Annals of Arid Zone 50(3&4): 209-224, 2011

Sustainable Soil Management under Changing Climate and Desertification

Rattan Lal*

Carbon Management and Sequestration Center, The Ohio State University, Columbus OH 43210, USA

Abstract: Desertification, soil/land degradation in arid regions is estimated to affect 3.5 billion hectares and 24% of the global population of 7 billion. Risks of desertification are exacerbated by the projected climate change caused by anthropogenic emissions of greenhouses gases (GHGs), because the terrestrial biosphere (soil and vegetation) may become a major source through depletion of the ecosystem C pool by accelerated erosion, salinization, depletion of nutrient and water holding capacity, etc. The downward spiral can be reversed by a widespread adoption of recommended management practices (RMPs) which improve soil quality and enhance ecosystem resilience. Even with a modest increase of 0.5 Mg C ha^{-1} yr^{-1} in soils and vegetation, conversion to a restorative land use and adoption of RMPs have a technical potential to sequester 1.75 Pg C yr^{-1} for 25 to 50 years until the sink capacity is filled. Adoption of RMPs, based on water harvesting and recycling and soil fertility enhancement through integrated nutrient management, can be promoted through payments to land managers for ecosystem services. Desertification control and restoration of soil quality are a truly win-win strategy with co-benefits of improving the environment, adapting to and mitigation of the climate change, and advancing global food security.

Key words: Recommend management practices, water harvesting, soil carbon sequestration, payments of ecosystem services.

Desertification refers to soil degradation in arid and semi-arid climates that are characterized by low precipitation and high evapotranspiration. The data in Table 1 show that >90% of the precipitation is lost as evapotranspiration compared with 59% globally, and 63% in the humid climates. Desertification is exacerbated by the interactive effects of biophysical processes, ecological and human dimension factors, and land use and managerial causes (Fig. 1). The interactive effects of processes, factors and causes perturb soil-vegetation-climate equilibrium, and alter coupled cyclings of water with those of C, N, P, and S (Fig. 1). The biophysical process of desertification is driven by the human dimension issues (e.g., poverty, civil strife, political instability), by exacerbating a strong interaction between the processes, causes and factors (Fig. 1). Processes of soil degradation include physical (i.e., erosion, compaction, crusting, decline in soil structure), chemical (i.e., nutrient depletion, acidification, salinization, and elemental imbalance) and biological (i.e., decline in soil organic matter or SOM, and reduction in soil biota). These processes are accentuated by the harsh climate of arid and semi-arid regions. Human activities exacerbate the process through deforestation, biomass burning, excessive grazing, residue removal and other extractive farming practices (Fig. 1).

The complex process of desertification adversely affects the per capita availability of cropland area and renewable fresh water supply, with attendant negative impacts on agronomic production, per capita grain consumption, and food security. Availability of croplands and fresh water for agriculture are also being constrained with the increasing demand on these limited resources for biofuel production. There exists a close link between food security on the one hand, and the climate change, soil degradation and desertification, and the land use change on the other (Fig. 2). Thus, increase in global temperature is likely to further reduce agronomic production already affecting billions of people living in the tropics and sub-tropics. Consequently, the U.N. Millennium Development Goals of reducing hunger and poverty by 50% by 2015 are in jeopardy.

As agronomic productivity stagnates or declines, as agronomic/animal/forestry production lags behind the demands, as perpetual food insecurity affects human well-being, as soils degrade and vegetation dwindles, which pollute and contaminate natural waters, as global warming accelerates and species disappear, and as natural capital decreases

*E-mail: lal.1@osu.edu

and ecosystem services are jeopardized, the necessity to sustainably manage the soil and water resources will be starkly evident. Therefore, the emerging paradigm must consider the strategy of improving soil quality by enhancing its resilience so that the problems of soil degradation and desertification can be minimized. Thus there is a strong need to: (i) strengthen communication between scientists on the one hand and policy makers, land managers and public on the other, and (ii) promote adoption of proven recommended management practices (RMPs) and discourage adoption of those land use and soil management practices which would jeopardize their quality and exacerbate the risks of soil degradation

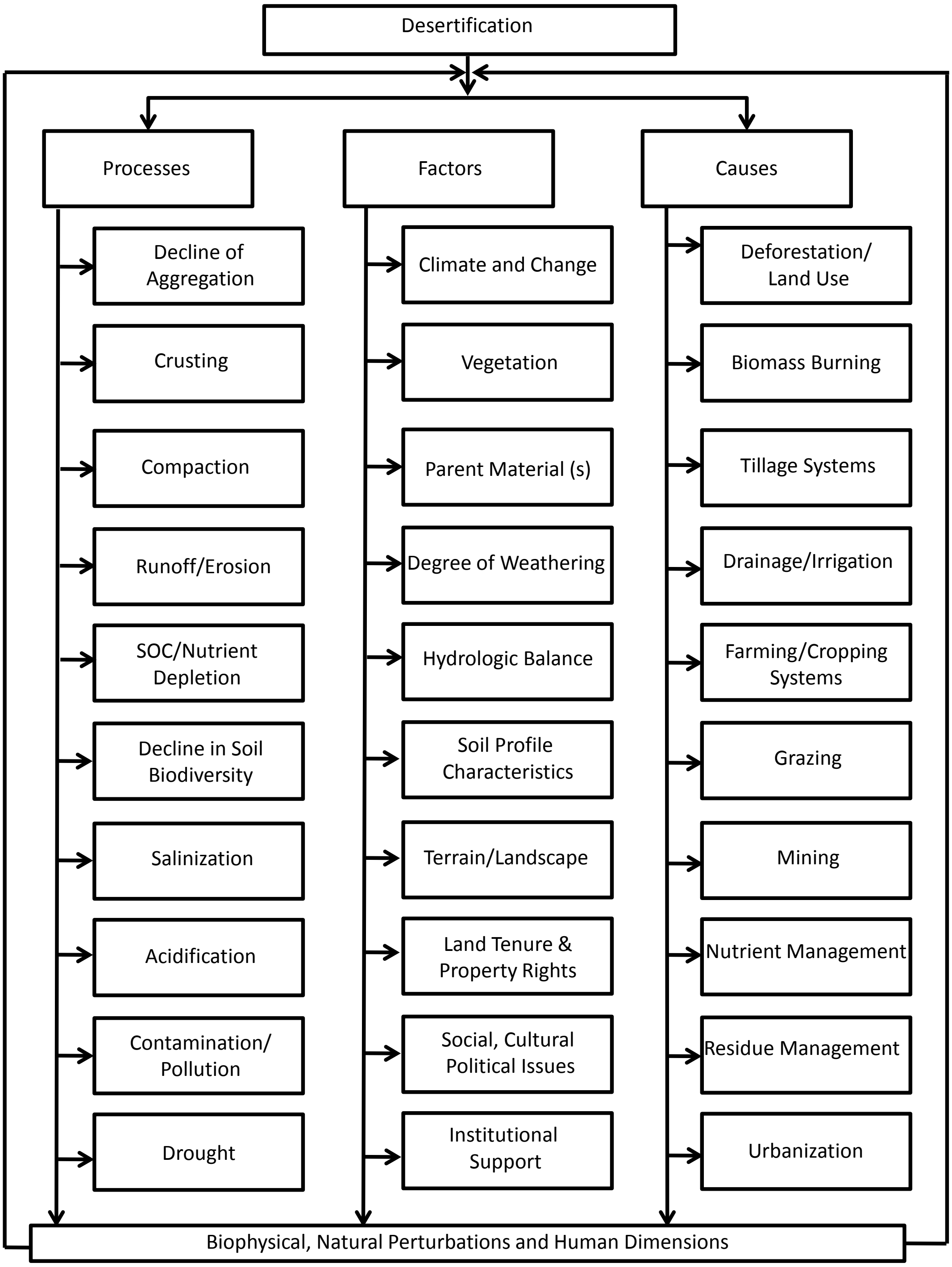

Fig. 1. Interactive effects of processes, factors and causes of soil degradeation.

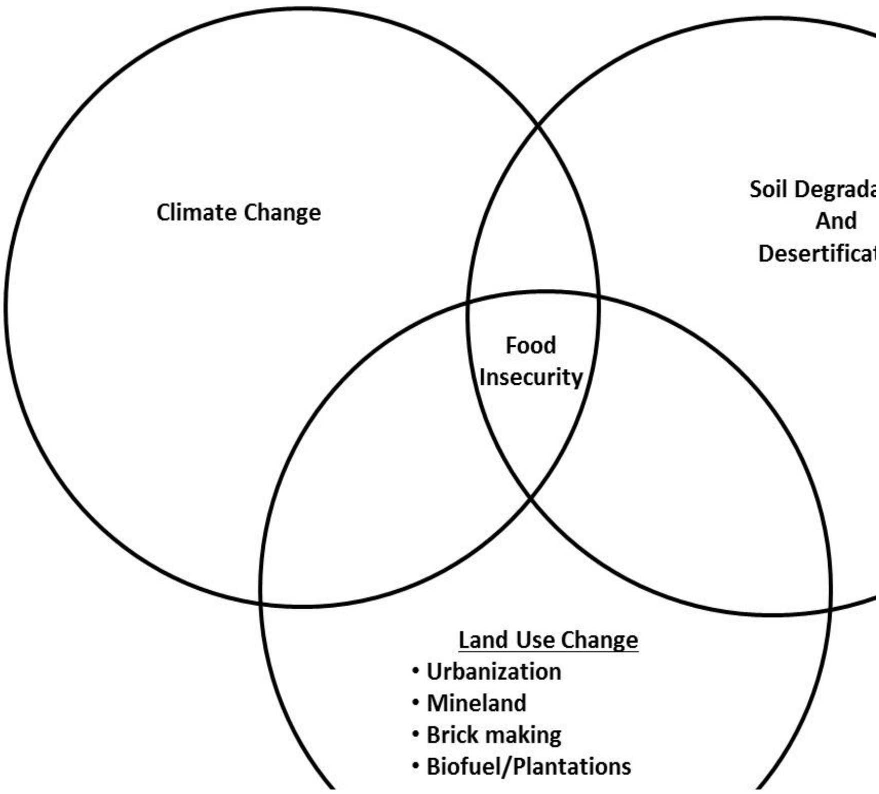

Fig. 2. Food insecurity impacts of climate change, soil degradation/desertification and conversion of agricultural land to other uses.

and desertification. With the historically strong emphasis on adverse impacts of desertification, there is a need to adopt a pragmatic and a positive approach to mitigate desertification and for restoration of degraded/desertified soils. It is thus important to understand interaction of desertification with climate change, food security, and potential of carbon (C) sequestration to mitigate global warming. Thus the objective of this article is to describe the effects of soil degradation in drylands, and to identify strategies of sustainable soil management under uncertain and changing climate.

Drylands and Desertification

Drylands, where the ratio of mean annual precipitation (P) to that of the potential evapotranspiration (PET) is <0.65, cover about 41% of Earth's land area and are home to about 38% of the world population of 7 billion in 2011. Using the Aridity Index (AI = P: PET), dry lands are classified into hyper-arid, arid, semi-arid and dry sub-humid regions. Predominant land uses in these regions are rangeland (3.96×10^9 ha), urban (0.12×10^9 ha) and others (0.48×10^9 ha) (Safriel *et al*., 2002). Because of harsh climate, dry lands are prone to several soil degradation processes affecting as much as 10 to 20% of

Table 1. Water balance of arid and semi-arid regions (Adopted from Shen and Chen, 2010)

Hydrological parameter	Arid	Semi-arid	Global
Precipitation (cm yr^{-1})	11.1	38.5	82.8
Runoff (cm yr^{-1})	0.8	3.5	34.0
Evapotranspiration (mm yr^{-1})	10.3	35.0	48.8
Evapotranspiration: Precipitation (%)	93.0	91.0	59.0
Runoff: Precipitation (%)	7.0	9.0	41.0

the total area. Desertification, a sub-set of land degradation, occurs in arid and semi-arid regions of all climates including the arctic and humid regions. Water mismanagement and misuse can lead to waterlogging and salinization, a serious cause of desertification. Increase in salinization often occurs because irrigated farming with poor quality water and without drainage causes waterlogging and rise in the ground water that brings salt to the surface. Erosion of the sloping lands occurs because of deforestation, excessive grazing, and plowing without use of conservation-effective measures and denudation in the watersheds. The problems of soil erosion and salinization are more severe now than in pre-historic times because of high population density and excessive demands on limited resources. An example of the positive feedback caused by a strong interaction among these processes on the extent and severity of soil degradation in Pakistan is shown by data in Table 2. The land area prone to different degradation processes include 31.57 million hectares (Mha) by salinity, 13.05 Mha by water erosion, and 6.17 Mha by wind erosion. A similar level of desertification exists in India. The elemental imbalances and deficiencies of plant nutrients (e.g., N, P, K, Zn) are also important factors. Depletion of SOM and mining of plant nutrients, through extractive farming and losses by erosion and volatilization are major causes of soil degradation and desertification.

Climate Change and Desertification

Global warming and the attendant climatic variability are likely to have strong impact on susceptibility of drylands to degradation processes which exacerbate desertification. The widespread problems of drought and desertification in arid regions are attributed to the prevalence of harsh climate in these regions characterized by intensity and duration of recurring droughts with adverse impacts on the net primary production (NPP). The climate change is projected to exacerbate its harshness by increasing frequency and intensity of extreme events such as “drought” (Fig. 3). There is a difference between “aridity” and “drought”. The term aridity refers to a low ratio of P:PET (Le Houérou, 1996): <1.1 in arid and semi-arid regions compared with 1.25 in semi-humid, 1.59 in humid, 2.35 in the tropics, and 2.70 in hyper humid climates (Shen and Chen, 2010). The term drought refers to decrease in availability of fresh water supply, which is exacerbated by soil degradation.

There are four types of drought: (i) meteorological due to deficiency of rainfall, (ii) hydrological due to deficiency of runoff in rivers or decline in the ground water level, (iii) edaphic due to deficiency of soil moisture reserves because of low water infiltration rate and high losses by surface runoff and evaporation, and (iv) agricultural or ecological due to low availability of soil water at critical stages of crop/plant growth (Williams and Balling, 1994; WMO, 1975). The edaphic and the ecological or the agricultural droughts are triggered by soil degradation and desertification through reduction in plant available water capacity (AWC). The latter is severely reduced by desertification through: (a) reduction in the effective rooting depth because of erosion-caused truncation of soil profile, (b) decline in field moisture capacity because of decline in soil organic carbon (SOC) and clay fractions, (c) decline in aggregation and degradation of soil structure and tilth because of reduction in SOC content, and (d) reduction in soil fauna and biodiversity because of decline in food availability and destruction of the habitat. These types of drought are exacerbated by an utter lack of good farming. There are at least 3 criteria of good farming (Worster, 1984): (i) that

Table 2. The extent of desertification in Pakistan (Calculated from Anjum et al., 2010; Shah at al., 2011)

Province	Total area (10^6 ha)	Area affected (10^6 ha)		
		Wind erosion	Water erosion	Salt-affected (2001-2003)
Balochistan	34.72	0.28	4.58	14.23
Norern areas	7.04	-	2.12	?
NWFP	10.17	0.04	4.29	1.73
Punjab	20.63	3.80	0.06	6.60
Sindh	14.09	2.05	1.90	9.01
Total	87.98	6.17	13.05	31.57

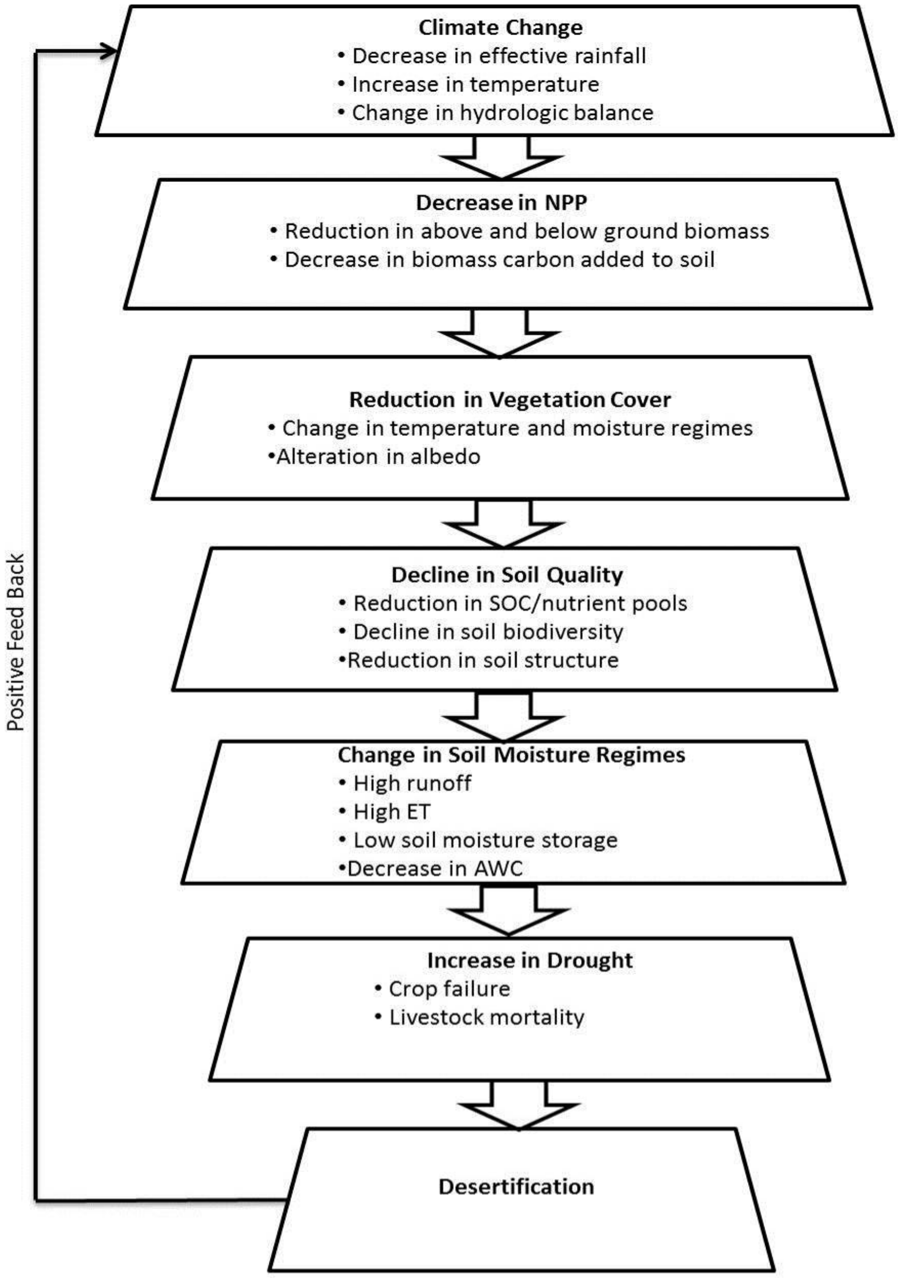

Fig. 3. Effects of climate change on desertification. (NPP= net primary production, ET= evapotranspiration, AWC= available water capacity).

preserves the earth and its network of life, (ii) that promotes a more just society, and (iii) that makes people healthier.

The most severe adverse impacts of desertification on soil quality and farming are caused by the decline in soil structure and aggregation, removal of crop residues as fodder or fuel, excessive grazing and use of dung as fuel rather than as manure, and negative nutrient budget which depletes the SOC pool. Not only do these farming practices reduce the top soil depth by accelerating soil erosion hazard, but also reduce the plant AWC by decreasing the relative proportion of moisture retention pores. Consequently, losses of water by surface runoff and evaporation are exacerbated. There is also a close interaction between drought and soil infertility. Lack of water accentuates buildup of salts in the root zone or salinization. Prevalence of dry environments also creates nutrient imbalance because of disruption in biogeochemical cycles. Most dryland soils, especially those prone to erosion and desertification, are deficient in N, P, and micronutrients.

In addition to strong relationship between drought and desertification, because rainfall received does not meet the evaporation demand, there is also a strong relationship between climate and desertification. Climate change impacts desertification from four perspectives (Puigdeja'bregas, 1998): (i) change in vegetation cover, (ii) positive feedback to atmosphere due to anthropogenic activities, (iii) adverse off-site effects, and (iv) severe governance and policy implications. Increase in aridization due to the projected change in climate impacts desertification through its impact on: (i) reduction in total amount of rainfall or its effectiveness, (ii) decline in duration of rainfall events, and (iii) increase in interval among consecutive rainfall events. For example, studying the process of desertification along a Mediterranean arid transect, Lavee *et al*. (1998) observed that potential increase in aridity with change in climate may exacerbate desertification through adverse impact on: (i) SOM content, (ii) soil structure, aggregation and stability, (iii) susceptibility to erosion by water and wind, and (iv) risks of salinization. Furthermore, the rate of change in these soil properties and processes is non-linear. Decrease in precipitation may also reduce the amount of water available for irrigation in arid regions (Thompson *et al*., 2005). Rather than being a sink of atmospheric CO_2, it is also feared that soils may become a major source of CO_2 with >3°C increase in temperature. Another scenario of the positive feedback on desertification with the change in climate may be due to changes in plant species and vegetation patterns (Ares *et al*., 2003), especially leading to reduction in vegetation cover and the attendant decline in the ecosystem C pool (Fig. 3).

Agronomic Productivity and Desertification

Desertification affects agronomic productivity through increases in extent and severity of soil degradation and drought stress. Reduction in farm income limits farmers' ability to purchase off-farm inputs (e.g., fertilizers and machinery). These factors reduce NPP, decrease ecosystem services, and jeopardize farmers'

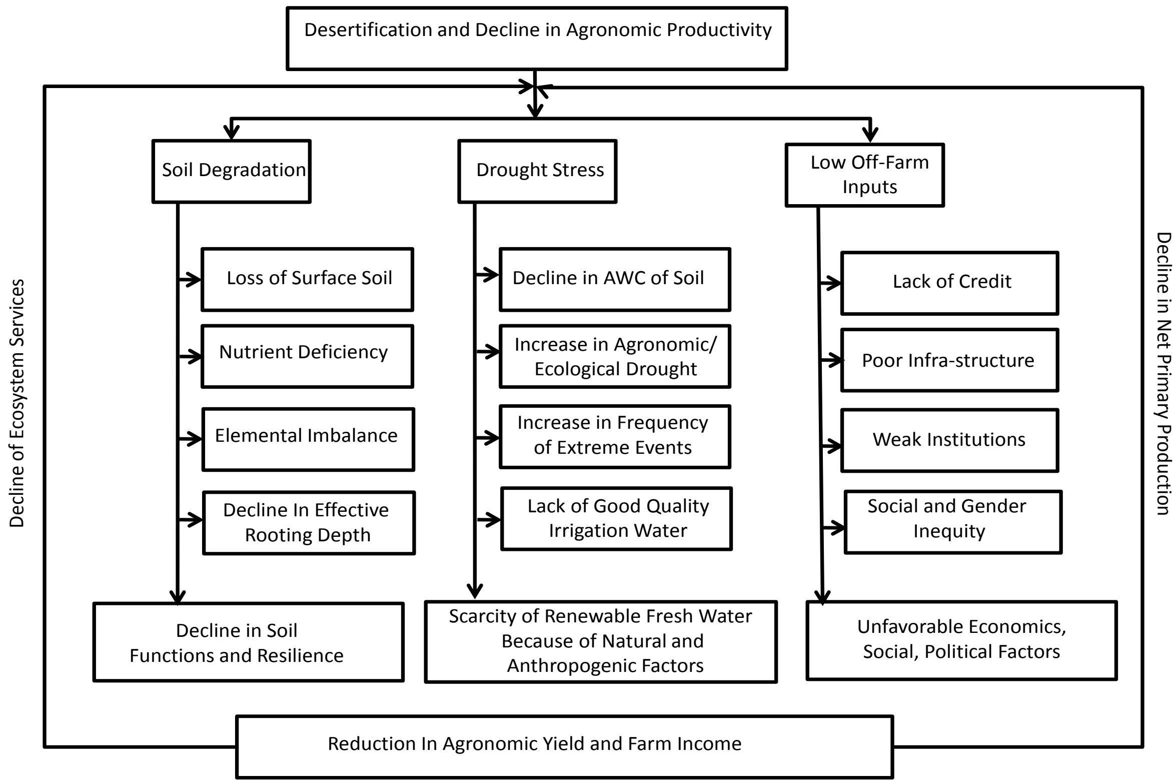

Fig. 4. Direct and indirect effects of desertification on agronomic production in relation to soil quality, drought stress, and the human dimensions.

ability to invest in land (Fig. 4). The problem is extremely severe in developing countries of South Asia (SA) and Central Asia, sub-Saharan Africa (SSA), and the Caribbean.

Several of these countries/regions (Lobell *et al.*, 2008) are prone to drought and desertification because of harsh climate and fragile soils. The problem is exacerbated by political unrest and civil strife. Several famines recorded during the 20th century in Africa were attributed to political unrest and civil strife. Some have linked food security to "living democracy where everyone has a say in their own future, therefore, the right to life's essentials, including food" (Hurley, 2008). Hunger is not necessarily a result of food insecurity. It is argued that world's agriculture produced 17% more calories per person in 2006 than it did in 1976, despite a 70% population increase. There is enough food to provide every person worldwide with at least 2,720 kilocalories a day (Mousseau and Mittal, 2006). It is often the human dimension issues which are impediments to achieving global food security. Important among these are the political stability, civil unrest, and ethnic conflict (Fig. 2).

Strategies of Desertification Control

Adopting an ecosystem approach is considered a useful strategy to restoring degraded soils and desertified ecosystem. The term ecosystem refers to "the whole system, including not only the organism complex, but also the whole complex of physical factors forming what we call the environment" (Tansley, 1935). Lindeman (cited by Schulz, 1967) defined it more succinctly as "systems composed of physical-chemical-biological processes active within a space-time unit of any magnitude." Ecosystem includes not only the physical components such as the soil, water,

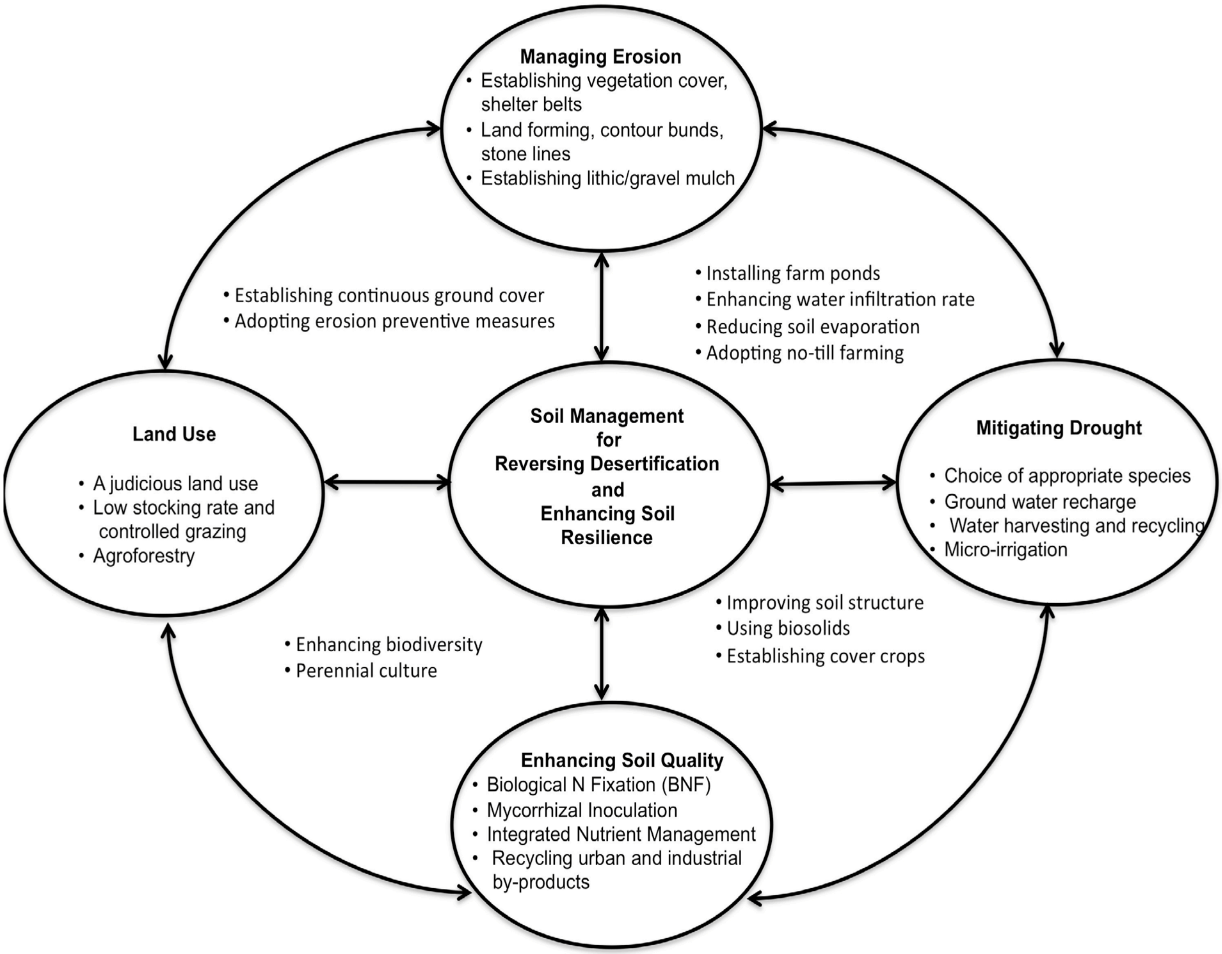

Fig. 5. Soil management strategies for desertification control, restoring soil/ecosystem functions, and enhancing soil resilience.

air and light in the system but also all of the living organisms present, their interactions with each other, and their responses to the physical factors around them (Gliessman, 1984). Soil restoration means rebuilding the soil so that better and higher yielding plants can be grown. Taking the near-virgin state as a reference point indicates in which direction and at what rates are the managed agricultural soils drifting. The goal of restoration is not necessarily to imitate nature's steady state, but to approach it through adoption of RMPs based on a judicious land uses and sustainable management (Jenny, 1984).

Restoring desertified soils in arid regions needs water to restore biota, vegetation cover to control erosion and recycle C, and plant nutrients to increase NPP and strengthen biogeochemical cycles. Any restoration strategy must be based on the most fundamental concept that soil "is the living skin of the Earth" (Yaalon, 2007). It is the foundation of all terrestrial life, and is the "ecstatic of the Earth" (Logan, 2007). Alleviating drought stress, a major edaphic factor, requires a dependable supply of water and an effective strategy to minimize losses by water runoff accentuated by surface sealing and poor soil structure, and evaporation enhanced by a high evaporative demand of the arid environment.

A low NPP of soils of SSA and SA is also attributed to soil infertility (Sanchez, 2002), and degradation by a range of physical, chemical and biological processes (Lal, 2008). Thus, controlling desertification and restoring desertified soils necessitate knowledge of the underlying processes. Strategies of desertification control and soil quality restoration to reverse these processes are outlined in Fig. 5. The goal is to: (1) mitigate drought and enhance water availability in the root zone by water harvesting and recycling, reducing loses by evaporation and runoff, and enhancing water use efficiency (WUE), (2) manage soil erosion by providing a continuous ground cover and minimize soil disturbances, (3) enhance soil quality and improve nutrient supply through integrated nutrient management (INM) including biological nitrogen fixation (BNF), strengthening nutrient cycling, and using supplemental doses of chemical fertilizers, and (4) adopt appropriate land use, and diverse and productive farming systems (Fig. 5). These generic recommendations must be made site-specific through local/adaptive research. Desertification control can also be achieved by adopting strategies of sustainable land management (SLM). The SLM is defined as, "a knowledge-based combination of technologies,

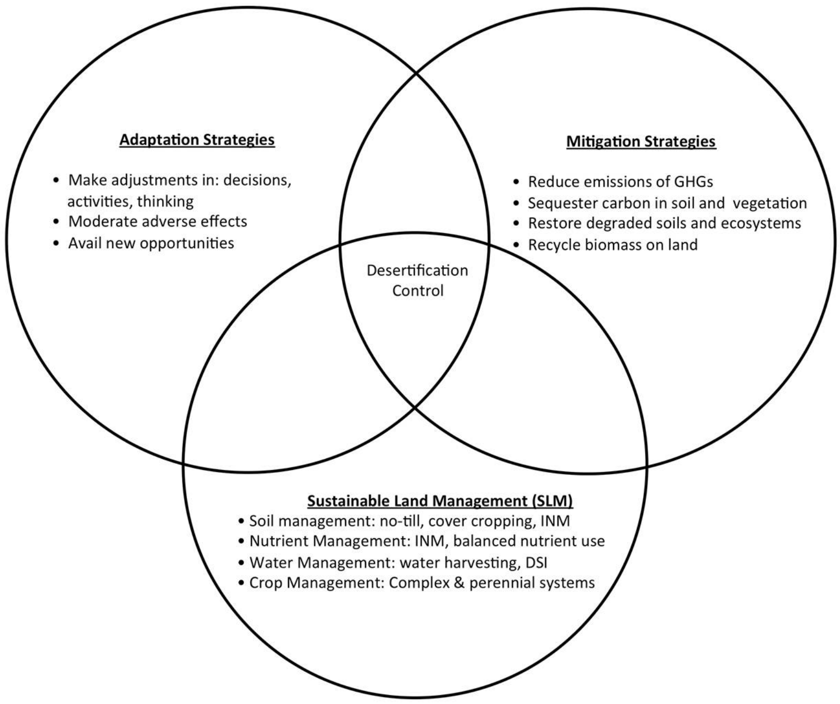

Fig. 6. Desertification control can be achieved by using strategies for sustainable land management (SLM) and those which enhance adaptation to and mitigation of climate change.

policies, and practices that integrate land, water, biodiversity and environmental concerns to meet rising and food and fiber demands while sustaining ecosystem services and livelihood" (World Bank, 2006). Combining SLM with other strategies of adaptation to and mitigation of climate change can be effective in desertification control while restoring soil quality and off-setting anthropogenic emissions (Fig. 6).

Adaptation to and Mitigation of Climate Change through Desertification Control

The term mitigation implies activities which reduce emissions of GHGs by human activities, and enhance C sinks through natural and engineering processes. Mitigation strategies through desertification control are those which: (i) enhance C sinks in soils and vegetation, and (ii) reduce emissions through biomass burning and soil amendments (N_2O from biosolids and fertilizers). The goal of mitigation strategies is to establish vegetation cover and enhance NPP, create favorable water and energy budgets, and improve soil quality especially with regards to nutrient pool and elemental cycling. Increasing the terrestrial sink by creating a positive C budget is the goal.

In comparison, adaptation to climate change consists of activities which reduce risks of decline in productivity because of increase in temperature, decrease in effective precipitation, and increase in frequency of extreme events

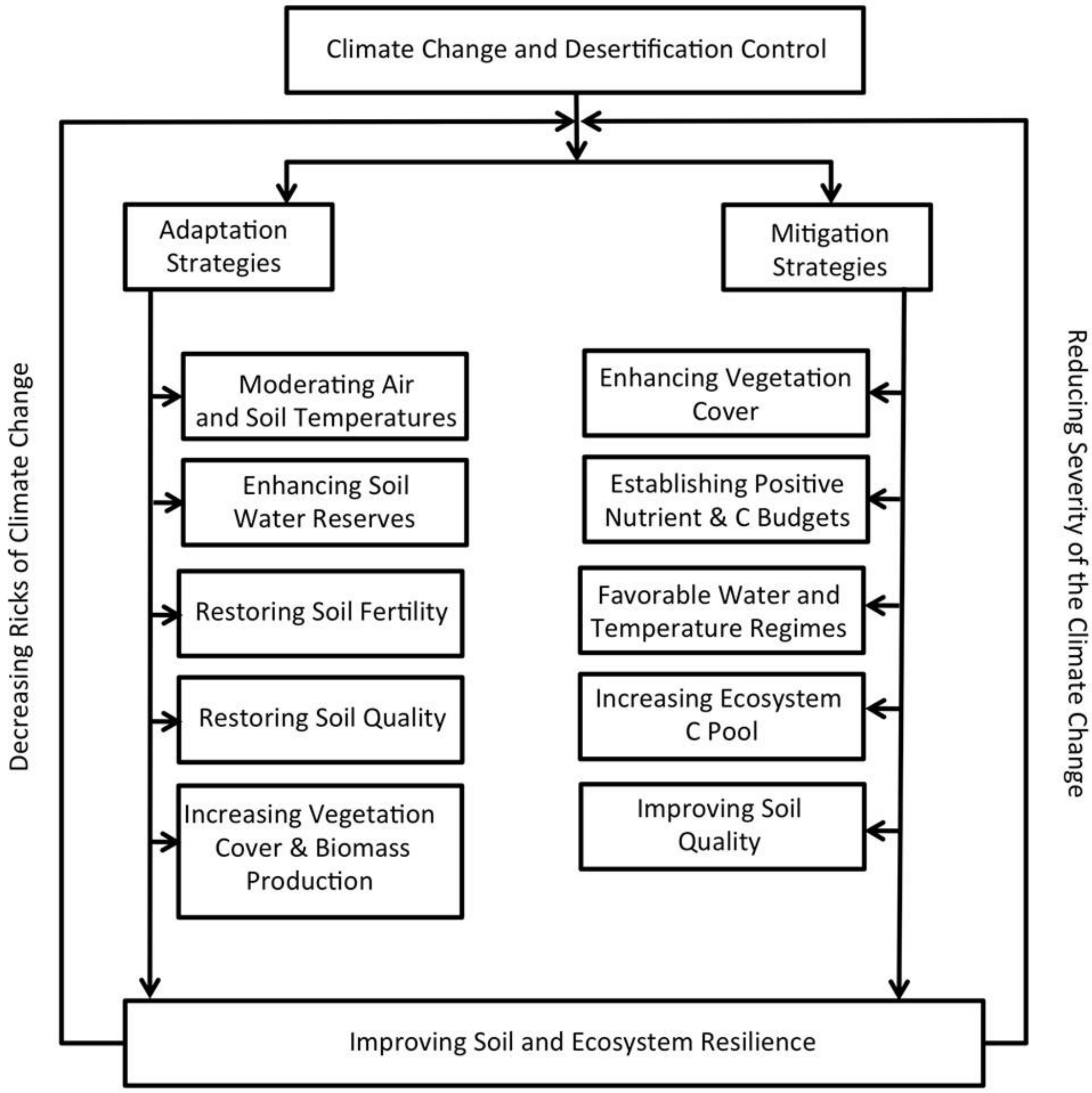

Fig. 7. Addressing climate change through desertification.

(e.g., drought.). Adaptation to climate change is especially relevant to resource-poor farmers who are extremely vulnerable. Furthermore, it may not be completely possible to mitigate the climate change because reducing atmospheric concentration of GHGs to the pre-industrial level may be an extremely challenging task. Some of the technological options for adaptation are also necessary for achieving sustainable use of soil and water (natural resources), and for restoring degraded and desertified soils.

Conceptual approaches to controlling desertification by adapting to and mitigating the climate change are outlined in Fig. 7. Adaptation strategies include the following: (1) moderating micro and meso-climates by reducing temperature through increasing albedo, improving vegetation cover, and using mulch materials (e.g., stones, crop residues, plastic), (2) increasing ecosystem water reserves, especially the plant AWC by reducing runoff and evaporation while increasing soil water storage capacity, (3) improving soil fertility especially the availability of N and P through enhancing BNF, applying new generation of slow-release fertilizers (nano-enhanced and zeolites), using biosolids including compost and biochar etc., (4) reversing soil degradation by improving soil structure, establishing runoff control devices (e.g., stone bunds, contour hedges, shelter belts) and reclaiming salt-affected soils, and (5) improving vegetation through introduction of dedicated plant species adapted to dry environments including genetically modified (GM) crops. These technologies have the potential to reduce the soil degradation and desertification trends. Reversal of desertification would enhance both natural and managed processes of adaptation by synergistic of effects, mutual reinforcement, and supplementation.

It is also prudent to identify those technologies which mitigate climate change through increasing C sequestration in soils and trees, but also adapt to climate change by reducing sources and increasing sinks. The goal is to increase ecosystem resilience through

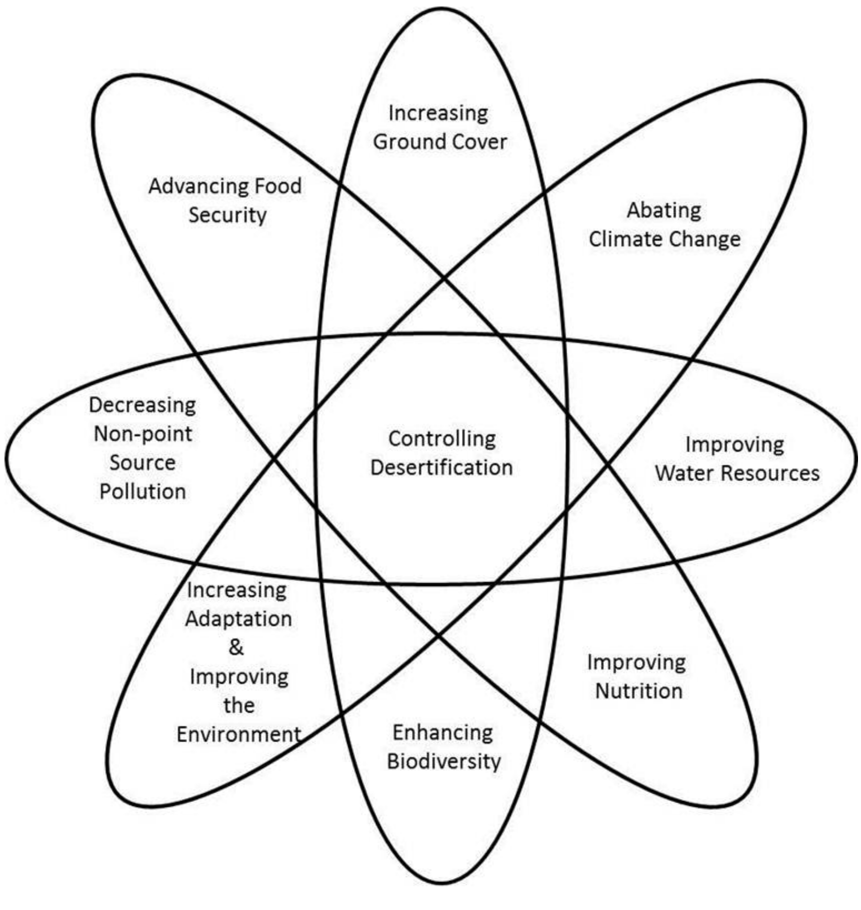

Fig. 8. Strengthening ecosystem services by controlling desertification.

innovative options such as: (i) enhancing vegetation cover and afforestation, (ii) establishing positive nutrient and C budgets, (iii) creating favorable water and temperature regimes, (iv) increasing ecosystem C pool, and (v) improving soil quality (Fig. 7). These options can help adjustments of agricultural systems by increasing resilience and reducing vulnerability. Desertification control and restorative measures would also enhance effectiveness of adaption and mitigation strategies while increasing ecosystem C pool.

Ecosystems Services and Desertification Control

Desertified soils have lost functionality especially for conserving soil and water, recycling water and nutrients/elements, storing C, providing habitat for flora and fauna, and producing biomass as NPP. Thus, the objective of desertification control is to restore these ecosystem functions (Fig. 8). The first step is to establish vegetation cover by identifying and establishing grasses and shrubs which can grow in arid environments and relatively infertile soils of low water and nutrient reserves. Establishment of ground cove creates micro-environment (microclimate) that has cooler temperature, more humidity and favorable rhizospheric conditions for microbial processes. Progressive increase in vegetation cover also increases favorable water and energy budgets, especially under vegetation patches. Soil beneath the patches has high water infiltration rate, low/no surface runoff, minimal crusting and higher SOM reserves. A gradual improvement in soil quality, over a decadal scale, sets-in-motion restorative processes that eventually restore degraded/desertified ecosystems, and sequester C in soil.

Desertification by different processes exacerbates the rate of profile SOC depletion. The magnitude of depletion is accelerated by erosion and widespread use of extractive farming. The data in Table 3 from China shows that the severity of SOC depletion is higher in land prone to accelerated erosion. The latter leads to a preferential removal of the light fraction (humus/SOM of low density), which is also concentrated in the soil surface.

Similarly, long-term studies in south-central Senegal indicated that the ecosystem C stock (vegetation and soil) was reduced by 37% between 1900 and 2000 (Liu *et al*., 2004). The SOC concentration is also extremely low in rainfed soils of the semi-arid regions of India and elsewhere in South Asia. The data in Table 4 show that low SOC concentration in 0-0.15m depth of 1.9 to 6.8 g kg^{-1} is below the critical or threshold level (Aune and Lal, 1994; Loveland and Webb, 2003). Vertisols/Vertic group soils have SOC stock of 28-96 Mg C ha^{-1} to 1 m depth with an average of 46 Mg C ha^{-1}. In general, SOC concentration and stock can be more in soils containing a higher content of expanding lattice clay (e.g., vertisols). The data in Table 5 show SOC stock of >130 Mg C ha^{-1} to 1.5 m depth in a Vertisol from peninsular India. Yet, long-term cultivation with extractive farming practices (e.g., residue removal, excessive grazing, little or no application of manure/compost or other biosolids) can severely deplete the SOC pool. Comparing the data in Tables 4 and 5 indicate that some vertisols have lost 50 to 80 Mg C ha^{-1} because of historic land use and soil management. Thus, these and other soils have a high soil C sink capacity because of the historic depletion.

Table 3. Effects of land use change and duration of cultivation in soil carbon depletion in the 0-20 cm layer of a soil in the semi-arid Bashang area of China (Recalculated from Zhao et al., 2005)

Cultivation duration (yr)	SOC pool (Mg ha^{-1})	
	Flat land	Sloping land
0	59.36	116.6
8	28.42	38.9
30	26.52	32.7
50	17.87	27.7

The technical potential of SOC sequestration, with multiple co-benefits and numerous ecosystem services, is high in degraded/desertified soils because of a large historic depletion. Thus, soil C sequestration implies transfer of atmospheric CO_2 into the SOC stock with a long residence time of decadal scale. There are direct and indirect processes of soil C sequestration (Fig. 9), involving increases in SOC and soil inorganic C (SIC) stocks.

The rate and magnitude of SOC sequestration can be enhanced through desertification control by the adoption of RMPs. The data in Table 6 from northwest China show increases in SOC stock (Mg C ha^{-1}) in 0.15 m depth from 0.66 under control to 2.45 in 7 yr and 6.48 in 32 yr by establishment of shrubs, to 8.25 in 7 yr and

10.01 in 32 year by establishment of forest, and to 6.81 in 7 year and 12.27 in 32 year by use of intensive cropping with RMPs. The average rate of SOC sequestration (kg C ha^{-1} yr^{-1}) was 182-256 under shrub, 292-1084 under forest, and 363-879 under cropland (Table 6). These data indicate that the rate of SOC sequestration, with adoption of RMPs, can be high even in soils of arid regions. The potential of C Sequestration through desertification control is estimated at about 1 Pg C yr^{-1} (Lal, 2001). The potential can be more with establishment of biofuel plantation consisting of salt-tolerant plants. High biomass can be produced by growing halophytes which can be irrigated with brackish water. Rates of C sequestration in reclaimed salt-affected soils can be >1 Mg C ha^{-1} yr^{-1} to more than 3 Mg C ha^{-1} yr^{-1}. Technical potential of C sequestration in salt-affected soils is 0.4-1.0 Pg C^{-1} yr^{-1}, and that of desertification control is 1.17 Pg C^{-1} yr^{-1}. In addition, establishing biofuel plantations on desertified lands has a technical potential of offsetting industrial emissions by 0.3-0.5 Pg C^{-1} yr^{-1} (Lal, 2001). Trading C credits, paying land managers for ecosystem services of societal interest, provides incentive to adopt BMPs. Creating a mechanism for trading of C credits by the development of transparent and a fair/just system is crucial to the widespread adoption of the RMPs. Commodification of C, creating another income stream for resource-poor farmers, is important to restoring degraded/desertified soils.

Technological Options for Desertification Control and SOC Sequestration

Principal constraints to enhance NPP and SOC stock in soils of arid and semi-arid region, and especially those prone to desertification are: (i) drought stress, (ii) low soil fertility, and (iii) none or low input of biomass-C. Thus alleviation of these constraints through adoption of RMPs

Table 4. The SOC stock to 1-m depth in predominant soils of the semi-arid regions of India managed by rainfed cropping systems (Adapted from Srinivasarao et al., 2009)

Soil Order	Location	SOC concentration (0.15 m, g kg^{-1})	SOC pool (1 m, Mg ha^{-1})
I. Incepisols			
	Varanasi	3.7	32.54
	Faizabad	5.2	39.81
	Agra	3.2	26.69
	Ballowal-Sauntri	5.2	56.73
	Rakh-Dhiansar	5.6	59.71
	Jhansi	4.8	56.97
II. Alfisols/Oxisols			
	Phulbani	2.4	23.28
	Ranchi	6.2	49.83
	Anantpur	1.9	25.41
	Bangalore	2.2	24.75
III. Vertisoils/Vertic			
	Rajkot	5.0	58.02
	Indore	6.8	95.90
	Rewa	2.3	28.71
	Akola	2.5	28.60
	Kovalpatti	4.2	48.20
	Bellary	3.0	34.67
	Bijapur	3.7	36.60
	Solapur	3.1	49.73
	Arjia	4.7	36.93
IV. Aridisols			
	Hisar	1.9	20.10
	SK Nagar	2.3	27.36

Table 5. The SOC concentration and pool of a Vertisol from Penninsular India (Recalculated from Pal et al., 2012)

Depth (cm)	Thickness (m)	Soil bulk density (Mg m^{-3})	SOC concentration (g kg^{-1})	SOC pool (Mg ha^{-1})
0-14	0.14	1.5	8.1	17.01
14-40	0.25	1.5	6.6	24.74
40-59	0.19	1.6	5.9	17.94
59-91	0.32	1.5	6.1	29.28
91-125	0.34	1.5	4.8	24.48
125-150	0.25	1.6	4.2	16.80
Total	1.50			131.25

is essential to reversing the downward spiral, restoring desertified soils, enhancing SOC stock, and improving soil quality.

Improving plant AWC, through water harvesting/recycling and supplemental irrigation along with increasing soil water storage in the root zone, is essential to enhance NPP. Water harvesting technologies include: (i) *in-situ* water harvesting at the field level, (ii) water harvesting and storage in above ground reservoirs, and (iii) ground water recharge through water harvesting (Pasternak *et al*., 2011). Small scale irrigation, especially through drip sub-irrigation of harvested water or other resources, is critical to improving NPP and agronomic yields from drylands. Irrigation studies conducted in the middle reaches of the Heihe River Basin (Gansu Province), northwest China, showed that the SOC concentration of 0-0.2 m depth increased with the increase in the duration of irrigated cropland use (Table 1). Expectedly, the correlation coefficient with duration of cultivation was positive with SOC concentration (Y(g/lg) = 0.115X + 1.379, R^2= 0.914) and with the mean weight diameter of aggregates (Y(mm) = 0.0853X+0.019, R^2= 0.887), but negative with soil bulk density (Y(g/cm^3) = 1.552X-0.0037, R^2=0.83). Improvement in soil

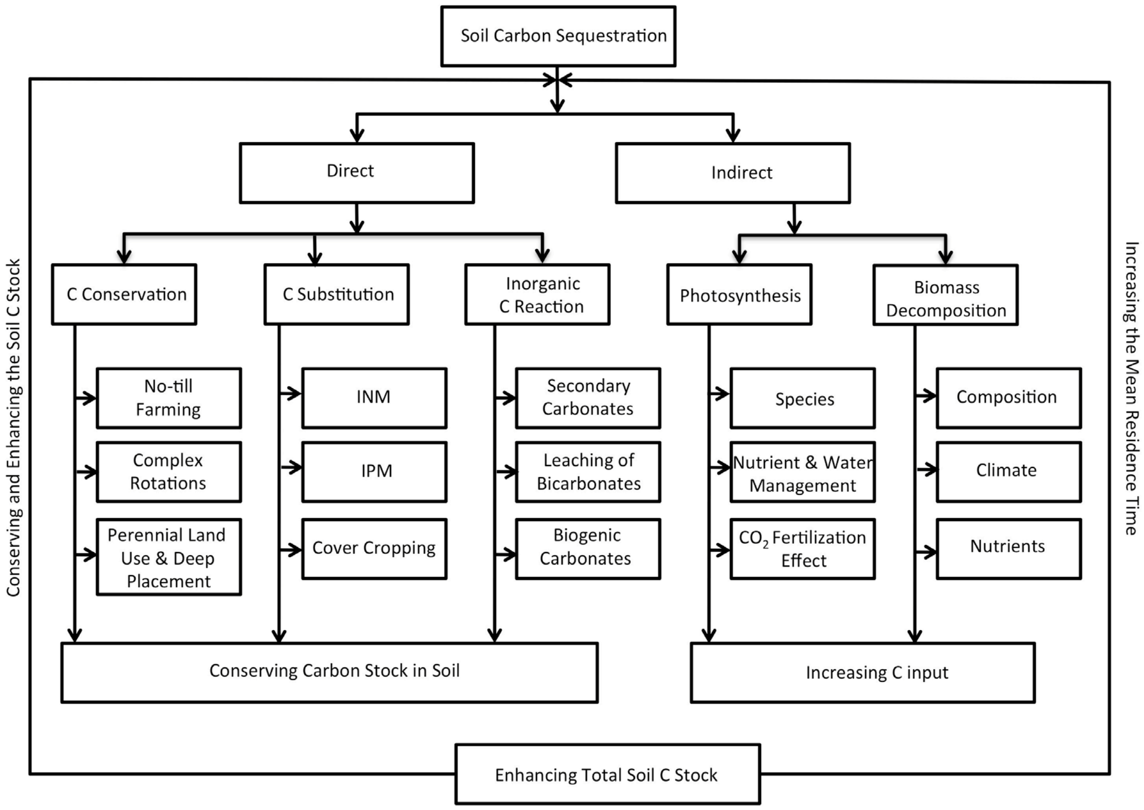

Fig. 9. Direct and indirect processes of soil carbon sequestration (INM= integrated nutrient maanagement, IPM= integrated pest management, C= carbon).

Table 6. Desertification control and carbon sequestration in Northwest China (Recalculated from Su et al., 2010a; b)

Treatment	SOC stock in 0.15 m depth ($Mg\ ha^{-1}$)	SOC sequestration rate ($kg\ ha^{-1}\ yr^{-1}$)
Untreated control	0.66	-
7-year-old shrub	2.45	256
32-year-old shrub	6.48	182
7-year-old forest	8.25	1084
32-year-old forest	10.01	292
7-year-old cropland	6.81	879
32-year-old cropland	12.27	363

quality can be even better if irrigation is adopted in conjunction with conservation agriculture, integrated nutrient management (INM), and other site-specific RMPs.

Soil fertility and especially moisture conservation can be greatly enhanced by the use of zeolites. The structure of zeolites is ideal for sorption of ions and retention of water (Reha'kova' *et al*., 2005). The low water and nutrient retention properties, of sand and other coarse-textured soils widely observed in arid and semi-arid regions, can be enhanced by zeolites (Ok *et al*., 2003). Thus, natural zeolites (and synthetic counterparts) are widely used as soil amendments in agronomy and horticulture (Mumpton, 1999). The most commonly used natural zeolite in agricultural soils is clinoptilolite because it has high absorption, cation exchange, catalysis and dehydration capacity (Polat *et al*., 2004). It can also be effectively used for phytoremediation (Leggo *et al*., 2006). Properly used, it can also reduce ammonia volatilization from chemical fertilizers (NH_4NO_3, $(NH_4)_2SO_4$). Thus, combination of zeolite and compost/manure can be useful to enhance use efficiency of nitrogenous fertilizers and reduce emissions of N_2O.

Establishment of forest plantations, and other perennial vegetation is a viable strategy to enhance SOC sequestration (Table 6). Zhany *et al*. (2011) elevated soil C sequestration under a poplar (*Populus alba*) plantation in northwest China. The average rate of soil C sequestration over a 15 year-period was 0.13 Mg C ha^{-1} yr^{-1}. Poplar-based agroforestry (wheat under poplar) has been practiced in northwest India (Lal, 2004). Agroforestry with *Faidherbia albida* and *Leucaena leucocephala* in the Old Peanut Basin of Senegal showed soil C sequestration rate of 0.22 and 0.12 Mg C ha^{-1} yr^{-1}, respectively (Tschakert *et al*., 2004). In addition to increase in soil C stock, woody biomass C is even more sensitive, especially to the projected climate change. Thus, short-term improved fallows (legumes and grasses) can also be useful options. Increasing SOC stock in depleted/desertified soils can provide multiple benefits to small size land holders of SA and SSA. The specific advantage of enhancing SOC stock in soil of the Sahel regions (and in arid climates elsewhere) is to reduce the vulnerability to the projected climate change of already impoverished and resource-poor societies (Tieszen *et al*., 2004).

Payments for Ecosystem Service

Improving soil quality can enhance the natural capital through restoration of desertified soils. The latter consists of water storage, biodiversity, nutrient services etc. (Daly *et al*., 2011). Ecosystem services provisioned by a soil depend on its natural capital (e.g. texture, clay content, SOC stock, clay minerals). Among numerous ecosystems services, the importance of advancing food security through desertification control and soil quality restoration cannot be over emphasized. Improving pastoral and silvi-pastoral systems can greatly enhance food production in these environments. There is a lot of potential of specialized agriculture (e.g., screen house farming), and establishment of horticultural crops. The number of food- insecure populations have increased to 1,020 million (FAO, 2009), and about two-thirds of these live in the Asia-Pacific region with predominance in SA. The problem will be aggravated by the projected climate change and increase in frequency and intensity of extreme events.

The scientific knowledge of RMPs for controlling, mitigating and reversing soil degradation has been available since 1960s, and the technological innovations have been improved drastically at least since 1990s (Brauch and Spring, 2009; NRC, 2008). However, there has been little progress in application of this knowledge in reversing degradation trends in site-specific situations. There are numerous factors responsible for non-adoption of the specific knowledge. Payments for ecosystem services can promote adoption of SLM approaches in conjunction with adaption and mitigation strategies.

Conclusions

1. The problem of desertification is widely recognized, and there is a strong link between the risks of desertification and the projected climate change - both are driven by increasing demands of the growing population on limited resources, fragile soils, and the harsh and uncertain climate.
2. The trilemma of desertification-climate change-food insecurity can be effectively addressed by improving soil quality and enhancing soil/ecosystem resilience.
3. Increasing soil C pool is an important strategy of restoring soil quality, increasing agronomic productivity, and enhancing use efficiency of scarce resources.
4. Recommended management practices for desertification control involve those which conserve soil and water, create positive nutrient and C budgets restore vegetation cover, and enhance biodiversity. Water harvesting and recycling, and integrated nutrient management are important strategies.
5. Desertification control through soil carbon enhancement and soil quality improvement is a win-win strategy. It advances food security and adapts to changing and uncertain climate.

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Printed in April 2013