. Salinization is a severe problem in China, India, Pakistan, and in countries of Central Asia (Babaev, 1999). The extent of land area salinized is 89% in Turkmenistan, 51% in Uzbekistan, 15% in Tadjikstan, 12% in Kyrgyzstan and 49% of the entire region (Pankova and Solovjev, 1995; Esenov and Redjepbaev, 1999). Salinization is also a problem in southwestern U.S.A., northern Mexico and dry regions of Canada (Balba, 1995). Lal et al., (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 carbonaecous 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.

Land type	Area (Bha)	Type of soil degradation	Area (Bha)
Degraded irrigated lands	0.043	Water erosion	0.478
Degraded rainfed croplands	0.216	Wind erosion	0.513
Degraded rangelands (Soil and vegetation)	0.757	Chemical degradation	0.111
Sub-total	1.016	Physical degradation	0.035
Degraded rangelands (Soil and vegetation)	2.576	Total	1.137
Total	3.592	Light	0.489
Total land area	5.172	Moderate	0.509
% degraded	69.5	Severe and extreme	0.139
		Total	1.137

UNEP (1991); Oldeman and Van Lynden (1998). The estimates by Oldeman and Van Lynden does not include the vegetation degradation on rangeland. (Bha= 10^9 ha)

Table 5. GLASOD estimates of desertification (e.g. land degradation in dry areas excluding hyber-arid areas)

4. Soil organic carbon storage

The soil organic C storage decrease with increase in temperature and increases with increase in soil water content. Studies show that a 3^0C increase in temperature is projected to decrease soil organic C concentration by about 11% in the upper 30 cm soil depth and increase CO_2 emission by 8 %. This may to some extent be counteracted by higher uptake of carbon dioxide by plants as they grow faster in warmer conditions and store carbon as biomass both in the soil and the plant. The world's dryland soils contain 241 Pg of soil organic carbon (SOC) (Eswaran et al., 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 et al., 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 et al., 2000). Total dryland soil organic carbon reserves comprise 27% of the global soil organic carbon reserves (MA, 2005). The soil properties, such as the chemical composition of soil organic matter and the matrix in which it is held, determine the different capacities of the land to act as a store for carbon that has direct implications for capturing greenhouse gases (FAO, 2004). 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).

Most soils may lose one-half to two-thirds of their SOC pool within 5 years in the tropics and 50 years in temperate regions. The new equilibrium may be attained after losing 20–50 Mg C/ha. Several studies has estimated the global loss at 40 Pg by Houghton (1995), 55 Pg by IPCC (1996) and Schimel (1998), 66–90 Pg by Lal (1999) and 150 Pg by Bohn (1978). Rozanov et al., (1990) observed that world soils have lost humus (58% C) at a rate of 25.3 Tg/year ever since agriculture began 10,000 years ago, 300 million tons/year in the past 300 years and 760 million tons per year in the last 50 years. The SOC is easily transported by runoff water or wind because it is of relatively low density (< 1.8 Mg/m^3) and is concentrated in the vicinity of the soil surface. A study on wind erosion in southwest Niger showed that wind-borne material trapped at 2-m height contained 32 times more SOC relative to the antecedent topsoil (Sterk et al., 1996).

In dryland soils, SOC declines with cultivation and even more so with desertification. In East Africa, Swift et al., (1994) reported that continuous cultivation for 14 years without recommended inputs of fertilizers and manures decreased SOC content by half from 2% to 1%. Pieri (1991) reported that continuous cropping without application of fertilizers and/or manure leads to rapid decline in SOC content. The experimental results revealed a marked decline in soil C, reaching some 13 tonnes/ha (Fig. 3) when aboveground material is harvested and removed and some FYM is applied at different times, equivalent to 3.9 tonnes/ha/year. The rate of depletion of SOC content is accentuated by soil erosion, because of the preferential removal of the finer soil fractions comprised of clay and organic matter. The SOC is often bound with the clay fraction (Quiroga et al., 1996, 1998) which is preferentially removed by erosion. Adoption of inappropriate land use and farming practices can deplete SOC content (Table 6). These trends, if unchecked, accentuate the process of desertification. Swift et al., (1994) indicated that land degradation around the world has led to an SOC loss of 8 to 12 Mg C ha^{-1}on land area of 1.02 Bha (UNEP, 1991), the total historic C loss would be 8 to 12 Pg C.

5. C sequestration to combat land degradation in drylands

Drylands are considered to be areas where average rainfall is less than the potential moisture losses through evaporation and transpiration. About 47 percent of the surface of the earth can be classified as dryland (UNEP, 1992). Droughts are characteristic of drylands and can be defined as periods (1–2 years) where the rainfall is below the average. The main characteristic of drylands is lack of water. This constrains plant productivity severely and therefore affects the accumulation of C in soils. The problem is aggravated because rainfall is not only low but also generally erratic. Therefore, good management of the little available water is essential. In addition, the SOC pool tends to decrease exponentially with temperature (Lal, 2002a). Consequently, soils of drylands contain small amounts of C (between 1 percent and less than 0.5 percent) (Lal, 2002b). The SOC pool of soils generally increases with the addition of biomass to soils when the pool has been depleted as a consequence of land uses (Rasmussen and Collins, 1991; Paustian et al., 1997; Powlson et al., 1998, Lal, 2001a). Soils in drylands are prone to degradation and desertification, which lead

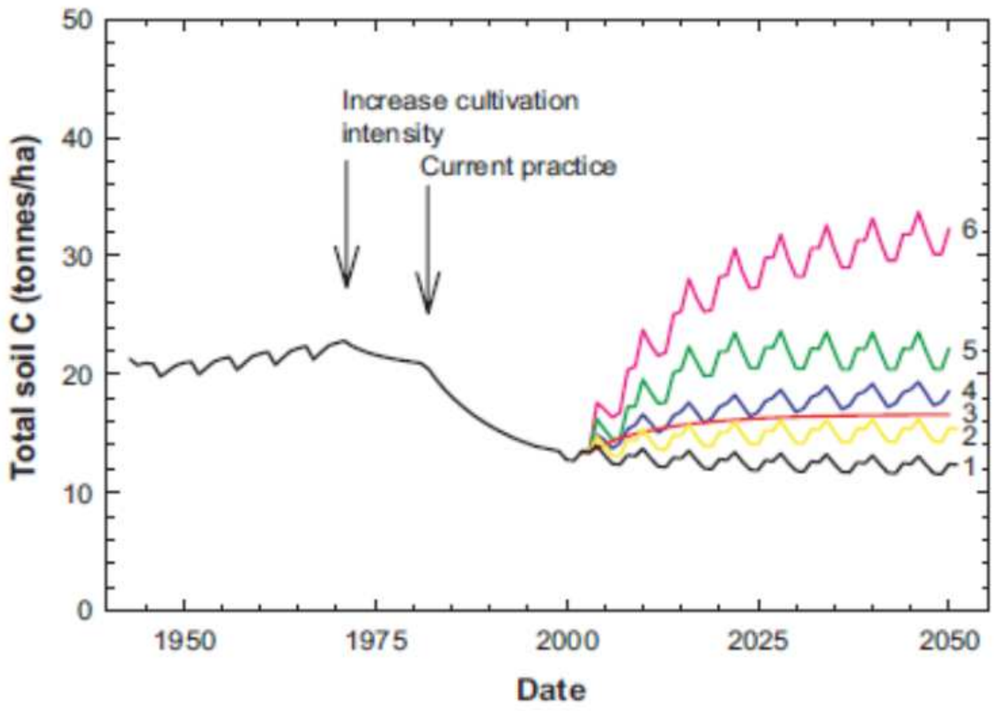

Figure 3. Change in total soil carbon for a rainfed farm

Traditional practices	Recommended
Plough till	Conservation till/ no till
Residue removal/ burning	Residue return as mulch
Summer fallow	Growing cover crop
Low off-farm input	Judicious use of fertilizers and integrated nutrient management
Regular fertilizer use	Soil- site specific management
No water controlFence-to fence cultivation	Water management/ conservation, irrigation, water table management
Fence-to fence cultivation	Conservation of marginal lands to nature conservation
Monoculture	Improved farming systems with several crop rotations
Land use along poverty lines and political boundaries	Integrated watershed management
Draining wetland	Restoring wetlands

Table 6. Agricultural practices for enhancing productivity and increasing the amount of carbon in soils

to dramatic reductions in the SOC pool. Soil-quality improvement as a consequence of increased soil C will have an important social and economic impact on the livelihood of people living in these areas. The ability of agriculture lands to store or sequester carbon depends on several factors, including climate, soil type, type of crop or vegetation cover and management practices. Carbon sequestration in the agriculture sector refers to the capacity of agriculture lands and forests to remove carbon dioxide from the atmosphere. Carbon dioxide is absorbed by trees, plants and crops through photosynthesis and stored as carbon in biomass in tree trunks, branches, foliage and roots and soils (EPA, 2008b). Forests and stable grasslands are referred to as carbon sinks because they can store large amounts of carbon in their vegetation and root systems for long periods of time. Soils are the largest terrestrial sink for carbon on the planet. The amount of carbon stored in soil organic matter is influenced by the addition of carbon from dead plant material and carbon losses from respiration, the decomposition process and both natural and human disturbance of the soil. By employing farming practices that involve minimal disturbance of the soil and encourage carbon sequestration, farmers may be able to slow or even reverse the loss of carbon from their fields. In the United States, forest and croplands currently sequester the equivalent of 12 percent of U.S. carbon dioxide emissions from the energy, transportation and industrial sectors (EPA, 2008b).

The sequestration of atmospheric C in the soil and biomass not only reduces greenhouse effect but also helps maintain or restore the capacity of the soil to perform its production and environmental functions on sustainable basis. Dry soils are less likely to lose C than wet soils (Glenn et al., 1992) as a lack of water limits soil mineralization and therefore the flux of C to the atmosphere. Consequenlty, the residence time of C in dryland soils is long, sometimes even longer than in forest soils.

6. Carbon sequestration potential

Several studies have attempted to assess the potential for carbon sequestration in drylands (Table 7). Lal (2001) estimated that they had the potential to sequester up to 0.4–0.6 Gt of carbon a year if eroded and degraded dryland soils were restored and their further degradation were stopped. Glenday (2008) measured forest carbon densities of 58 to 94 tonnes C/ha in the dry Arabuko-Sokoke Forest in Kenya and concluded that improved management of wood harvesting and rehabilitation forest could substantially increase terrestrial carbon sequestration. Farage et al., (2007) in dryland farming systems in Nigeria, Sudan and Argentina showed that it would be possible to change current farming systems to convert these soils from carbon sources to net sinks without increasing farmers' energy demand. Hülsbegen and Küstermann et al., (2008) compared 18 organic and 10 conventional farms in Bavaria, Germany and calculated the organic farms annual sequestration at 402 kg carbon, while the conventional farms had losses of 202 kg. Hepperly et al., (2008) estimated that compost application and cover crops in the rotation were particularly adept at increasing soil organic matter, also compared to no tillage techniques (Table 8).

Technological options	Sequestration potential (Tonnes C/ha/year)
Croplands	0.10 – 0.20
Conservation tillage	0.05 – 0.10
Mulch farming (4-6 Mg/ha/year)	0.10 – 0.20
Compost (20 Mg/ha/year)	0.05 – 0.10
Elimination of bare fallow	0.10 – 0.20
Integrated nutrient management	0.10 – 0.20
Restoration of eroded soils	0.05 – 0.10
Restoration of salt effected soils	0.10 – 0.20
Agricultural intensification	0.10 – 0.30
Water conservation and management	0.05 – 0.10
AfforestationGrassland and pastures	0.05 – 0.10

Lal et al. (1998)

Table 7. Effects from land management practices or land use on carbon sequestration potential in drylands

Practices	Soil Carbon sequestration (kg/ha)
Compost	1000 to 2000
Cover crop	800 to 1200
No-till	100 to 500
Rotation	0 to 200
Manure	0 to 200
Cover+rotation	900 to 1400
Compost + Cover + Rotation + No till	2000 to 4000

Table 8. Soil carbon sequestration estimates for different agricultural practices. Data projected from Rodale long-term trials

7. Management options to control sequester carbons

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, evaporation and decreasing soil temperature by residue mulching, is important. Application of fertilizers, irrigation and manuring are all common practices that consume C. Innovative farming practices such as conservation tillage, organic production, improved cropping systems, land restoration, land use change, irrigation and water management are the strategies to increase the C storage. Organic systems of production increase soil organic matter levels through the use of composted animal manures and cover crops

(Rodale Institute, 2008). Organic cropping systems also eliminate the emissions from the production and transportation of synthetic fertilizers. Land restoration and land use changes that encourage the conservation and improvement of soil, water and air quality typically reduce greenhouse gas emissions. Soil quality is largely governed by soil organic matter (SOM) content, which is a dynamic pool and responds effectively to changes in soil management, primarily tillage and carbon inputs resulting from biomass production.

8. Conservation agriculture

Conservation tillage as an integral part of conservation agriculture includes a minimum 30% soil cover after planting to reduce soil erosion implies conformity with all three of its pillars: (i) minimum soil disturbance (ii) diverse crop rotations and/or cover crops and (iii) continuous plant residue cover. Reducing tillage reduces soil disturbance and helps mitigate the release of soil carbon into the atmosphere. Conservation tillage also improves the carbon sequestration capacity of the soil. The amount of carbon released from soils depends directly on the volume of soil disturbed during tillage operations. Therefore, lesser the soil is disturbed, better the conservation of soil carbon. Additional benefits of conservation tillage include improved water conservation, reduced soil erosion, reduced fuel consumption, reduced compaction, increased planting and harvesting flexibility, reduced labour requirements and improved soil tilth. Stewart and Robinson (2000) indicated 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. In northern Colorado, Potter et al., (1997) observed 560 kg C/ha/y accumulation during 10 years of no-till continuous cropping wheat system. Kihani et al., (1984) conducted soil analyses on a 45-year old tillage experiment and reported that incorporation of biosolids improved SOC concentration. Murillo et al., (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. Holland (2004) gives the interactive processes as a consequence; conservation agriculture generate the soil's structural stability and have a substantial impact on the environment (Fig 4).

9. Organic input and manuring

Mineral nitrogen in soils may contribute to the emission of nitrous oxides and is one of the main drivers of agricultural emissions. The efficiency of fertilizer use decreases with increasing fertilization, when a great part of it is not taken up by the plant but emitted into the water bodies and the atmosphere. In summary, the emission of GHG in CO_2 equivalents from the production and the application of nitrogen fertilizers from fossil fuel amounts at approximately 480 million tonnes (1 percent of total global GHG emissions) in 2007. In 1960, 47 years earlier, it was less than 100 million tones. In dryland areas, several studies demonstrated the importance of judicious use of fertilizer, compost and nutrient management (Fuller, 1991; Traore and Harris, 1995; Singh and Goma, 1995; Pieri, 1995; Miglierina et al., 1996; Laryea et al., 1995). 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 et al.,

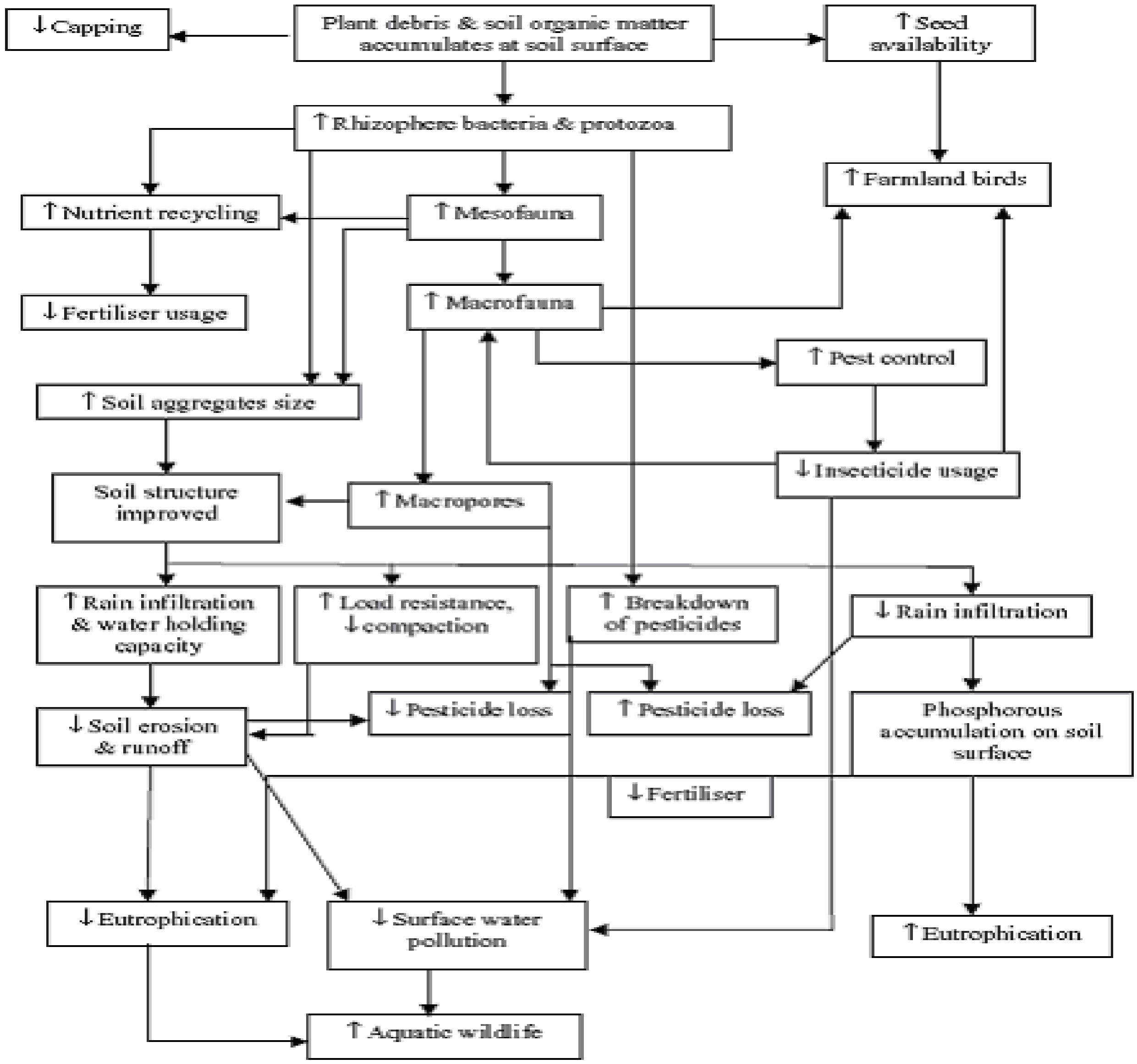

Figure 4. Interactive process through which conservation tillage can generate environmental benefits (Holland, 2004)

1994; Dalal et al., 1995). Recycling nitrogen on the farm by using manure and nitrogen fixing plants (the predominant technique of organic and low external input agriculture) enhances soil quality and provides nutrients. However, timing and management of its use are essential. Nambiar (1995) reported increase in SOC content with manuring from 0.20% to 0.25% in 1997-1989 for a sandy soil. Ryan (1998) observed a significant increase in SOC concentration by application of recommended rates of fertilizers. Mäder et al., (2002) compare the relative input and output of three farming systems: organic agriculture; integrated production with farmyard Manure and stockless integrated production in a 28 years experiment. Input of nutrients, organic matter, pesticides and energy as well as yields were calculated. Crop sequence was potatoes, winter wheat followed by fodder intercrop, vegetables (soybean), winter wheat (maize), winter barley (grass-clover for fodder production, winter wheat), grass-clover for fodder production, grass-clover for fodder production. Crops in brackets are alterations in 1 of the 4 crop rotations. The results indicated an increased efficiency of organic agriculture for most arable crops, with grain crops showing a yield reduction of only 20 percent while fertilizer inputs were lower by 50-60 percent (Fig. 5). Mishra et al. (1974) reported that application of manure at the rate of 9–30 Mg ha^{-1} y^{-1} caused significant increase in SOC content. 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 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. Mathieu et al., (2006) pointed out that higher soil carbon levels may lead to N_2 emission rather than N_2O. Petersen et al., (2005) found lower emission rates for organic farming compared to conventional farming in five European countries. In a long-term study in southern Germany, Flessa, et al. (2002) also found reduced N_2O emission rates in organic agriculture, although yield-related emissions were not reduced. A reduction of the Global Warming Potential (GWP, 64 %) has also been found at Michigan State University for organic crops as compared to the conventional (Robertson et al., 2000). In India, Gupta and Venkateswarlu (1994) observed that application of manure at 10 Mg/ha increased SOC concentration. For Vertisols in the Ethiopian Highlands, Wakeel and Astartke (1996) recommended adoption of improved agricultural practices (nutrient management, water conservation, new varieties and crop rotation) to minimize risks of soil degradation. Use of high-lignin amendments, recalcitrant to decomposition, increases SOC concentration.

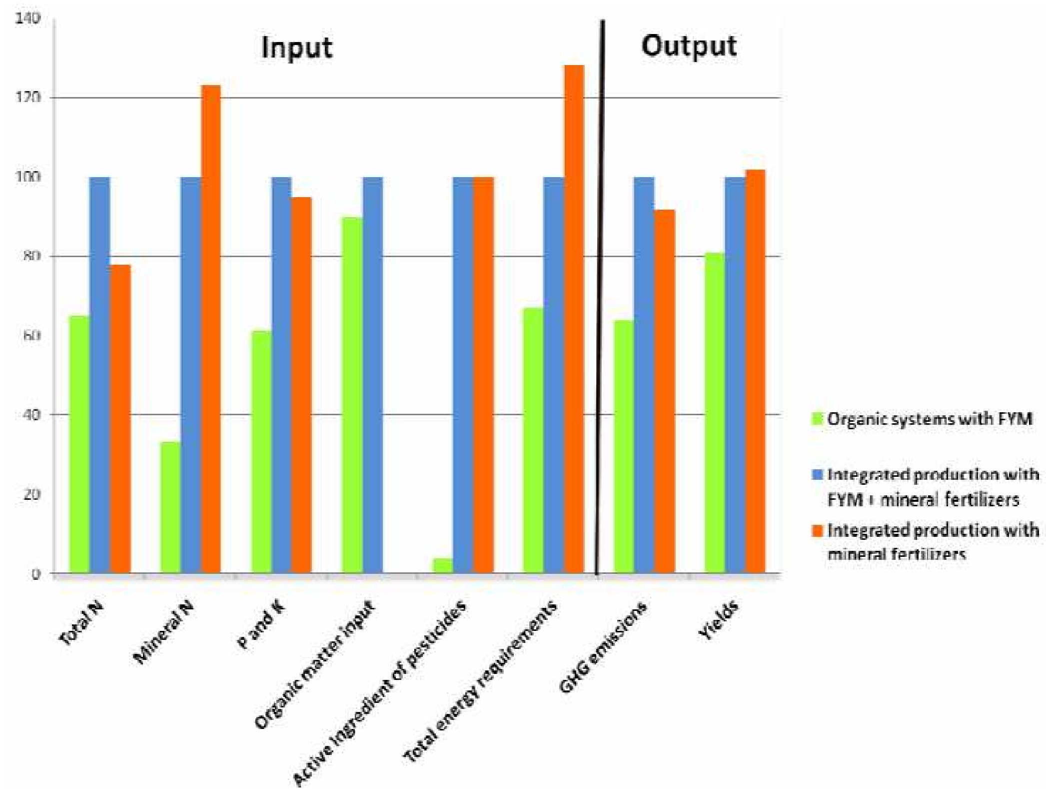

Figure 5. Comparison of GHG and crop productivity in different farming systems in long term field experiments

10. Crop rotation

Numerous case studies show that in comparison to traditional subsistence farming, organic yields were 112 percent higher due to crop rotation, legumes and closed circuits. Miglierina et al., (1993, 1996) observed that SOC content was high in wheat-grassland and wheat-alfalfa (*Medicago sativa*) rotations, especially with a conservation tillage system. In another study, Ryan et al., (1997) reported the beneficial effects of using reduced tillage for enhancing SOC concentration are accentuated when used in conjunction with rotations based on appropriate cover crops or pastures. Skjemstad et al., (1994) reported an increase of 550 kg C/ha/y in a Vertisol under Rhodes grass. In Saudi Arabia, Shahin et al., (1998) observed that introducing alfalfa in rotation with wheat grown on a sandy soil increased SOC concentration threefold as compared with continuous wheat. In Syria, Ryan (1998) reported that incorporation of *Medicago* in rotation increased SOC concentration to 1-m depth. Jenkinson et al., (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. In a Vertisol in central India, Mathan et al., (1978) reported that continuous cropping and manuring increased SOC concentration by 20%–40% over 3 years. In northern India, Singh et al., (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. Barber (1994) observed that sub-soiling and incorporation of cover crops in rotation enhanced soil quality. Lomte et al., (1993) reported that intercropping sorghum (*Sorghum bicolor*) with legumes and application of manure increased SOC content and aggregation. Some examples of soil management practices that may lead to SOC sequestration are listed in Table 9 and 10. 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.

11. Grazing management

Excessive and uncontrolled grazing are a major cause of the acceleration of the desertification process. 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. In the Sahel, deposition of droppings ranges from 1 tonne/ha to 50 tonnes/ha depending on the time that animals are kept on the same field (Sagna-Cabral, 1989; Hoffmann and Gerling, 2001). However, direct exposure to the elements can reduce the nutrient value of dung and droppings considerably. Although stubble grazing has a long tradition in drylands, increasing land scarcity, limited purchasing power among many smallholders and increased risks of animal theft in many areas have contributed to a general decline in herd sizes and in some cases, led to the abandonment of

Strategy/technique	Practice	Location/region	Reference
Erosion control/water conservation	a) No-Till farming	Bushland, TX, USA Northern CO, USA Queensland, Australia West Africa Sahel Southern Spain	Jones and others 1997 Potter and others 1997 Dalal and others 1997 Bationo and others 2000 Murillo and others 1998
	b) Mulching • stone cover • residue mulch • mulch	Negev Desert Chihuahuan Desert Suriname	Lahav and Steinberg 2001 Rostagno and Sosebal 2001 Breeman and Protz 1988
Crop Diversification	a) Rotations	Saudi Arabia, West Asia, Alegria, North Africa	Shahin and others 1998 Arabi and Roose 1989
	b) Legumes	Syria, West Asia Australia Northern India Argentina	Jenkinson and others 1999 Whitehouse and Littler 1984 Singh and others 1996 Galantini and Rosell 1997
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
Water management	a) Irrigation and conservation tillage	Mexico	Folleu and others 2003
	b) Irrigation with sewage	Israel	Hillel 1998
	c) Irrigation with silt-laden water	China	Fullen and others 1995
	d) Saline aquaculture	Drylands	Glen and others 1993

Table 9. Strategies of soil management in dryland ecosystems for carbon sequestration

stubble grazing altogether. Pluhar et al., (1987) observed that grazing caused a significant decline in infiltration capacity by reducing the protective vegetal cover and increasing the surface area of the bare ground. Thurow et al., (1988) also observed that infiltration capacity decreased and inter-rill erosion increased in the heavily stocked pastures. In Alice, Texas, Weltz and Blackburn (1995) observed that the saturated hydraulic conductivity was the least for the bare soil. Biomass burning also affects soil hydrological properties. Hester et al., (1997) showed that fire reduced water infiltration capacity in case of the oak and juniper vegetation types. Therefore, controlled grazing, fire management and planting improved species are important considerations of enhancing biomass production and improving soil quality. Some examples of improved practices with positive impact on the SOC pool are listed in Table 11. Important among these are grazing management through controlled stocking and rotational grazing, fire management, and agroforestry practices involving legume species (Conarc et al., 2001).

Strategy/technique	Location/region	Reference
Surface application of biosolids	Chihuahuan Desert	Rostagno and Sosebal 2001
Stone cover	Negev Desert	Lahav and Steinberg 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

Table 10. Soil management options for C sequestration in soils of dryland ecosystems

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

Table 11. Strategies of pasture and range land management for soil carbon sequestration.

12. Erosion control

Soil C losses can occur both as a result of mineralization as well as through erosion often making it a complex relationship. Where water erosion dominates, a high proportion of soil C may be washed into alluvial deposits close to the erosion site and stored there in forms which decay more slowly than in the parent soils. Therefore, this kind of erosion may have a positive effect on soil CS. In Western Nigeria Gabriels and Michiels (1991) observed C losses from bare fallow Alfisol plots with slopes of 1, 5 and 10 % , varied from 54 to 3080 $kgha^{-1}$. Erosion does not always decrease productivity, but if it could be shown to do so, it would be perverse to favour decreased productivity for a medium term and perhaps one-off gain in sequestered C. The same arguments probably do not apply where wind erosion is the main erosional process, for organic matter is usually blown great distances and dispersed to places where it may decay rapidly and release its C. Management options that increase the amount of live and dead biomass left in agricultural areas decrease erosion in general while simultaneously increasing the C input to the soil (Tiessen and Cuevas, 1994). Assuming that 20% of the C displaced is emitted to the atmosphere (Lal et al., 1998), erosion (e.g., light, moderate, severe and extreme forms) leads to emission of 0.206 to 0.262 Pg C $y^{-1.}$ Erosion also leads to exposure of the sub-soil rich in calciferous materials. These areas, severely affected by strong and extreme wind erosion, are estimated at about 103.6 Mha. If 10% of these areas have calciferous horizons exposed at the soil surface, about 10 Mha are subject to the impact of anthropogenic perturbations and environmental factors (e.g., ploughing, application of fertilizers, root exudates, acid rain, etc.). These factors may lead to dissolution of carbonates and emission of CO_2. If this exposed layer containing high amounts of carbonates and bicarbonates leads to emissions of C at the rate of 0.2 to 0.4 Kg C ha^{-1} yr^{-1}, the annual rate of emissions of C from SIC is 2 to 4 × 10^6 Kg C y^{-1}. Therefore, total C emission due to soil erosion and exposure of calciferous horizon is 0.21 to 0.26 Pg C y^{-1}. Three main type of erosion preventive techniques are (Lal, 1990) i) those that increase the soils' resistance against agents of erosion; ii) soil surface management techniques that help establish quick ground cover and; iii) techniques that provide a buffer against rainfall and runoff erosivity.

13. Summary

Many of the factors affecting the flow of C into and out of the soil are affected by land-management practices. The soils of drylands have lost a significant amount of C and, therefore, offer a great potential for rehabilitating these areas. There are vast areas of dryland ecosystems in developing countries where improvements in farming systems could add C to soils. Tillage-based agriculture damages the soil, conservation agriculture builds soil quality, protects water quality, increases biodiversity and sequesters carbon. Considering the growing concern of elevated atmospheric greenhouse gases, the complex economics and availability of fossil fuels, the deterioration of the environment and health conditions, a shift away from intense reliance on heavy chemical inputs to an intense biologically based agriculture and food system is possible today. Sustainable and conservation agriculture offer multiple opportunities to reduce greenhouse gas emissions and counteract global warming. Improving energy efficiency by managing agricultural and food inputs can make a positive contribution to reducing agricultural greenhouse gas emissions. This environmentally beneficial and economically viable method of production agriculture should be supported and endorsed through policy mechanisms so that worldwide adoption is increased and global benefits are realized. Mitigation of atmospheric CO_2 by increase CS in the soil, particularly make sense in the scope of other global challenges such as combating land degradation, improving soil quality and preserving biodiversity. Effective mitigation policies will likely be based on a combination of modest and economically sound reduction which confer added benefits to society.

Author details

Peeyush Sharma
Division of Soil Science & Ag-Chemistry, SKUAST-J, India

Vikas Abrol
Dryland Research Substation, RakhDhiansar, SKUAST-J, India

Shrdha Abrol
GGM Science College, Jammu, J&K, India

Ravinder Kumar
KVK, Rampur, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, India

14. References

Arnalds, O. 2000. Desertification: An appeal for a broader perspective. Pages 5–15 *in* O. Arnalds, and S. Archer. Eds, Rangeland desertification. Kluver Academic Publishers, Dordrecht, The Netherlands.

Babaev, A. G. (ed.): 1999, Desert Problems and Desertification in Central Asia, Springer, Berlin,p. 293.

Baird, A. J.: 1997. 'Overland Flow Generation and Sediment Mobilization by Water', in Arid Zone Geomorphology: Process, Form and Change in Drylands, J.Wiley and Sons, U.K., pp. 165–184.

Balba, A. M.: 1995. Management of Problem Soils in Arid Ecosystems, CRC/Lewis Publishers, Boca Raton, FL, p. 250.

Barber, R. G.: 1994, 'Soil Degradation in the Tropical Lowlands of Santa Cruz, Eastern Bolivia', Land Degrad. Rehab., 6: 95–108.

Batjes, N. H. 1998. Mitigation of atmospheric carbon dioxide concentrations by increased carbon sequestration in the soil. Biology & Fertility of Soils. 27:230–235.

Blum, C. Valentine, and B. A. Stewart. Eds, Methods for assessment of soil degradation. CRC Press, Boca Raton, Florida.

Brandt, C. J. and Thornes, J. B. (eds.): 1996, Mediterranean Desertification and Land Use, J. Wiley & Sons, Chichester, U.K., p. 554.

Change 2007: Mitigation', Contribution of Working Group III to the Fourth Assessment Report of the IPCC [B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, L. A. Meyer (eds)], Cambridge and NY, USA: Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Conacher, A. J. and Sala, M. (eds.): 1998., 'Land Degradation in Mediterranean Environments of the World: Nature and Extent, Causes and Solutions', J. Wiley & Sons, Chichester, U.K., p. 491.

Conacher, A. J. and Sala, M.: 1998b. 'The Causes of Land Degradation 2: Vegetation Clearing and Agricultural Practices', in Conacher, A. J. and Sala, M. (eds.), *Land Degradation in Mediterranean Environments of the World: Nature and Extent, Causes and Solutions*, J. Wiley & Sons,Chichester, U.K., pp. 285–307.

Conant, R. T., K. Paustian, and E. T. Elliott. 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecological Applications, 11:343–355.

Dalal, R. C. 1989. Long-term effects of no-tillage, crop residue and nitrogen application on properties of a Vertisol. Soil Science Society of America J., 53:1511–1515.

Dalal, R. C. 1992. Long-term trends in total nitrogen of a Vertisol subjected to zero tillage, nitrogen application and stubble retention. Australian Journal of Soil Res., 30:223–231.

Dalal, R. C., W. M. Strong, E. J. Weston, J. E. Cooper, K. J. Lehane, A. J. King, and C. J. Chicken. 1995. Sustaining productivity of a Vertisol at Warra, Queensland, with fertilizers, no-till or legumes. I. Organic matter status. Australian Journal of Experimental Ag., 37:903–913.

Dregne, H. E.: 1983. *Desertification of Arid Lands,* Harwood Academic Publishers, New York.

Dregne, H.E. 1976. Soils of Arid Regions. Elsevier, Amsterdam. p. 237.

EPA. 2008b. Carbon Sequestration in Agriculture and Forestry. www.epa.gov/sequestration/index.html

Esenov, P. E. and Redjepbaev, K. R.: 1999. 'The Reclamation of Saline Soils', in Babaev, A. G. (ed.), *Desert Problems and Desertification in Central Asia*, Springer, Berlin, pp. 167–177.

Eswaran, H., P. F. Reich, J. M. Kimble, F. H. Beinroth, E. Padamnabhan, P. Moncharoen, and J. M. Kimble. 2000.Global carbon stocks. Pages 15–250 *in* R. Lal, H. Eswaran,and B. A. Stewart. Eds, Global climate change and pedogeniccarbonates. Lewis Publishers, Boca Raton, Florida.540.

FAO 2004. Carbon Sequestration in Dryland Soils, World Soils Resources Reports 102. Food and Agriculture Organization Of The United Nations, Rome.

FAO: 1993, *Key Aspects of Strategies for Sustainable Development of Drylands*, FAO, Rome, Italy

Flessa, H., Ruser, R., Dörsch, P., Kamp, T., Jimenez, M.A., Munch, J.C., Beese, F. 2002. Integrated evaluation of greenhouse gas emissions (CO2, CH4, N2O) from two farming systems in southern Germany. Agriculture, Ecosystems and Environment, 91: 175-189.

Fuller,W. H.: 1991, 'Organic Matter Applications', in Skujins, J. (ed.), *Semi-Arid Lands and Deserts:Soil Resource and Reclamation*, Marcel Dekker Inc., New York, pp. 507–542.

Glenn, E.P., Pitelka, L.F. & Olsen, M.W. 1992. The use of halophytes to sequester carbon. Wat. Air Soil Poll., 64: 251–263.

Gupta, J. P., and J. Venkateswarlu. 1994. Soil management and rainwater conservation and use. V. Aridisols*in* Soil management for sustainable agriculture in dryland areas. Bulletin on Indian Society of Soil Science ,16:Pages 66–77.

Hepperly, P., Moyer, J., Pimentel, D., Douds Jr, D., Nichols, K. And Seidel, R. (2008) Organic Maize/Soybean Cropping Systems Significantly Sequester Carbon and Reduce Energy Use. In: Neuhoff, D. *et al.*:(Eds): Cultivating the Future Based on Science. Volume 2 -

Livestock, Socio-economy and Cross disciplinary Research in Organic Agriculture. Proceedings of the Second Scientific Conference of the International Society of Organic Agriculture Research (ISOFAR), held at the 16th IFOAM Organic World Congress in Cooperation with the International Federation of Organic Agriculture Movements (IFOAM) and the Consorzio ModenaBio, 18 – 20 June 2008 in Modena, Italy.

Hester, J. W., Thurow, T. L., and Taylor, C. A., Jr.: 1997, 'Hydrologic Characteristic of Vegetation Types as Affected by Prescribed Burning', J. Range Manage., 50: 199–204.

Hoffmann, I. & Gerling, D. 2001. Farmers' management strategies to maintain soil fertility in a remote area in northwest Nigeria. Ag. Ecosys. Env., 86: 263–275.

Holland, J.M. 2004.The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence Agriculture, Ecosystems and Environment 103 :1–25

Houghton, R.A. 1995. Changes in the storage of terrestrial carbon since 1850. *In* R. Lal, J. Kimble, E. Levin & B.A. Stewart, eds. *Soils and global change*, pp. 45–65. CRC Press.

Hülsbergen, K.-J., Küstermann, B. 2008. Optimierung der Kohlenstoffkreisläufe in Ökobetrieben. Ökologie und Landbau, 145: 20-22.

IPCC. 2001. Climate Change 2001: The scientific basis. Executive summary. Cambridge Univ. Press, Cambridge, U.K.

IPCC. 1996. Climate change 1995. Impacts, adaptations and mitigation of climate change: scientific, technical analyses. Working Group II. Cambridge, UK, Cambridge University Press.

IPCC. 2001. Climate change: the scientific basis. Cambridge, UK, Cambridge University Press.

IPCC. 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning (eds)].*http://ipcc-wg1.ucar.edu/wg1/wg1-report.html*

Jenkinson, D. S., H. C. Harris, J. Ryan, A. M. McNeil, C. J. Pilbeam, and K. Coleman. 1999. Organic matter turnover in calcareous soil from Syria under a two-course cereal rotation. Soil Biology & Biochemistry, 31:643–649.

Kihani, K. N., and D. A. More. 1984. Long-term effect of tillage operation and farmyard manure application on soil properties and crop yield in a Vertisol. Journal of Indian Society of Soil Science ,32:392–393.

Lal, R. 2001a. World cropland soils as a source or sink for atmospheric C. Adv. Agron., 71: 145–174.

Lal, R. 2001a. World cropland soils as a source or sink for atmospheric C. Adv. Agron.,71: 145–174.

Lal, R. 2002. Carbon sequestration in dryland ecosystems of West Asia and North Africa. *Land Degradation & Development* 13:45–59.

Lal, R. 2002a. Soil carbon dynamics in crop land and rangeland. Env. Poll., 116: 353–362.

Lal, R. 2002b. Carbon sequestration in dryland ecosystems of west Asia and north Africa. Land Deg. Dev., 13: 45–59.

Lal, R., Hassan, H. M. and Dumanski, J.: 1999, 'Desertification Control to Sequester Carbon and Mitigate the Greenhouse Effect', in Rosenberg, N., Izaurralde, R. C., and Malone, E. (eds.), *Carbon Sequestration in Soils: Science, Monitoring and Beyond*, Proc. St. Michael Workshop, December 1998, Battelle Press, Columbus, OH, pp. 83–151.

Lal, R., Kimble, J.M., Follet, R.F. & Cole, C.V. 1998. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Chelsea, USA, Ann. Arbor. Press.

Laryea, K. B., Andres, M. M., and Pathak, P.: 1995, 'Long-Term Experiments on Alfisols and Vertisols in the Semi-Arid Tropics', in Lal, R. and Stewart, B. A. (eds.), *Soil management:Experimental Basis for Sustainability and Environmental Quality*, CRC/Lewis Publishers, Boca Raton, FL, pp. 267–292.

Le Hou´erou, H. N. 1975. Science, power and desertification. Meeting on desertization. Dept. Geogr. Univ. Cambridge,22–28 Sept, 1975, 26pp.

Lomte, M. H., Ateeque, M., Bharambe, P. R., and Kawarkhe, P. K.: 1993, 'Influence of Sorghum Legume Association on Physico-Chemical Properties of Soil', J. Maharashtra Agric,. 18: 388–390.

M.A. 2005. Millennium Ecosystem Assessment. Ecosystems and Human Well-being:Desertification Synthesis. World Resources Institute, Washington, DC.

Mabbutt, J. A.: 1984. 'A New Global Assessment of the Status and Trends of Desertification', Env.Cons., 11: 100–113.

Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U. (2002): Soil Fertility and Biodiversity in Organic Farming. Science, 296: 1694-1697.

Mainguet, M. 1991. Desertification: Natural background and human mismanagement. Springer Verlag, Berlin.

Mainguet, M. and Da Silva, G. G.: 1998. 'Desertification and Dryland Development: What Can Be Done?', Land Degrad. Develop., 9: 375–382.

Mathan, K. K., K. Sankaran, K. Kanakabushan, and K. K. Krishnamoorthy. 1978. Effect of continuous rotational cropping on the organic carbon and total nitrogen contents in a black soil. Journal of Indian Society of Soil Science, 26:283–285.

Middleton, N. J., and D. S. G. Thomas. 1992. World atlas of desertification. Edward Arnold/UNEP, Seven Oaks.

Miglierina, A. M., Galantini, J. A., Iglesias, J. O., Rosell, R. A., and Glave, A. 1996, 'Crop Rotation and Fertilization in Production Systems of the Semi-Arid Region of Buenos Aires', Revista de la Faculatd de Agronomia, Universidad de Buenos Aires, 15: 9–14.

Miglierina, A.M., Landriscini,M. R., Galantini, J. A., Iglesias, J. O.,Glave, A., and Gallardo Lancho, J. F. 1993, 'Fifteen Years of Crop Rotation and Fertilization in the Semi-Arid Pampas Region. I. Effect on the Chemical Properties of the Soil', *El estudio del suelo y de su degradacion en relacion con la desertification. Actas del 12 Congreso Latinamericano de la Ciencia del Suelo*,Sevilla (Espana), 19–26 Sept. 1993, pp. 751–758.

Mishra, M. M., Neelakantan, S., and Khandelwal, K. C. 1974, 'Buildup of Soil Organic Matter Continuous Manuring and Cropping Practices', *J. Res. Hayana Agric. Univ.* 4, 224–230.

Mortimore, M.: 1994. *Roots in the African Dust: Sustaining the Sub-Saharan Drylands*, Cambridge University Press, Cambridge, U.K., p. 219.

Murillo, J. M., F. Moreno, F. Pelegrin, and J. E. Fernandez. 1998. Response of sunflower to traditional and conservation tillage in southern Spain. Soil & Tillage Research, 49:223–241.

Nambiar, K. K. M.: 1995, 'Major Cropping Systems in India', in Barnett, V., Payne, R., and Steiner, R. (eds.), a*gricultural Sustainability, Economic, Environmental and Statistical Considerations*, J. Wiley & Sons, Chichester, U.K., pp. 133–170.

Noin, D. and Clarke, J. I.: 1997. 'Population and Environment in Arid Regions of the World', in Clarke, J. and Noin, D. (eds.), *Population and Environment in Arid Regions*, MAB/UNESCO,Vol. 19, The Parthenon Publishing Group, New York, pp. 1–18.

Ojima, D. S., Parton, W. J., Schimel, D. S., and Scurlock, J. M. O.: 1993, 'Modeling the Effects of Climatic and CO2 Changes on Grassland Storage of Soil C', Water Air Soil Pollut,. 70: 643–657.

Oldeman, L. R. and Van Lynden, G. W. J.: 1998. 'Revisiting the GLASOD Methodology', in Lal, R., Blum, W. H., Valentine, C., and Stewart, B. A. (eds.), *Methods for Assessment of Soil Degradation*, CRC Press, Boca Raton, FL, pp. 423–440.

Pankova, E. I. and Solovjev. D. S.: 1995. 'Remote Sensing Methods of Dynamics of Irrigated Land Salinity for Reconstruction of Geotechnical Systems', *Prubliemy Osvoieniia Pustin*, 1995, No. 3.

Paustian, K., Collins, H.P. & Paul, E.A. 1997. Management control on soil carbon. *In*:E.A. Paul, K. Paustian, E.T. Elliot & C.V. Cole, eds. *Soil organic matter in temperate agroecosystems. Long term experiments in north America*, pp. 15–49. Boca Raton, USA,CRC Press.

Petersen, S.O., Regina, K., Pöllinger, A., Rigler, E., Valli, L., Yamulki, S., Esala, M., Fabbri, C., Syväsalo, E., Vinther, F.P. 2005. Nitrous oxide emissions from organic and conventional crop rotations in five European countries. Agriculture, Ecosystems and Environment, 112: 200-206.

Pieri, C.: 1991. *Fertility of Soils: A Future for Farming in the West African Savannah*, Springer Verlag, Berlin, p. 348.

Pieri, C.: 1995, 'Long-Term Soil Management Experiments in Semi-Arid Francophone Africa', in Lal, R. and Stewart, B. A. (eds.), *Soil Management: Experimental Basis for Sustainability and Environmental Quality*, CRC/Lewis Publishers, Boca Raton, FL, pp. 225–266.

Pluhar, J. J., Knight, R.W., and Heitschmidt, R. K.: 1987. 'Infiltration Rate and Sediment Production as Influenced by Grazing Systems in the Texas Rolling Plains', J. Range Manage., 40: 240–243.

Polwson, S.D., Smith, P. & Coleman, K. 1998. European network of long-term sites for studies on soil organic matter. Soil Till. Res. 47: 309–321.

Potter, K. N., O. R. Jones, H. A. Torbert, and P. W. Unger. 1997. Crop rotation and tillage effects on organic carbon sequestration in the semi-arid southern Great Plains. Soil Science ,162:140–147.

Quiroga, A. R., Buschiazzo, D. E., and Peinemann, N.: 1996. 'Soil Organic Matter Particle Size Fractions in Soils of the Semi-Arid Argentinian Pampas', Soil Sci., 161, 104–108.

Quiroga, A. R., Buschiazzo, D. E., and Peinemann, N.: 1998. 'Management Discriminate Properties in Semi-Arid Soils', Soil Sci. 163, 591–597

Reynolds, J. F., and D. M. S. Smith. 2002. Do humans cause deserts?. Pages 1–21 *in* J. F. Reynolds, and D. M. Stafford Smith. Eds, Global desertification: do humans cause deserts?. Dahlem Univ. Press, Berlin.

Robertson, G.P., Paul, E.A., Harwood, R.R. 2000. Greenhouse gases in intensive agriculture: contributions of individual gases to the radioactive forcing of the atmosphere. Science, 289: 1922-1925.

Rodale. 2003. Farm Systems Trial, The Rodale Institute 611 Siegfriedale Road Kutztown, PA 19530-9320 USA

Rozanov, B. G., Targulian, V., and Orlov, D. S.: 1990. in Turner, B. L., Clark, W. C., Kates, R. W.,Richards, J. F., Mathews, J. T., and Meyer, W. B. (eds.), *The Earth as Transformed by Human Action*, Cambridge University Press, Cambridge, U.K., pp. 203–214.

Russell, J. S. 1981. Models of long-term soil organic nitrogen change. Pages 222–232 *in* M. J. Frissel, and J. A. Van Veen. Eds, Simulation of nitrogen behavior of soil-plant systems. Center for Agricultural Publishing and Documentation, Wageningen, Holland.

Ryan, J. 1998. Changes in organic carbon in long-term rotation and tillage trials in northern Syria. Pages 285–296 *in* R. Lal, J. M. Kimble, R. F. Follett, and B. A. Stewart. Eds, Management of carbon sequestration in soils. CRC/Lewis Publishers, Boca Raton, Florida.

Ryan, J., S. Masri, S. Garabet, and H. Harris. 1997. Changes in organic matter and nitrogen with a cereal legume rotation trial. Pages 79–87 *in* J. Ryan Eds, Accomplishment and future challenges in dryland soil fertility research in the Mediterranean area. ICARDA, Aleppo.

Sagna-Cabral, M.A. 1989. *Utilisation et gestion de la matière organique d'origine animale dans un terroir du centre nord du Sénégal. Cas du village de Ndiamsil*. Montpellier,France, Centre National d'Etudes gronomiques des Régions Chaudes.

Schimel, D. S., J. I. House, K. A. Hubbard, and P. and others Bousquest. 2001. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. Nature

Schimel, D.S. 1998. The carbon equation. Nature, 393: 208 - 209.

Shahin, R. R., M. A. El-Meleigi, A. A. Al-Rokiba, and A. M. Eisa. 1998. Effect of wheat stubble management pattern on organic carbon content and fertility of sandy soils under pivot irrigation system. Bulletin of the Faculty of Agriculture,Univ. of Cairo. *Cairo* 42:283–296.

Singh, G. and Goma, H. C. 1995. 'Long-Term Soil Fertility Management Experiments in East Africa', in Lal, R. and Stewart, B. A. (eds.), *Soil Management: Experimental Basis for Sustainability and Environmental Quality*, CRC/Lewis Publishers, Boca Raton, FL, pp. 347–384.

Singh, Y., D. C. Chaudhary, S. P. Singh, A. K. Bhardwaj, and D. Singh. 1996. Sustainability of rice-wheat sequential cropping through introduction of legume crops and green manure crops in the system. Indian Journal of Agronomy,41:510–514.

Skjemstad, J. O., V. R. Catchpoole, and R. P. LeFeuvre. 1994. Carbon dynamics in Vertisols under several crops as assessed by natural abundance 13C. Australian Journal of Soil Research, 32:311–321.

Skjemstad, J. O., V. R. Catchpoole, and R. P. LeFeuvre. 1994. Carbon dynamics in Vertisols under several crops as assessed by natural abundance 13C. Australian Journal of Soil Research, 32:311–321.

Sterk, G., Herrmann, L., and Bationo, A.: 1996. 'Wind-Blown Nutrient Transport and Soil Productivity Changes in Southwest Niger', Land Degrad. Develop., 7: 325–336.

Stern, N. 2006. The Stern Review on the Economics of Climate Change, Cambridge: Cambridge University Press.

Stewart, B. A., and C. A. Robinson. 2000. Land use impact on carbon dynamics in soils of the arid and semi-arid tropics. Pages 251–257 *in* R. Lal, J. M. Kimble, and B. A. Stewart. Eds, Global climate change and tropical ecosystems. CRC/Lewis Publishers, Boca Raton, Florida.

Swift, M. J., Seward, P. D., Frost, P. G. H., Qureshi, J. N., and Muchena, F. N.: 1994, 'Long-Term Experiments in Africa: Developing a Database for Sustainable Land Use under Global Change',in Leigh, R. A. and Johnston, A. E. (eds.), *Long-Term Experiments in Agricultural and Ecologica Sciences*, CAB International, Wallingford, U.K., pp. 229–251.

Swift, M.J., Seward, P.D., Frost, P.G.H., Qureshi, J.N. & Muchena, F.N. 1994. Longterm experiments in Africa: developing a database for sustainable land use under global change. *In* R.A. Leigh & Johnston A.E., eds. *Long-term experiments in agricultural and ecological sciences*, pp. 229–251. Wallingford, UK, CAB International.

Thurow, T. L., Blackburn, W. H., and Taylor, C. A., Jr. 1988. 'Infiltration and Inter-Rill Erosion Responses to Selected Livestock Grazing Strategies, Edwards Plateau Texas', J. Range Manage., 41: 296–302.

Tiessen, H. & Cuevas, E. 1994. The role of organic matter in sustaining soil fertility. Nature, 371: 783–785.

Traoré, S. and Harris, P. J. 1995, 'Long-Term Fertilizer and Crop Residue Effects on Soil and Crop Yields in the Savanna Region of Côte d'Ivoire', in Lal, R. and Stewart, B. A. (eds.), *Soil Management: Experimental Basis for Sustainability and Environmental Quality*, CRC/Lewis Publishers, Boca Raton, FL, pp. 141–180. UN: 1977, *Status of Desertification in the Hot, Arid Regions,Climatic Aridity Index Map and Experimental World Scheme of Aridity and Drought Probability, at a Scale of 1:25,000,000. Explanatory note*, UN Conference on Desertification A/Conf. 74/31, New York.

UNCED: 1992. Earth Summit Agenda 21: Programme of Action for Sustainable Development, UNEP, New York.

UNEP 1991. Status of desertification and implementation of the plan of action to combat desertification. UNEP, Nairobi, Kenya.

UNEP. 1992. World atlas of desertification. Nairobi.

UNEP. 1992. World atlas of desertification. Nairobi.

UNEP. 1997. World atlas of desertification. 2nd Edition. Nairobi.

UNEP: 1990. Desertification Revisited, UNEP/DC/PAC, Nairobi, Kenya.

US-EPA 2006 Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2020. United States Environmental Protection Agency, EPA 430-R-06-003, June 2006.

Verstraete, M. M. 1986, 'Defining Desertification: A Review', Clim. Change, 9: 5–18.

Wakeel, A. El and Astartke, A. 1996, 'Intensification of Agriculture on Vertisols to Minimize Land Degradation in Parts of the Ethiopian Highlands', Land Degrad. Develop., 7: 57–68.

Warren, A. 1996. Desertification. Pages XX–XX *in* . Eds, The physical geography of africa. Oxford Univ. Press, New York.

Weltz, M. A. and Blackburn, W. H. 1995, 'Water Budget for South Texas Rangelands', J. Range Manage,. 48: 45–52.

Whitehouse, M. J., and J. W. Littler. 1984. Effect of pasture on subsequent wheat crops on a black earth soil of the Darling Downs. II. Organic carbon, nitrogen and pH changes. Queensland Journal of Agriculture & Animal Science, 41:13–20.