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# Carbon Sequestration in Drylands

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**Abstract:** Drylands occupy 40% of the earth's surface and are prone to land degradation by different processes. Desertification, a vague and qualitative term, implying degradation of soil and vegetation due to anthropogenic activity, reportedly affects 3.6 billion ha of the drylands. Although desertification is most severe in sub-Saharan Africa, the problem is not confined to the developing countries and is also prevalent in arid and semi-arid regions of North America, Australia, and parts of Europe. Degradation of soil and vegetation leads to emission of greenhouse gases (e.g., $CO_2$, $CH_4$, $N_2O$) to the atmosphere. In contrast, improvement of soil quality through adoption of restorative measures can lead to increase in soil organic carbon content, improvement in biomass productivity, and mitigation of the greenhouse effect. Technological options for soil and vegetation restoration depend on ecozone characteristics and need to be validated and fine-tuned for site-specific situations. Restorative technologies include introducing appropriate plant species adopted to harsh environments, controlling erosion and reclaiming salt-affected soils, adopting water harvesting techniques and efficient irrigation systems. The potential of C sequestration of such measures may be 30 to 200 kg $ha^{-1}$ $y^{-1}$ depending on soil and ecozone characteristics. Identification of "trigger spots" may be necessary to set in motion the restorative process. While the potential of C sequestration in drylands may be high (0.9-1.9 Pg $y^{-1}$), realization of even a fraction of this potential requires a coordinated effort at national and international levels. Development of a policy that involves participation of farmers and land managers is crucial in this endeavor.

**Key words:** Soil organic carbon, soil degradation, soil stability, carbon sequestration, drylands.

Drylands, regions where evapotranspiration exceeds precipitation for an extended period, globally cover a total land area of about 6.1 billion ha (Bha) or about 40% of earth's land surface (Goudie, 1990). These lands are classified into different ecozones on the basis of a climatic aridity index which is the ratio of precipitation to evapotranspiration (P/ET). The latter is calculated by the method of Penman (1948) considering humidity, wind and solar radiation. Drylands are ecozones for which the aridity index is <0.50. As per this criteria, three ecozones (e.g., hyper-arid, arid and semi-arid) come under the category of

| Ecozone | Aridity Index (P/ET) |
|---|---|
| **A. Drylands** | |
| Hyper-arid | <0.03 |
| Arid | 0.03-0.20 |
| Semi-arid | 0.20-0.50 |
| **B. Humid lands** | |
| Sub-humid | 0.50-0.70 |
| Humid | 0.70-1.0 |
| Perhumid | >1.0 |

*Table 1. Soil physical properties of an Aridisol from Lyon County, Nevada, USA (unpublished data of NRCS, Courtesy of Dr. John Kimble)*

| Depth (cm) | SOC content (%) | Soil bulk density ($Mg\ m^{-3}$) | Texture (%) Clay | Silt | Sand | PWP (%) |
|---|---|---|---|---|---|---|
| 0-6 | 0.08 | 1.70 | 4.4 | 2.6 | 93.0 | 1.8 |
| 6-20 | 0.07 | 1.70 | 4.4 | 3.7 | 91.9 | 1.8 |
| 20-42 | 0.09 | 1.67 | 22.1 | 5.3 | 72.6 | 6.7 |
| 42-52 | 0.08 | 1.60 | 15.9 | 10.8 | 73.3 | 5.6 |
| 52-65 | 0.08 | 1.60 | 15.1 | 12.7 | 72.2 | 5.5 |
| 65-97 | 0.06 | 1.60 | 10.1 | 4.2 | 85.7 | 3.6 |
| 97-116 | 0.10 | 1.40 | 20.2 | 30.6 | 49.2 | 8.5 |
| 116-152 | 0.21 | 1.15 | 63.9 | 29.1 | 7.0 | 29.0 |

SOC = Soil organic carbon; PWP = Permanent wilting point.

drylands. The hyper-arid regions cover about 0.9 Bha. The remaining 5.2 Bha are drylands where some forms of agriculture and forestry are feasible.

Drylands are characterized by water deficit for an extended period that limits biomass production. Supplemental irrigation is the principal mean to prolong the growing season and increase production. Because of the shortage of good quality water, however, the extent of land area under irrigation is also limited. Out of the total area, irrigated land comprises 3%, rainfed cropland about 9%, and rangeland about 88%. As much as 28% of earth's land area is too arid to support economic plant growth.

Most soils of hyper-arid and arid ecozones (mean annual rainfall of 100-200 mm) are not well developed due to low rainfall, none or slight leaching, and sporadic vegetation. Therefore, topography plays an important role in soil development. Predominant soils of these ecozones are Aridisols, Alfisols, Inceptisols and Vertisols (Soil Survey Staff, 1999). Because of low leaching and high evaporation, most soils are characterized by high salt concentration. In addition, wind blown or loess-derived soils also cover large areas (Dregne, 1976).

With progressive increase in precipitation from arid to semi-arid ecozones, there is increase in plant community and the biomass added to the soil. Therefore, soil organic carbon (SOC) content increases and soil horizons are more developed. Predominant soils of semi-arid regions comprise Aridisols, Alfisols, Entisols and Vertisols (Kampen and Burford, 1980). These soils are also subject to intense rains concentrated in a short time, and are thus exposed to severe water and wind erosion hazards.

In addition to low SOC content (often <0.1%), even in the surface horizon, soils of arid ecozones may also have high sand content (>90%), high soil bulk density (>1.6 $Mg\ m^{-3}$) and low plant-available water holding capacity (Table 1). These soils tend to have more sandy particle size, and low degree of aggregation. Some soils have high salt content, including high concentrations of $CaCO_3$ and $CaSO_4$. Therefore, there are numerous soil-related constraints to biomass production (Table 2). Important among these are drought, poor

*Table 2. Soil-related constraints to biomass production in dry regions*

| Soil | Constraints | References |
|---|---|---|
| Salt-affected soils | High salt content, drought, poor soil structure, poor drainage | Dregne (1976, 1977); Balba (1981), Massoud (1974) |
| Calcareous soils | Drought stress, crusting, low fertility, micronutrient deficiency, high pH | Reullan (1973) |
| Gypsic soils | Drought stress, high salt contents | Soil Survey Staff (1999) |
| Sandy soils (Entisols) | Unfavorable physical condition, low soil fertility, drought stress, wind erosion | Goudie (1990) |
| Desert Pavement Gravelly horizon | Poor root growth, drought stress | Balba (1995) |

soil structure, low effective rooting depth, and high salt content.

The objective of this paper is to review technological options for restoration of degraded soils, and assess the potential of drylands for C sequestration and mitigate the greenhouse effect.

## Soil Degradation and Desertification

Harsh climate, weak soil structure, low ground cover, and low rate of biomass production make soils of drylands highly prone to degradation. Soil degradation implies decline in soil quality, its biomass productivity and environmental moderating capacity. Determinants of soil quality include structure, SOC content, available water capacity, nutrient reserve, rooting depth, electrical conductivity, etc. Soil degradation and desertification lead to decline in these key indicators, and drylands are prone to severe problems by several degradative processes (e.g., erosion, salinization, compaction). Further, degradative processes are exacerbated by anthropogenic factors, including agricultural activities and biomass burning. Human-induced soil degradation in dry regions is also termed desertification. The latter implies spread of desert-like environments, especially in semi-arid regions. The process has been misnomered by terms such as "creeping desert", "encroachment of the desert", etc. The term also is often implied to denote ecological degradation, including reduction of vegetative cover, decline in biodiversity, accelerated soil erosion. In general, desertification means decline in productivity of land due to land misuse and soil mismanagement. The concept, even at best, is qualitative, subjective and vague.

Desertification affects some 3.6 billion ha, which is about 25% of the earth's land area, and a home to about 1 billion people. Estimates of desertified lands include 43 million hectares (Mha) of irrigated lands, 216 Mha of rainfed croplands, 777 Mha of degraded rangeland, and 2556 Mha of degraded vegetation in rangeland (Dregne, 1977; UNEP, 1991, 1992). Desertification exacerbates and perpetuates the problems of poverty, lack of food security, and decline of environment quality. Some 73% of Africa's agricultural drylands are severely to moderately degraded, and the problem is equally severe in Asia and Australia.

Desertification is most severe in sub-Saharan Africa because of harsh climate

*Table 3. Options to increase SOC content*

| Option | Location | Soil | Reference |
|---|---|---|---|
| Conservation tillage and residue management | Texas, U.S.A. | Torrertic Paleustoll | Unger *et al.* (1997), Unger (1997) |
| Long fallow | Queensland, Australia | Vertisol | Hulugalle and Entwistle (1997); Dalal (1992) |
| Crop rotations | Argentina | Entic Haplustoll | Galantini and Rosell (1997) |
| Fuel wood plantations | Haryana, India | Aridisols | Bhatia *et al.* (1998) |
| | UP, India, | Inceptisols | Garg and Jain (1996) |
| | NE Sudan | – | Alstad and Vetas (1994) |

with low and erratic rainfall, and fragile soils. Desertification is exacerbated by accelerated soil erosion and other forms of degradation. At least 200 million inhabitants of Africa are affected by desertification. Principal causes of desertification in Africa include over-grazing, affecting 194 Mha (15.1% of the total land area of Africa), inappropriate agricultural practices used on 60 Mha (4.7%), overexploitation on 56 Mha (4.3%), and deforestation on 22 Mha (1.7%) (IFAD, 1998). These causes are driven by high growth of population, increasing at the rate of about 3% $y^{-1}$. Asia has a large area of land prone to desertification. World-wide, as many as 110 countries have drylands that are at risk of desertification.

Soil degradation and desertification are not necessarily confined to poor developing countries, although both severity and extent are large in those areas than in developed countries. Among developed countries, Australia has a large area prone to desertification (Mabbutt, 1992). Intensive cropping and monoculture has led to decline in soil structure, accelerated erosion, and release of C from soil to the atmosphere. On the Vertisol plains of NSW, Australia, Chan *et al.* (1995) observed an average of 32% loss in SOC content in the cropped soils over a 2- to 50-year period. Decline in SOC content resulted in significantly lower water stability of surface soil under cropping. The cropped soil had lower porosity and pore continuity than that under pasture. Desertification is also reported to be serious problem in U.S. rangeland where 51% of rangeland is supposedly in poor to very poor conditions (Le Houérou, 1992).

## Soil Degradation and the Greenhouse Effect

The accelerated greenhouse effect, the risk of increase in radiative forcing due to rising tropospheric concentration of some trace gases (e.g., $CO_2$, $CH_4$, $N_2O$, CFCs, H-CFCs), is accentuated by soil degradation in general and desertification in particular. Soil degradation affects atmospheric concentration of greenhouse gases, both directly and indirectly (Fig. 1). Important among direct effects are oxidation/ mineralization of SOC and exposure of caliche or the carbonate-rich material to the surface through removal of topsoil by accelerated erosion. Oxidation of SOC is accentuated by plowing, resource-based or subsistence agriculture, removal of crop residue and other biomass, overgrazing, etc.

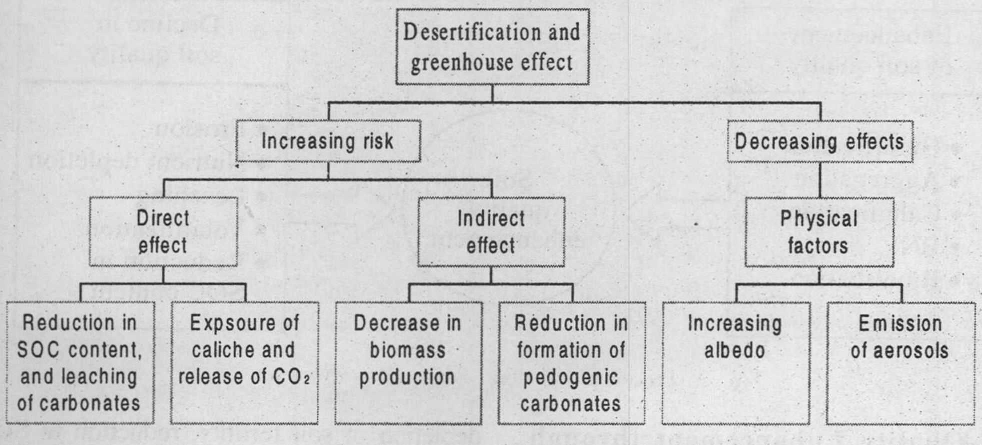


*Fig. 1. Desertification impacts on emission of greenhouse gases.*

Exposure of caliche to the surface can lead to its acidification and release of $CO_2$. There are no known observations on the impact of the exposed caliche on emission of $CO_2$. Such effects need to be quantified. Acidification may be accentuated by agricultural activities, use of acidifying fertilizer (e.g., ammonium sulfate) and impact of root exudates. Indirect effects of desertification are those due to reduction in biomass production, and no or minimal return of crop residue to the soil. Decrease in biomass production on degraded soils is due to decline in soil structure with attendant increase in soil bulk density. Charreau and Nicou (1971) observed that soil bulk density of 0-10 cm depth increased from 1.37 Mg $m^{-3}$ in woody savannah to 1.65 Mg $m^{-3}$ on crop land. Similarly, the structural instability index increased from 0.42-0.79 under woodland savannah to 1.32-1.56 in cropland (Chauvel, 1966). Consequently, hydraulic conductivity also decreased from 2.21-3.90 cm $h^{-1}$ under savannah to 1.10-1.18 cm $h^{-1}$ on cultivated soils. Reduction in soil biodiversity leads to decrease in soil respiration and decline in the rate of formation of secondary carbonates (Lal *et al.*, 1997).

Desertification may also lead to some decrease in radiative forcing. There are two possible scenarios that may reduce the risks of global warming (Fig. 1). One is the possibility of increase in albedo due to denudation of vegetation cover and decrease in SOC content. The other is the increase in concentration of dust particles in the atmosphere with a net cooling effect. Desertification accentuates "Harmattan", wind-blown fine dust in the atmosphere, that has been observed as far west as the Caribbean and as far north as Scotland.

The overall net effect of desertification, however, is on increase in radiative forcing through increase in emission of radiatively-active gases.

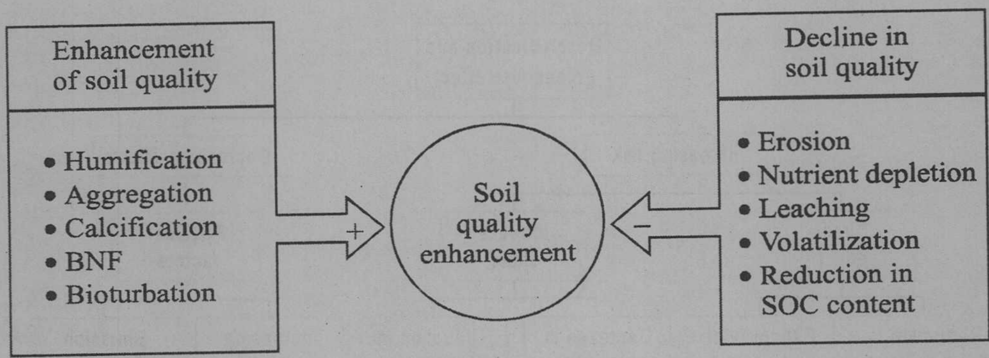


*Fig. 2. Processes affecting soil quality dynamics.*

## Soil Quality Enhancement through Desertification Control and Land Restoration

Soil quality is the resultant impact of a dynamic equilibrium between soil restorative and degradative processes (Fig. 2). Soil restorative processes include humification, aggregation, bioturbation, biological nitrogen fixation (BNF), and formation of secondary carbonates. Soil degradative processes comprise erosion, leaching, fertility depletion, and reduction in SOC content. Soil erosion control is an important strategy of combating desertification. In arid regions of India, Venkateswarlu and Kar (1996) and Hazra (1996) proposed several vegetative measures to stabilize sand dunes. They proposed several trees and shrubs for land restoration (e.g., *Prosopis juliflora*, *Acacia tortilis*, *Acacia senegal*, *Ziziphus* spp.). Establishing plantation of *Prosopis* spp. has also been found to be useful in restoring salt-affected soils (Singh and Singh, 1995; Singh, 1992). Desertification is a biophysical process driven by socio-economic and political factors. Poverty accelerates the desertification spiral, and leads to erosion, depletion of soil fertility, reduction in SOC content, leaching and volatilization. The SOC content is an important factor governing soil quality. It affects soil structure and aggregation. There exists a critical level of SOC content below which soils lose their physical stability. This critical or threshold level depends on soil texture. Pieri (1992) proposed a relationship between physical stability of soil and its clay and silt and organic matter content:

$$S_t(\%) = \frac{(OM\%)}{(clay+silt)\%} \times 100.$$

Based on this index for soils of sub-Saharan Africa, Pieri (1992) proposed the following characteristics:

| St. (%) | Soil physical condition |
|---|---|
| <5 | Loss of soil structure and increased susceptibility to erosion |
| 5-7 | Unstable structure, risk of loss of soil structure |
| 7-9 | Soils of moderate structure, low risk of loss of stability |
| >9 | Soils of stable structure |

Watts and Dexter (1977) observed that quantity of dispersed clay increased and water-stable aggregation decreased with

*Table 4. Technological options for C sequestration in soils and ecozones through desertification control*

| Vegetation management | Soil management | Water management |
|---|---|---|
| $C_4$ and CAM plants | Erosion control through afforestation, and vegetation establishment | Enhancing WUE through water harvesting, soil-water conservation |
| Plant adaptation, e.g., Amaranth, bambara groundnut, gum weed, gum trees, jojoba, mesquite, acacia, neem, vetiver, etc. | Soil fertility management, especially application of P and N | Appropriate irrigation methods, e.g., drip irrigation |
| Growing halophytes | Land application of biosolids including residue mulch, etc. | Irrigation with saline water |
| Improved crops and cropping systems | Soil salinity control | Crop/plant growth in draw-down areas of dams |

decline in SOC content. Unger (1997) derived empirical equations between SOC content and dry aggregate and water-stable aggregates for a Torrertic Paleustoll (Pullman clay loam) in Texas.

The basic strategy to reverse the degradative trend, enhance soil quality and improve productivity is to increase SOC content (Finkel, 1986; Unger, 1997; Unger *et al.*, 1997). The latter is a challenging task, but achievable through adoption of appropriate soil restorative techniques.

## Desertification Control and C Sequestration

There are several options of soil quality restoration through combat of desertification. These options and their potential in C sequestration have been discussed in detail by Squires *et al.* (1995), Finkel (1986); Hazra (1996), IFAD (1998) and Lal *et al.* (1998). Appropriate land use and soil/vegetation management practices for C sequestration are outlined in Table 4. There are numerous options of vegetation, soil and water management that can lead to increase in biomass production. Technological options for vegetation management include growing $C_4$ and CAM plants, growing halophytic plants in salt-affected soils, growing non-food crops of industrial importance (e.g., Amaranth, gum weed, neem, acacia, jojoba, vetiver, etc.). There are also numerous soil management options, especially those involving erosion control through establishment of vegetation cover and afforestation, soil fertility management through application of fertilizer (P and N), biological nitrogen fixation and land application of biosolids, and reclamation of salt-affected soils. There are also numerous practices of water management that can enhance productivity and sequester C in soil. Relevant water management practices for dry ecozones include water harvesting techniques, appropriate irrigation methods that save water and improve efficiency (e.g., drip irrigation), irrigation with saline water, and growing crops in draw-down regions along large reservoirs.

There are an estimated 3.6 Bha of degraded and desertified lands in dry ecozones. It is apparent that not all of these lands are reclaimable. Further, some lands are more easily and economically

*Table 5. Some indicators of "trigger spots" for land restoration and desertification control*

| Landscape | Vegetation | Soil | Water |
|---|---|---|---|
| Slope shape: Concave | Ground cover: >10% | Relatively high clay content | Ground water of favorable quality |
| Slope gradient: <10% and gently rolling | Biomass: Relatively high root and shoot biomass | >20 cm effective rooting depth | Surface water usable for irrigation |
| Slope aspect: North-facing in northern, and south-facing in southern hemisphere | Vegetation: Adaptable to harsh climate and drought-prone environments with some economic values | Low susceptibility to soil erosion by wind and water | Water usable for non-agricultural purposes e.g., aquaculture |
| Landscape: Gently rolling which facilitates water harvesting and storage | | Favorable water storage capacity | |
| | | Low susceptibility to crusting | |

reclaimable than others. There are examples of successful reclamation of such lands. The objective is to identify regions with potential of economic and easy reclamation, enhance productivity and restore soil's life support systems. These regions (bright spots) may be called "trigger spots" which can have a snow-balling effect on restoration of surrounding areas. There is a need to establish criteria for delineating/identifying these "trigger spots", and indicators may differ among soils, ecozones and landscape characteristics. Some possible indicators are listed in Table 5 but need to be assessed and validated under site-specific conditions. These indicators should be routinely identifiable by simple surveys including remote sensing.

## A Win-win Strategy

Restoration of degraded lands have a potential to sequester C, involving both organic and inorganic components. The magnitude of potential for C sequestration is related to the rainfall regime, soil characteristics and land use. Gross estimates of rate of C sequestration for different ecoregions are outlined in Table 6. The potential of SOC sequestration is none or little for the hyper-arid ecozone. The potential is also low for arid ecozone, ranging from 0.02 to 0.08 Mg $ha^{-1}$ $y^{-1}$ (20 to 80 kg $ha^{-1}$ $y^{-1}$) depending on soil, landscape and vegetational/land use characteristics. The potential of C sequesterration is somewhat high for semi-arid regions and may range from 0.03 to 0.12 Mg $ha^{-1}$ $y^{-1}$ ( 30 to 120 $kg^{-1}$ $ha^{-1}$ $y^{-1}$). Apparently, the potential is high for semi-humid and sub-humid regions and may range from 0.08 to 0.20 Mg $ha^{-1}$ $y^{-1}$ (80 to 200 kg $ha^{-1}$ $y^{-1}$). Realization of this potential may require some inputs, including development of water harvesting techniques, establishment of erosion measures, application of nutrient (e.g., P), and introduction of appropriate vegetation adapted to the specific environment.

There is also a potential to sequester soil inorganic carbon (SIC) as secondary

*Table 6. Estimates of rate of SOC sequestration in drylands (in Mg $ha^{-1}$ $y^{-1}$)*

| Soil | Arid | Semi-arid | Semi-humid |
|---|---|---|---|
| Aridisol | 0.02-0.03 | 0.03-0.05 | – |
| Alfisol | 0.03-0.04 | 0.05-0.07 | 0.08-0.10 |
| Vertisol | 0.04-0.06 | 0.06-0.10 | – |
| Inceptisol | 0.06-0.08 | 0.08-0.12 | 0.12-0.15 |
| Ultisol | – | – | 0.15-0.20 |

carbonates in drylands. The rate of SIC sequestration is often low and may be 5 to 100 g $m^{-2}$ $y^{-1}$ (Lal *et al.*, 1997). It is even more difficult to achieve SIC sequestration than SOC sequestration. Addition of biosolids, increasing activity of soil fauna, applying Ca and Mg to the soil may be some of the practices that enhance SIC sequestration.

Lal *et al.* (1998) estimated that total potential of C sequestration through restoration of degraded soils and desertification control in drylands is 0.9 to 1.9 Pg $y^{-1}$ with a mean of 1.4 Pg $y^{-1}$. This is a high potential and probably achievable only under ideal conditions. Even if 25% of this potential were to be achieved (0.25 to 0.50 Pg $y^{-1}$), it would require a coordinated effort at international level. There is an urgent need to develop and implement national and international soil policy to use and restore soil resources for enhancing productivity and improving environment quality (IFAD, 1998). The bottom-up approach of involving farmers and land managers in implementation of restorative measures is crucial to the success.

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