MITIGATING DESERTIFICATION AND CLIMATE CHANGE THROUGH SOIL QUALITY RESTORATION AND CARBON SEQUESTRATION

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Executive Summary

Desertification, soil degradation in dry regions, is exacerbated by climate change and excessive demands on natural resources because of increase in population. The problem manifests itself by increasing severity and frequency of drought, accelerated soil erosion, depletion of soil fertility and soil organic matter reserves, decline in net primary productivity, and drastic reduction in agronomic yields. The biophysical process of desertification is accentuated by the human dimensions involving economics, social, political, cultural and ethnic factors. Consequently, 3 to 4 billion hectares of land (Soil and vegetation) are vulnerable to desertification. There exists a strong link between the extent and severity of desertification on the one hand and food insecurity, poverty, civil unrest and political instability on the other.

Restoring desertified soils implies: (i) alleviating drought stress by conserving, harvesting and recycling water, (ii) controlling soil erosion by establishing vegetation cover, (iii) enhancing soil and ecosystems, carbon (C) pool by its sequestration in soil and vegetation, (iv) creating a

positive nutrient budget by use of soil amendments, and (v) adopting diverse and productive land use/farming systems. The strategy is to enhance ecosystem/soil resilience by sequestering C and improving soil quality.

In addition to erosion control, reclaiming salt affected soils by establishing energy plantations and irrigating these with brackish water are useful strategies of both mitigating and adapting to climate change. Improving soil quality is essential to restoring ecosystem services. There exists a strong body of knowledge about sustainable management of soil and natural resources. There are also over 200 laws, resolutions, charters and policies on soil protection and restoration. However, there is little progress in application of the scientific knowledge and implementation of laws and policies. Therefore, 3 specific strategies are proposed to mitigate desertification and restore degraded soils and ecosystems. These strategies are: (i) enhancing awareness about "Soil Ethics" and involving general public about cultural and spiritual issues related to soils, (ii) strengthening communication with land managers, policy makers and researchers about the basic laws governing sustainable management of soil recourses, and (iii) creating Intergovernmental Panel on Dryland and Desertification (IPDD) under the auspice of UNCCD. The IPDD will: (i) strengthen the data base, and collate and disseminate credible information on the extent, severity and rate of desertification, (ii) assess economic, ecologic, social and political impact on the vulnerable ecoregions, (iii) evaluate the interaction among biophysical and social controls of degradation process, (iv) strengthen institutional support, and (v) develop and implement a specific action plan at international scale. There is a strong need to strengthen UNCCD through IPDD by identifying four task forces. Describing scientific basic of desertification is the responsibility of Task Force #1. Impact assessment on food security and ecological services is the mandate of Task Force #2. Identifying global hotspots and prioritizing strategies for pilot projects will be the goal of Task Force #3. Task Force #4 will liaise with other U.N., and international organizations (UNFCC, UNFCBD, UNEP, FAO, World Bank, U.N. Millennium Development Goals) to identify commonalities and themes of mutual interest.

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I. INTRODUCTION

Among serious global issues of the 21st century are: (i) food-insecurity affecting 963 million people (Rosegrant and Cline, 2003; Bourlaug, 2007; FAO, 2008a) and increasing because of increase in prices of cereals and other staples since 2006 partly as a result of conversion of grains to biofuels (Battisti and Naylor, 2009; FAO, 2008b), (ii) a rapid increase in atmospheric concentration of CO_2 from 280 ppm in the pre-industrial era to 385 ppm in 2008 and increasing at the rate of 0.5%/yr or 2 ppm/yr because of fossil fuel combustion, land use conversion and soil cultivation (WMO, 2008; IPCC, 2007), (iii) decline in per capita crop land area to <0.07 ha (hectares) by 2025 for 30 densely populated countries because of increase in population, converion to other land uses and soil degradation (e.g., China, Bangladesh, Egypt), (iv) reduction in renewable fresh water supply to <1000 m^3/yr for 58 countries by 2050 along with increasing competition among agricultural, industrial and urban uses (Gleik, 2003), and (v) global energy consumption of 435 Quads/yr (1 Quad = 10^{15} BTU) and increasing by 2.5%/yr between 2001 and 2025 (Wiesz, 2004; EIA, 2007) because of increase in industrialization and rising aspiration and standards of living. All these issues are closely linked to the severe problem of soil degradation and desertification.

Desertification, soil degradation in arid regions, is exacerbated by the interactive effects of biophysical processes, ecological and human dimension factors, and land use and managerial causes (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 and per capita grain consumption, which have been declining globally but especially in developing countries since mid 1990s (Kondratyev et al., 2003). Availability of croplands and fresh water for agriculture are also being constrained with the demand on these limited resources for biofuel production. Increase in global temperature is likely to further reduce agronomic production affecting more the 3 billion people living in the tropics and sub-tropics, a large proportion of whom live on <$2/day and depend primarily on agriculture for their livelihood (World Bank, 2008; Battisti and Naylor, 2009). Consequently, the U.N. Millennium Development Goals of reducing hunger and poverty by 50% by 2015 will not be met.

As agronomic productivity sputters, as food production lags behind the demands, as hunger and malnutrition adversely affect human health and wellbeing, as soils degrade and desertify, as natural waters pollute and contaminate, as climate warms and species disappear, and as environments deteriorate and jeopardize ecosystem services, there will be a growing realization among scientists and policy makers that taking soils for granted has been the root cause of the downward spiral. The emerging paradigm must consider the strategy of enhancing soil and ecosystem resilience so that the problems of soil degradation and desertification can be minimized. For this strategy to take hold, there is a need to: (i) nurture strong communication between scientists on the one hand and policy makers, land managers and public on the other, and (ii) develop "The Soil Ethics" that would require soil managers to consider consequences and take responsibility of their decision on adopting those land use and soil management practices which would jeopardize their quality and exacerbate the risks of soil degradation and desertification.

In essence, the issue of the 21st century is the "ecological crisis" encompassing soil degradation, and desertification exacerbated by global warming and the attendant decline in quality and quantity of water, and reduction in biodiversity. With industrialization, leading to increase in pollution and economic growth along with enhanced aspirations of materialistic possessions, the problem of soil degradation and desertification have been more severe during the 20th and 21st centuries than ever before. Thus, there is a need for development of a strong "Soil Ethic" in accord with an "ecocentric" rather than "anthrocentric" approaches to management of natural resources. The objective of this report is to emphasize the importance of "Soil Ethics" as an integral component of any charter, resolution, policy or an action plan implemented to mitigate soil degradation and desertification, and restore degraded soils and desertified ecosystems. The report also proposes development of an Intergovenment Panel on Drylands and Desertification (IPDD) as an integral component of UNCDC, as is IPCC to UNFCC.

II. DRYLANDS AND DESERTIFICATION

Drylands, where the ratio of mean annual precipitation (P) to that of the potential evapotransportation (PET) is <0.65, cover about 41% of Earth's land area and are home to about 38% of the world population of 6.5 billion in 2005 (Reynolds et al., 2007). 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., 2000). Because of harsh climate, dry lands are prone to several soil degradation processes affecting as much as 10 to 20% of the total area. The term desertification "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities (UNCCD, 1994), has been widely debated (Reynolds et al., 2008). The land area prone to desertification has been assessed and re-assessed (Tables 1, 2, 3). Including degradation of vegetation, area affected by land degradation may be as much as 3.5 to 4.2 Bha (Tables 1 and 2). Consequently, water resources are getting scarce, especially so in Africa (Gleik, 2003). With the historically strong emphasis on adverse impacts of desertification (UNCED, 1978; UNEP, 1991; 1992; UNCED, 1992; Slegers and Stroosnijer, 2008; UNCCD, 1994; Le Houreau, 1996; 2002), 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 abrupt climate change or global warming. For state-of-the-knowledge report on desertification and its causes and effects, readers are referred to reviews by UNEP (1991; 1992), Mainguet and da Silva (1998), Le Houreau (2002) among others.

Adopting an ecosystem approach is considered a useful strategy to restoring degraded soils. 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 “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, 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 (Jenny, 1984).

III. CLIMATE CHANGE AND DESERTIFICATION

Global warming and the attendant climatic variability are likely to have strong impact susceptibility of dryland those to degradation processes which exacerbate desertification (Hulme, 1996; Noble and Gitay, 1996; Oba et al., 2001). The widespread problems of drought and desertification in arid regions (Tables 1, 2 and 3, Le Houérou, 1996) are attributed to the prevalence of harsh climate in these regions characterized by intensity and duration of recurring droughts with adverse impacts on NPP. The climate is projected to exacerbate its harshness by increasing frequency and intensity of extreme events such as "drought". There is a difference between "aridity" and "drought". The term aridity refers to a low ratio of P:PET (Le Houérou, 1996). The term drought refers to decrease in availability of fresh water supply, and the latter 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** drought caused by deficiency in soil moisture reserves because of low water infiltration rate and high losses by surface runoff and evaporation, and (iv) **agricultural or ecological drought** caused by 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 which are triggered by soil degradation and desertification through reduction in plant available water capacity. 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 fraction, (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 and habitat. These types of drought are exacerbated by prevalence of extractive farming and utter lack of good farming. There are at least 3 criteria of good farming (Worster, 1984): (i) good farming is farming that preserves the earth and its network of life, (ii) good farming is farming that promotes a more just society, and (iii) food farming is farming 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-available water capacity by decreasing the relative proportion of 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 build up of salts in the rootzone 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 (Puidgdabregas, 1998): (i) change in vegetation cover, (ii) positive feedback to atmosphere due to anthropogenic activities, (iii) adverse off-site effects, and (iv) 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) 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) soil organic matter (SOM), (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 ºC increase in temperature. Another scenario of the positive feedback on desertification with the change in climate may be due to changes in plant vegetation patterns (Ares et al., 2003), especially leading to reduction in vegetation cover and the attendant decline in the ecosystem C pool.

IV. FOOD SECURITY AND DESERTIFICATION

Desertification affects food security directly and indirectly (Fig. 2). Food security refers to a "situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life (FAO, 2002). Thus, there are four key dimensions of food security: (i) availability, (ii) stability, (iii) access, and (iv) utilization (Schmidhuber and Tubiello, 2007; Moyo, 2007). The "availability" component implies ability of agricultural systems (e.g., soil and water resources, climate, agronomic systems) to produce food. The "stability" component refers to availability of food at all times to all people and implies reliability of the food availability, which may be affected by climatic factors, drought and desertification. The term "access" refers to the ability of a community to acquire sufficient food on a sustainable basis, or to the purchasing power of a household or nation. The "utilization" component involves food safety, quality and health. Number of food-insecure people has increased from 854 million in 2000 (Borlaug, 2007) to 963 million in 2008 (FAO, 2008a). A vast majority of these people live in South Asia and Sub-Saharan Africa. However, 36.2 million live in the U.S. (FRAC, 2008). Increase in the number of food-insecure people is also caused by diversion of food grains to biofuel, increasing the price of food staples (Agola, 2008). Several of these countries/regions

(Lobell et al., 2008) are prone to drought and desertification (e.g., South Asia, China, West Africa, Sahel). Food insecurity is also a cause of 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 world wide with at least 2,720 kilocalories a day (Mousseau and Mittal, 2006). It is the human dimension issues which are also extremely important to global food security. Important among these are the political stability, civil unrest, and ethnic conflict (Fig. 2).

V. RESTORING DESERTIFIED AND DEGRADED SOILS

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 controlled by surface sealing and poor soil structure, and evaporation accentuated by a high evaporative demand of the arid environment. Those civilizations which had abundance of water also had abundance of food: " There was famine in all lands, but throughout the lands of Egypt there was bread" (Genesis 42:54). However, water mismanagement and misuse can also lead to waterlogging and salinization, a serious cause of desertification. For example, soil degradation in Mesopotamia was set-in-motion by salinization of the valleys and erosion of the highlands. Increase in salinization occurred because irrigated farming with poor quality water and without drainage caused waterlogging and rise in the ground water that brought salt to the surface (Adams, 1981). Erosion of the sloping lands occurred because of deforestation, excessive grazing, and plowing without use of conservation-effective measures and denudation in the watersheds of Tigris and Euphrates Rivers caused server erosion and siltation. Soil degradation and desertification, caused by erosion and salinization along with siltation of irrigation canals, adversely affected Mesopotamians, Hittites, Aramaems, and Phoenicians (Hillel, 2005; Lowdermilk, 1953). The problems of soil erosion and salinization are more severe now (Oldelman, 1994; Lal, 2001b; 2003; Bai et al., 2008) than in pre-historic times because of high population density and excessive demands on limited resources. Once water is available and erosion is effectively controlled, availability of plant nutrients (e.g., N, P, K, Zn) becomes essential to enhancing agronomic production. Depletion of SOM and mining of plant nutrients, through extractive farming and losses by erosion and volatilization are major causes of soil degradation and the attendant desertification.

Similar to its adverse impacts on ancient civilizations presently observed low productivity of soils of Sub-Sarharan Africa (SSA) and South Asia (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. The biophysical process of desertification is driven by the human dimension issues (e.g., poverty, civil strife, political instability). There is a strong interaction between the processes, causes and factors (Fig. 1). Processes of soil degradation include physical (erosion, compaction, crusting, decline in soil structure), chemical (nutrient depletion, acidification, salinization, and elemental imbalance) and biological (decline in SOM, 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 etc. (Fig. 3).

In accord with these causes outlined in Fig. 3, strategies of desertification control and soil quality restoration to reverse these processes are outlined in Fig 4. The goal is to: (1) enhance water availability in the root zone by water harvesting and recycling, reducing loses by evaporation and runoff, and enhancing water use efficiency, (2) control soil erosion by providing a continuous ground cover and minimize soil disturbances, (3) improve nutrient supply through integrated nutrient management (INM) including biological nitrogen fixation (BNF), strengthening nutrient cycling, and using supplemental doses of chemical fertilizers, (4) adopt diverse and productive farming systems. These generic recommendations must be made site-specific through local/adaptive research.

VI. ECOSYSTEM RESILIENCE AGAINST DESERTIFICATION

Ecosystem resilience implies ability to cope with randomness, shocks and extreme events of the arid climate and yet maintains functions and services (Holling, 1986; Gunderson and Holling, 2002). The basic premise of the resilience concept is based on the assumption that "things change" and to ignore or resist change implies increasing the vulnerability of ecosystem to desertification. The change in soil ecosystem, natural or anthropogenic, may be rapid or slow. Examples of rapid change include depletion of SOM and plant nutrients along with the attendant decline in SOC pool, soil erosion edaphic and agronomic drought. In contrast, examples of slow change include alteration in soil texture, meteorological and hydrological drought, climax vegetation. Two central themes of the resilience approach are to recognize the importance of: (i) threshold/critical level of key soil properties and processes (e.g., 1.1% SOC concentration, 30 cm effective rooting depth) beyond which the system undergoes a drastic regime change, (ii) four stages of adaptive cycles through which a soil ecosystem passes as a result of change (e.g., rapid growth, conservation, release and re-organization). A schematic of the regime change in relation to the threshold level of an eroding soil system is shown in Fig. 5. Once the system (e.g., ball) crosses the thresholds, a severely eroded soil can undergo an irreversible degradation due to loss of the entire topsoil and severe depletion of the SOC pool. The soil-ecological system has multiple regime or stable states, which are separated by thresholds (Fig. 6). The degree of resilience depends on the length of the threshold. These concepts are explained in the details by Walker et al. (2004), Folke et al. (2004) and Walker and Salt (2006). A schematics of the adaptive cycle in rangeland management with regards to feedbacks are shown in Fig. 7. Knowledge of the thresholds is important to ascertain that thresholds limits are not crossed to avoid the regime change or irreversible degradation. With conversion of a natural to managed ecosystem, it is important to adopt judicious soil/crop/pasture management options so that soil retains its capacity to buffer any perturbation by erosion, fire, drought, climate change etc. while maintaining its ecosystem services and still behaving as it was before the disturbance. Resilience of the soil ecosystem is proportional to the distance of the threshold part (Fig 5) because it reflects its ability to "get back" or "bounce back". If soil erosion is the principle perturbation, it is crucial to understand how the ball is moving, and how the erosion forces shape the "thresholds" or contour of the basin.

An irreversible degradation, such as by severe or strong erosion, when the loss of topsoil is too severe so that a soil's adaptive capacity declines to a level that is no longer able to support plant growth because of the exposed bed rock or another form of root-restrictive layer. The soil has lost its resilience and the result is an ecological crisis. Other examples of ecological crisis include severe salinization, strong depletion of SOC pool, complete elimination of soil faunas by heavy input of pesticides (e.g., furadon) resulting in collapse of soil structure, acidification and toxicity of Al, Mn etc. at extremely low pH.

A rapid climate change with rate of increase in temperature at > 0.1°C/decade can alter the hydrologic cycle, dominance of plant species, and the ecosystem C pool(s).

VII. SOIL CARBON SEQUESTRATION THROUGH DESERTIFICATION CONTROL

There are 5 principal global C pools (Fig. 8). The largest C pool is oceanic (38,000 Pg) followed by geologic (4500 Pg comprising of fossil fuels), atmospheric (~800 Pg) and biotic (620 Pg comprising of all flora especially trees). The pedologic pool is estimated at 2500 Gt to 1-m depth, and comprises of 1500 Pg of soil organic carbon (SOC) and 950 Pg of soil inorganic carbon (SIC).

Depending upon the specific pool to which the atmospheric CO_2 is being transferred, a range of strategies of C sequestration include geologic, oceanic, chemical and the terrestrial. Conversion of atmospheric CO_2 into biomass is a natural process which photosynthesizes 120 Gt C into biomass annually. Thus, an amount equal to about 15% of atmospheric C pool is annually photosynthesized into biomass. However, most of the C photosynthesized is returned back to the atmosphere. Some of the biomass-C returned to the soil (e.g., crop residues, leaf litter, detritus material, root turnover) is humified and converted into humic substances and organo-mineral complexes. Thus, terrestrial C sequestration had two distinct components: (i) biomass C (above and below ground), and (ii) soil C. Soil C sequestration into the SIC pool is through formation of secondary carbonates and leeching of bicarbonates into the ground water especially in 275 Mha of irrigated soils in arid and semi-arid climates. Soil degradation depletes the SOC pool, and the goal of restoration is to enhance the SOC pool above the threshold level. Extractive farming practices mine and deplete the SOC pool. Good farming practices put more humus underground by SOC sequestration. Principal strategy of SOC sequestration is through restoration of degraded and desertified soils, by creating a positive C budget. This process also enhances numerous ecosystem services.

VII. 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 good 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 (Fig. 9). Increasing the terrestrial sink by creating a positive C budget is the goal.

In comparison, adaptation to climate change consists of activities which reduce sinks of decline in productivity because of increase in temperature, decrease in effective precipitation, and increase in frequency of extreme events (e.g., drought.). Adaptation to climate change is especially relevant for 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 climate change are outlined in Fig. 10. These approaches 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 available water capacity runoff and evaporation while increasing soil water storage capacity, (3) Improving soil fertility especially the availability of N and P through enhancing biological N fixation (BNF), applying new generation of slow-release fertilizer (nano-enhanced and zeolites), using biosolids including compost and biochar etc, (IV) Reversing soil degradation by improving soil structure, establishing runoff control devices (e.g., stone blends, contour hedges, shelter belts) and reclaiming salt-affected soils, and (V) improve vegetation through introduction of dedicated plant species adapted to dry environments including GM crops. Savannah under diverse notations as agroforestry systems and energy plantations (Fig. 9). These adaptation 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 synthetic C effects and mutual reinforcement and supplementation.

It is prudent to identify these technologies which mitigate climate change through increasing C sequestration soils and trees, but also adapt to climate change by reducing sinks (Fig. 10). The goal is to increase ecosystem resilience through innovative options such as afforestation, diverse and complex systems, soil quality restoration etc. These options will help adjustments of agricultural systems by increasing resilience and reducing vulnerability.; Identification can be done in anticipation of privileged change as well as in response to change that has already occurred. Desertification control and restorative measures would enhance adaptive capacity while also increasing C sink.

IX. ECOSYSTEMS SERVICES AND DESERTIFICATION CONTROL

Desertified soils have lost functionality especially for conserving soil and water, recycling water and nutrients/elements, storing carbon, providing habitat for flora and fauna and producing biomass as net primary productivity (NPP). Thus, the objective of desertification control is to restore these ecosystem functions (see Fig. 4). The first step is to establish vegetation cover by identifying 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 a favorable water and energy budgets, especially under vegetation patches. Soil beneath the patches have high water infiltration rate, low/no surface runoff, minimal crusting and higher soil organic matter reserves. A gradual improvement in soil quality, over a decadal scale, sets-in-motion restorative processes that eventually restore degraded/desertified ecosystems.

There are three important ecosystems services of relevance to the global issues of the 21st century. The potential of C Sequestration through desertification control is estimated at about 1 Gt C/yr (Lal, 2001a). The potential can be more with establishment of biofuel plantation consisting of salt-tolerant plants (Table 4). High biomass can be produced by growing halophytes which can be irrigated with brackish water (Table 5). Rates of C sequestration in reclaimed salt-affected soils can be >1 t C/ha/yr (Table 6) to more than 3 t C/ha/yr (Fig. 12). Technical potential of C sequestration in salt-affected soils is 0.4-1.0 Gt C/yr (Table 7), and that of desertification control is 1.17 Gt C/yr (Table 8). In addition, establishing biofuel plantations on desertified lands has a technical potential of offsetting industrial emissions by 0.3-0.5 Gt C/yr (Lal, 2001a). Trading C credits, paying land managers for ecosystem services of societal interest, provides incentive to adopt best management practices (BMPs). Creating a mechanism for trading of C credits, a transparent and a fair/just system, is crucial to the widespread adoption of the BMPs. Commodification of C, creating another income stream for resource-poor farmers, is important to restoring degraded/desertified soils.

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 scientific knowledge for controlling, mitigating and reversing soil degradation has been available since 1960s, and the technological innovations have been improved drastically 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. Three strategies discussed below are: (i) enhancing awareness about "Soil Ethics" by strengthening spiritual and cultural linkages and involving general public about the soil mystique, (ii) strengthening communication with land managers, policy makers and researchers about the basic laws of sustainable soil management, and (iii) creating an Intergovernment Panel on Drylands and Desertification (IPDD) under the auspices of UNCCD.

X. SOILS AND SPIRITUALITY

The problems of soil degradation and desertification have plagued humanity ever since the dawn of civilization from the prehistoric times. Beginning with discovery of fire and invention of a primitive "ard" (Lal, 2009a), a forked branch of a tree designed to scratch the soil with the objective of placing the seed at a shallow depth and covering it with the topsoil, humans have accelerated extinction of plants and animals, rate and magnitude/severity of soil degradation by erosion and salinization, risks of water pollution and siltation of reservoirs and waterways, and emissions of greenhouse gases (e.g., CO_2, CH_4, N_2O) into the atmosphere. Indeed, several once thriving civilizations have perished and collapsed because they ignored the soils that supported them (Montgomery, 2006; Diamond, 2005).

The problems of desertification and soil degradation are not just biophysical and socioeconomical or political issues, these are also religious and spiritual as well. The spiritual realm was especially important during the pre-historic periods when the scientific knowledge about biophysical processes underpinning drought, soil erosion and salinization did not exist. Thus, these natural catastrophes, especially the drought caused by failure of rains, were attributed to the wrath of gods and goddesses (e.g., Lord Indra of Indo-Aryans) rather than El-Niño-La Niña cycles as we now know. Because of the dependence of crops on rains, and of rain on the approval of a god or gods, numerous ancient cultures developed strong rituals to please god(s) which presumably controlled the rain and crop yields. Because the problem is as old as the human civilization, it is not surprising therefore, that every generation developed its own code of "The Soil Ethics" in accordance with their perception and knowledge at the time. In many ancient cultures, soil has been regarded as personification of nature or god, and thus a direct object of worship and reverence. In these ancient cultures, soils are esteemed, even venerated, and soil is “Mother Earth”. Thus, religious rituals require people to kneel and kiss the ground in the belief “that from the soil we come and to the soil we return”. Such a veneration adds up to a soil mystique that transcends the notion of soil as a mere economic commodity (Jenny, 1984).

The Soil Ethic was strongly supported by numerous ancient religions and culture (Table 1). The Hebrew concept “Tikkun Olam” means “repairing the world” or “Perfecting the world”, originated in the early rabbonic period, was given new meanings in Kabbalah of the medieval period and further connotation in modern Judaism. According to Greco-Roman Philosophy (Homer’s Iliad and Odyssey, and Hesiod’s Theogony and Works and Days) the Earth goddess “Gaea” (also called Hekate, Eurynome, Demeter, and Rhea) was worshipped throughout the Mediterranean Basin. The Indo-Aryans, whose philosophies form the basis of Hinduism and Buddhism/Jainism, also worshipped mother Earth and all its creatures. These beliefs acknowledge the power of nature, the need for human symbiosis with it, and recognizing that “all life is one”. A hymn Atharva Veda (12.1.35) reads “ Whatever I dig out from you, O Earth! May that have quick regeneration again, may we not damage thy vital habitat and heart”. These spiritual concepts form the basis of “ahimsa”, non-injury to all, and loving care of everything in nature, and part of the stewardship of Earth (Table 9).

Vedic concepts on forestry affirm that a village is complete only when certain categories of forest, vegetation or trees are preserved in and around its territory. Three predominate types of forest around the village include “Mahavan” (the great natural forest), “Shrivan” (forest of prosperity or wealth), and “Tapovam” (forest of prayers/religion) (Prime, 2002; Kumar, 2008). These three types of forests described in ancient scripture correspond to the present day forest reserves, production forest, and protected forests. Similar concepts exist in Buddhism. With *nirvana* (Buddhism), valuable plants and animals and other resources are not necessarily good, as weeds or pests and marginal lands are not necessarily bad, and the many useless creatures and landscapes filling out the rest of nature are not irrelevant. Pythagoras's philosophy must have been strongly influenced by South Asian beliefs because he also believed that one's aim in life is to live as purely as possibly in order to transcend earthly existence, and in soul's reincarnation in an animal or human body, and in vegetarianism. Plato and Aristotle also followed these concepts. According to the Judeo-Christian traditions, Callicott (1994) sums up these possible interpretations of environmental ethics: (i) an indirect anthrocentric or human interest/human rights associated with "despotic" interpretation (Genesis 1:26-28), (ii) a more direct ecocentric environmental ethic associated with "stewardship" and (iii) an uncompromising ecocentric environmental ethic associated with "citizenship" (Table 9).

Islam, with its roots similar to Judeo-Christian traditions, arose in West Asia during the 7th century A.D., and spread to North Africa and South and Southeast Asia . According to Islam, Allah created "Adam" (as stated in Judaism and Christianity) from clay (soil) and "breathed into His creation the breath of life" (Quran, Chapter 95). Quran explicitly states " Unto Allah (belongth) whatsoever is in the heavens and whatsoever is the earth; and whether ye make known what is in your mind or hide it, Allah will bring you to account for it. He will forgive whom He will and He will punish whom He will" (Zaidi, 1981). Thus man is a manager of the Earth and not a proprietor. This is a "stewardship" interpretation of Quran (Quran Surah 33:72), and there is a strong emphasis on rights and responsibilities of other forms of life on earth and its recourses (Quran 6:38, Table 9), as is also stated in the Old Testament (Ecclesiastes 3:19). Quran further states that to deface, defile or destroy nature would be an impious or even blasphemous act (Callicott, 1994).

"The Gaea" hypothesis/model, proposed by James Lovelock (1979), combines Judeo-Christian and Vedic/Buddhism philosophy with scientific understanding of Earth's processes. It states that "biosphere is more than just the complete range of all living things within their natural habitat of soil, sea and air". Thus Earth is "a single organism", an organic whole, greater than the sum of its parts". The hypothesis is based on two scientific principles: (1) the biosphere maintains the Earth's lithosphere, hydrosphere and atmosphere, and (2) the biosphere maintains a critical optima in the absence of which life on Earth would not be possible. Earth maintains a constant temperature of about 15°C through its organismic components. The Gaea hypothesis is in accord with the ancient writings of Indo-Aryans. In Śrīmad Bhāgavatam (2.1.33), Lord Krishna explains to the warrior Arjuna in the battle field of Mahabarata "nadyo `sya nādyo `tha tanū-ruhāni mahī-ruhā viśva-tanor nṛpendra ananta-vīryah śvasitaṁ mātariśvā gatir vayah karma guna-pravāhah". It is translated in to English as "O King, the rivers are the veins of the gigantic body, the trees are the hairs of His body, and the omnipotent air is His breath, the passing ages are His movements, and His activities are the reactions of the three modes of material nature."

Conservationalists and environmentalists of the 20th century (Tables 10, 11) including Aldo Leopold, Luis Bromefield, and Wes Jackson have proposed ideas similar to those embodied in the Gaea model forging strong link between science and spirituality. Leopold suggested that we are cells in the body of Mother Earth and realized the individuality of the Earth. He stated that "Earth comprises of soil, mountains, rivers, forest, climate, plants and animals" and must be respected "collectively as a living being" (Leopold, 1991).

The disregard of these spiritual and ethical concepts may have been an important factor of the degraded and desertified state of world's soils and natural resources. These problems have been especially severe during the 20th century, when population increased and large scale conversion of natural ecosystems (e.g., forest, savannahs and prairies) was under taken to meet the ever increasing demands of industrializing and urbanizing world. Indeed, the problems of soil degradation and desertification have perpetuated despite continued emphasis on understanding biophysical processes and alleviating the causes since 1940s, especially since the World War II. It is natural, therefore, to adopt a different approach to address the severe problem, the approach that links religious/ethical concepts of land stewardship with scientific principles in tackling this global issue. Therefore, the objective of this report is to address the issue of soil degradation through synthesis of ethical/moral/spiritual concepts with biophysical processes, technical skills and modern innovations. The strategy is to involve policy makers and the general public in developing a bottom up approach in restoring degraded soils and desertified ecosystems.

XI. LAWS OF SUSTAINABLE SOIL MANAGEMENT

The problems of soil degradation and desertification are rooted in unsustainable use of natural resources. The strategy is to promote the sustainability concept among policy makers, land managers, and researchers. These concepts are briefly outlined below (Lal, 2009a;b).

I. Policy Makers:

Establishing a dialogue with policy makers is important to identifying policies which reverse the degradation trends. Five basic laws of soil management which are related to appropriate policies are the following.

1. **Causes of Soil Degradation and Desertification:** The biophysical process of desertification is driven by economic, social, and political forces. The effectiveness of managing

biophysical processes in minimizing degradation risks and enhancing restoration mechanisms depends on addressing the human dimensions that affect land misuse, soil management, and prevalence of extractive farming practices.

2. Human needs And the Stewardship of Natural Resources: Because humans are always dependant on agriculture, improving agriculture is essential to the stewardship of natural resources. In this context, it is important to realize that, when people are poverty stricken, desperate and starving, they pass on their sufferings to the land. The stewardship concept is important only when the basic needs are adequately met. A sermon about the virtues of saving a tree falls on deaf ears when there is no fuel for cooking the family meal. In other words, starving people do not care about stewardship (Barttlett, 2004).

3.) Poverty, and Soil Degradation: There exists a close relationship between poverty and soil degradation. Poor farmers carve out meager living from marginal and impoverished soils. Marginal soils cultivated with marginal inputs produce marginal yields and support marginal living. The sustainable soil management strategy is to cultivate best soils by best management practices to produce the best yields so that surplus land can be saved for nature conservancy. Sustainable management of soils is the engine of economic development, political stability, and economic transformation of rural communities in developing countries.

4.) Soil Degradation is a Cause of Global Warming: Degraded soils and ecosystems are sources of CO_2 and other GHGs. Mining C has the same effect on global warming whether it is by mineralization of SOM and releasing nutrients through plowing and extractive farming or it is through burning fossil fuels (coal, gas, oil), using petrol-based products, or draining and cultivation of peat soils.

5.) <u>Desertification Control and Mitigation of Climate Change:</u> Degraded and desertified ecosystems have a large C sink in soils and biota because of historic loss and perpetual misuse of natural resources. Thus, restoration of these ecosystems can be a major sink for atmospheric CO_2 and CH_4 through conversion to a restorative land use adoption of recommended management practices that lead to positive C and nutrient budgets. Filling the C sink capacity of the pedosphere (~4 Gt C/yr) in soils of croplands, grazing lands, and degraded and desertified lands), being cost-effective and a natural process, has numerous ancillary benefits. While advancing food security and improving water quality, C sequestration in the biosphere also mitigates climate change.

II. Land Managers:

The strategy of establishing dialogue with land managers is to emphasize the importance of adoption of those farming practices which create a positive C and nutrient budget, and enhance soil resilience. Basic laws which govern these processes are the following:

1. <u>Nutrient Bank</u>: Soils are analogous to a bank account. Similar to a bank account, it is also not possible to take more out of a soil than what is put into it without degrading its quality. In addition to the amount taken out, soil quality also depends on the rate, timing, method, and form of what is being extracted or replaced. Thus, managed ecosystems are sustainable in the long term if the output of all components produced balances the input into the system. Soils are vulnerable to degradation and desertification when inputs are perpetually less than the output. Soils of sub-Saharan Africa have had a negative nutrient budget since 1960s. Therefore, these soils do not respond to other inputs (e.g., improved varieties) because of severe nutrient-related constraints.

2. **<u>Organic and Inorganic Sources of Plant Nutrients</u>:** The debate on organic vs. inorganic sources of plant nutrients is futile and irrational rather than factual. Plants cannot differentiate the nutrients supplied through inorganic fertilizers or organic amendments. Rather than an 'either/or' question, it is a matter of logistics and practicality in making nutrients available in sufficient quantity, appropriate form, and at the critical time needed for optimum crop growth and desired yields. It is logistically difficult to find enough quantity of biofertilizers, and transport bulk amount of manure, especially in arid and semi-arid regions.

3. **<u>Modern Issues and Ancient Technologies:</u>** The problems of the 21st century, exacerbated by 6.7 billion people increasing at the rate of 70-80 million/yr, cannot be addressed by technologies developed during the middle ages. Thus, it is important to build upon the traditional knowledge and avail the benefits of modern innovations. Similar to the debate on inorganic vs. organic fertilizers, this is also not an "either/or" scenario. Modern science must synthesize the traditional knowledge and build upon it. Those who refuse to use modern science to address urgent global issues of the 21st century must be prepared to endure more suffering.

4. **<u>Masters of Their Own Destiny:</u>** Land managers (farmers, ranchers, foresters) are the masters of their own destiny. While numerous hardships and suffering can be attributed to harshness of the nature and to poor governance, land managers are also masters of their own destiny. Soil restoration and desertification control are more effectively addressed through farmer-driven initiatives in addressing their own problems. The lack of rain has been blamed on nature (e.g., climate change), yet, it is farmer's responsibility to conserve water in the soil, harvest and recycle excess rainfall, and adopt technologies which produce more crop per unit drop (of rain).

5. **<u>Being Pro-Active</u>:** Land managers must be pro-active in demanding from policy makers implementation of programs which reduce their vulnerability to climate change and from researchers innovative technologies which adapt to harsh environments and reverse degradation. These programs include those that involve expansion in irrigation, making timely availability of seeds and fertilizers, providing institutional support and marketing facilities and initiating research relevant to the needs of resource-poor farmers. It is the squeaking wheel that gets the grease.

III. <u>Researchers</u>:

Researchers must also undertake some appropriate projects which are relevant to societal needs, and those which address issues of soil degradation, desertification and food security. Some relevant laws of sustainable soil management for researchers are the following:

1. **<u>Relative Importance of Natural Resources versus Improved Germplasm</u>:** Both are important and must complement one another. However, it is important to realize that even the elite varieties, developed through biotechnology and genetic engineering, cannot extract water and nutrients from any soil where they do not exist. The yield potential of improved germplasm can be realized only if grown under recommended management practices of soil, water, and crop husbandry. Being the foundation of agrarian societies, sustainable management of soils is the engine of economic development, political stability, and transformation or rural communities in developing countries.

2. **<u>Indicators of Soil Quality Improvement</u>:** Even modest improvements in soil quality can have a drastic positive effect on agronomic productivity, food security, farm income and the environment. Thus, it is important to develop indicators of soil quality improvement (soil health score card system) which farmers can relate to and scientists can quantify.

3. Training Cadre of Young Researchers: Regional problems of soil degradation and desertification (e.g., those in SSA and SA) will be solved by researchers from the regions who also understand social, cultural, ethnic and political issues. Therefore, cadre of young scientists, and researchers must be trained who are good world citizens, prepared for life, responsive to societal needs, and useful to humanity. Science without humanity is one of the serious blunders (Mahatma Gandhi). Researchers must be trained in problem-solving skills, creativity, and originality.

4. Building Bridges Across Nations: Soil degradation and desertification are global issues, they do not respect political boundaries, equally affect all irrespective of ethnicity, and cannot be addressed in isolation. Research programs must be developed which strengthen linkages among institutions in different countries facing similar problems. Building bridges across nations is essential to mitigating desertification.

5. Lack of Technology Adoption: There has been a serious lack of adoption of improved soil and water management technologies especially by the resource-poor farmers of SSA and SA (e.g., mulch farming, no-till, cover cropping, INM). It is probably because the top down approach is not effective in technology transfer. Scientists need to identify reasons for the lack of technology adoption and develop programs based on participatory approaches. Scientists must also understand that adoption of "technology without wisdom" is equally problematic (Lal, 2007).

XII. INTER-GOVERNMENT PANEL ON DRYLANDS AND DESERTIFICATION

Laws and Policies on Soil Management

One of the defining themes of the last two decades (1990s and 2000s) is the growing awareness about the degradation of soil and the environment. The big question facing the policy makers is what to do about it (Gallaher et al., 1995). As the magnitude of the anthropogenic impact on ecological processes of Earth increases, the need to restore and improve these vital but scarce resources also increases. Because of the ever increasing significance, some have dubbed the present era as “The Century of the Environment” (Lubchenco, 1998). As much as 43% of Earth’s terrestrial vegetated surface has diminished capacity to supply ecosystem services. Soils, a non-renewable resource under the human time frame, are also under increasing pressure because of urbanization, industrialization and other land uses (Lal, 2009). The global loss of potential direct instrumental value (PDIV) due to soil degradation is estimated at 10 to 20% by 2020 (Daily, 1995). The problems of soil degradation get worrisome as global population may grow by 50% by 2050 (Khan and Hanjra, 2009). Thus, policy instruments are needed for restoring value to the world’s degraded soils. In addition to degradation caused by natural processes (e.g., erosion, salinization, compaction, nutrient depletion), there are also worrisome issues with regards to industrial pollution, and contamination, including that from abandoned dredged soils and sediments (Ohimain et al., 2004).

There are several examples of soil protection laws at national, regional and global scales (Table 12). Notable among these are the World Soil Charter (FAO, 1982), U.S. Senate Resolution 401 (U.S. Senate 24 June 2008). There are over 200 multilateral environmental agreements already in force (Hurni, 2002). Several international symposia have been organized to place “Soils on the Global Agenda” (Hurni, 2006). Legal and institutional frameworks have been described to emphasize the vital role of world soils in human welfare (Hannam and Boer, 2002; Boer and Hannam, 2003). Ecological questions relevant to policy makers have been identified (Sutherland et al., 2006). Most of these policies and resolutions have ethically correct and morally sound languages. Yet, there is no international policy that places value on the soil resource or on restoring degraded soils. Furthermore, there are numerous challenges in implementation of policies at national level (Rodrigues et al., 2008). Rather than to considering these charters just a memorandum of understanding (Kördel and Terytze, 2004; Wyatt, 2008), it is important to implement a specific action plan with sharply defined focus.

Of numerous treaties/protocols and MOUs which originated from the Rio convention and the Agenda 21, the U.N. Framework Convention to Combat Desertification (UNCCD) is most relevant to the global issue of soil and environmental degradation. Parties (U.N. member countries) are required and encouraged to develop National Action Programs (NAPs) to mitigate desertification and its effects, identify underlying causes and direct NAPs to alleviate these causes. The Global Environment Facility (GEF) coordinates activities of the developed countries towards mobilizing the financial support.

Establishment of Intergovernmental Panel on Climate Change (IPCC) has created tremendous awareness about the global warming, with panel sharing 2007 Nobel Peace Prize with Vice President Al Gore. Concerns about the depletion and degradation of world forests by deforestation and other human activities have also led to calls for creation of the United Nations Intergovernmental Forum on Forests (UNIFF) (Pearce et al., 2003). With severe problems of soil degradation and desertification, there is a strong need for creation of an international forum which creates awareness about the problem and develops a coordinated action plan. Along these lines, the resolution 2.59 of IUCN Environmental Law Program adopted in October 2000 was a step in the right direction (IUCN, 2001). The resolution called for "preparation of the guidelines for national legislation and policy to assist countries to manage their specific soil degradation problems and to investigate the format for an international instrument for the sustainable use of soil". The resolution emphasized that specific action be undertaken towards "ecological needs of soil and their ecological functions for the conservation of biodiversity and the maintenance of human life" (IUCN, 2001). Subsequently, "Protocols on Soils" was released in 2005. To date, however, no international agreement, similar to that of IPCC, has been reached.

In view of the severe problem of soil degradation and desertification and its adverse impacts on global climate change and food security, there is a strong need to establish the Inter-Government Panel on Drylands and Desertification (IPDD) with focus on controlling desertification, restoring degraded soils, sequestering carbon in terrestrial ecosystems, improving quality and quantity of fresh water availability, enhancing soils/ecosystem biodiversity, advancing food security and eliminating hidden hunger and malnutrition. This proposal builds upon several ideas proposed in the broader context of the stewardship of natural resources. Important among these are: (i) the "Land Ethics" (Leopold, 1949), (ii) The Earth Charter (Kung, 1993, Rockefeller, 2002), and (iii) Environmental Stewardship and Ethics (Rohlston, 1988; 1994). The proposed IPDD addresses specific issues with focus on sustainable management of soil resources for maintaining its resilience against natural and anthropogenic perturbations, enhancing biomass/agronomic productivity per unit area and time through improving the use-efficiency of input by decreasing losses, and improving ecosystem services. The IPDD acknowledges, among other global issues, a severe problem of soil degradation and desertification with threat to human wellbeing and ecosystem functions. It addresses the biophysical processes underpinning soil degradation and relate these to the human dimensions of social, ethnic, political, cultural and religious factors. It tackles the problem from its historical roots in land misuse and soil mismanagement caused by human behavior. It calls for a coordinated effort at national level to holistically address the "quiet crisis". It differs from the "Land Ethics" of Leopold by focusing on "soils". In accordance with the philosophy of Walter Lowermilk (The Eleventh Commandment), the IPSS calls upon each nation for an urgent action on stewardship of soil for both present and future generations.

MISSION OF IPDD

It is important that goals of IPDD are sharply defined. Wagner proposed "The UNCCD is global authority on policies and measures to reverse and prevent desertification and land degradation and mitigate the effects of drought through scientific excellence, standard setting and advocacy". Along the same line, the mission of IPDD may be: Enhancing awareness about the extent and severity of desertification, evaluating economic and ecological costs of desertification, understanding processes and factors affecting it, identifying biophysical and socioeconomic drivers, developing action plan at national and regional levels, strengthening financial support for desertification control and restoration of desertified soils, and linking IPDD with other global fora.

Despite numerous laws, action plans and MOU's the utter lack of progress on desertification control is attributed to several factors.

(i.) <u>Reliable Data</u>: Credible data on the extent and severity of desertification, especially in relation to the dominant factors, are not available. The available statistics (refer Tables 1, 2 and 3) is highly variable, usually not validated by ground truthing and often based on unstandardized methodology. There is a strong need to develop and standardize the methodology. The latter must be based on the cutting edge of science and involve criteria related to soil quality, water quality, vegetation cover, NPP and ecosystem services. Techniques to access desertification must be based on assessment of soil quality and NPP, ecosystem C budget, water resources and components of the hydrologic cycle. Using remote sensing techniques, GIS and other innovations is essential to creating credible data.

(ii.) <u>Impact</u>: Similar to the extent and severity of desertification, quantitative and reliable (verifiable) information on economic and ecologic impacts of desertification is scanty. There is little if any, information on the cost of inaction on behalf of the national, regional and international organizations. Objective and credible data on the economic, social and environmental impacts of desertification are needed for creating NAPs.

(iii.) <u>Interactive Effects</u>: The impact of biophysical factors on desertification processes (e.g., soil properties, climate factors, vegetation, terrain, aridity), and those of soil drivers (e.g., demographics, land tenure, income) have been studied in isolation. Yet, it is the interaction between biophysical X social drivers which governs the rate of diverse processes and positive feedbacks that it creates. Ecosystem refer 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). More succinctly, it is "a system composed of physical-chemical-biological processes active within a space-time unit of any magnitude.

(iv.) <u>Institutional Support</u>: There is no denying the fact that implementation of NAPs requires financial and institutional support. Most NAPs fail when either financial or institutional support is not available. Yet, institutional support is relatively more critical. Unsolicited financial support, given as emergency aid based on knee-jerk approach, creates dependency and is counter productive. Funding support for IPDD will come through payments for ecosystem services (e.g. trading credits).

(v.) <u>Specific Action</u>: Several more than 200 policy interventions, charters and resolutions have been proposed since 1960s (some examples are listed in Table 12). Such policy frameworks, legally-binding interventions, and resolutions have also been undertaken in piecemeal manner and in specific geographical regions. Yet, no specific political action, similar to that of creating

IPCC, has been taken to implement a meaningful program on desertification control. Yet, such a poltical action is needed at the international scale to address this important global issue of the 21st century.

XIII. STRENGTHENING UNCCD THROUGH IPDD

Similar to an interactive and a highly successful program of UNFCC through IPCC, there is a strong need to strengthen UNCCD through creation and implementation of IPDD. Such a panel could be very productive and play a role similar to that of IPCC. An important reason for the success of IPCC was the existence of strong data base on long-term trends in regional climate, protocols for predicting climate change for different scenarios, and on economic and social impacts of climate change. Therefore, success of IPDD will also depend on the availability of credible data as outlined under the mission statement. Creation and implementation of IPDD may also depend on easy access to and sharing of the available data among parties.

Similar to the Working Groups of IPCC, the modus operandi of IPDD can be several Task Forces. Objectives of these Task Forces, to be deliberated and fine tuned by members under the leadership of elected coordinating lead authors, may include the following.

Task Force 1: Describe scientific basis of the desertification with regards to: (i) specific processes including erosion, salinization, fertility depletion etc, (ii) vulnerability of different soils and ecoregions, and (iii) extent, severity and rate at regional and global scales.

Task Force 2: Evaluate impact of desertification with regards to: (i) food security, (ii) income and poverty, and (iii) ecosystem services at national and global scale.

Task Force 3: Identify and prioritize strategies of desertification control, establish pilot projects on some global hot spots, and quantify the impact of such interventions.

Task Force 4: Create in interactive and operational programs with other organizations (e.g., UN Millennium Development Goals, UNFCC, UNFCBD, other organizations) as outlined in Fig. 13.

CONCLUSIONS

In his book "Dirt: The Ecstatic Skin of the Earth", W.B. Logan (2007) states "How can I stand on the ground every day and not feel its power? How can I live my life stepping on this stuff and not wonder at it?." The author sums up the importance of soil and the vital role that it plays in the survival and future of humanity. Despite several hundreds of policy instruments and resolutions, there is no coordinated effort to address this important global issue of the 21st century. There is a strong need to undertake a concrete international action to restore, improve and enhance world's soil resources. The action must be comprehensive and address spiritual cultural issues in conjunction with biophysical processes and international soil law and policy instruments (Fig. 13).

There has been an increasing awareness about the widespread problems of: (i) food insecurity along with malnourishment and hunger, (ii) global warming and extreme events, and (iii) loss of biodiversity, all of which are directly and indirectly linked with degradation of soil and desertification of land. Several recommendations have been made by international scientific organizations (IUSS, IUCN) about the need to undertake a specific action plan.

Thus, creation and implementation of Intergovernmental Panel on Drylands and Desertification (IPDD) is essential to protection, restoration, and improvement of world's soil resources. The relation of IPDD to UNCCD is similar to that of IPCC to UNFCC. The IPDD will have four Task Forces with specific mandates to: (i) describe the scientific basis, (ii) evaluate impact, (iii) identify strategies, and (iv) create an interactive program.

Rather than provide emergency aid, IPDD will create and strengthen regional institutions to implement four Task Forces under the National Action Programs. Implementation of NAPs under IPDD will be funded by national governments with seed money from GEF and other international organizations. Land managers will be paid for ecosystem services created through soil restoration (e.g., trading C credits).

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Table 1. Estimates of area affected by land degradation (Bai et al., 2008).

Parameter	Value
Area affected ($10^6 km^{2)}$	35.06
Percent of the land area	23.54
Total NPP Loss (Tg C/y)	955
Percent of Total Population Affected	23.9
Total Population Affected (billion)	1.54

Table 2. Estimates of land area in human-induced desertification risk classes (Eswaran et al., 2001).

Vulnerability Class	Population Density (persons/km^2)			Total
	<10	11-40	>41	
	------------------$10^6 km^2$---------------------			
Low	7.1	3.2	4.3	14.6
Moderate	5.4	4.0	4.2	13.6
High/Very High	7.4	4.4	3.2	15.0
Total	19.9	11.6	11.7	43.2

Table 3. Comparison between Glasod estimates of desertification in dry areas with that of UNEP methodology (Lal, Hassan and Dumanski, 1999).

UNEP (1991)	Area (10^6 km^2)	Oldeman and Van Lynden (1998)	Area (10^6 km^2)
Degraded irrigated land	0.43	**Water erosion**	4.78
Degraded rainfed cropland	2.16	**Wind erosion**	5.13
Degraded rangeland (Soil & vegetation)	7.57	**Chemical degradation**	1.11
Sub-total	10.16	**Physical degradation**	0.35
Degraded rangeland (vegetation only)	25.76	**Total**	11.37
Grand total	35.92	**Light**	4.89
Total arid land area	51.72	**Moderate**	5.09
% degraded	69.5	**Severe and extreme**	1.39
		Total	11.37
		These estimates refer to soil degradation only	

Table 4. Some salt tolerant plants.

	Plant	Latin Name	
I	**Fruit trees**		
	Tamarind	(*Tamarindus indica*)	
	Mango	(*Mangifera indica*)	
	Loquat	(*Eriobotyra japonica*)	
	Jamun	(*Syzygirum cuminii*)	
	Coconut	(*Cocos nucifera*)	
	Oil Palm	(*Elaeis guineensis*)	
	Guava	(*Psidium guajava*)	
II	**Halophytes**		
	Pickle weed	(*Salicornia* spp) Turtle weed	*Batis maritima*
	Salt Grass	(*Distichlis palmeri*) Seep weed	*Suaeda esteroa*
	NyPa Forage	(*Distichlis* spp)	*Sesuvium portulacastrum*
	Salt bushes	(*Atriplex numularia*)	
	Algae	(*Spirulina geitleri*)	
III	**Trees**		
	Gum trees	(*Eucalyptus* spp)	
	Accacia	(*Accacia* spp)	
	Shisham	(*Dalbergia sissoo*)	
	Ye-eb	(*Cordeeauxia edulis*)	
	Pine	(*Pinus oocarpa*)	
	Mesquite	(*Prosopis juliflora*)	
	Jojoba	(*Simmondsia chinensis*)	
	Casuarina	(*Casuarina equisetifolia*)	
	Albizia	(*Albizia lebbeck*)	
	Ber	(*Zizyiphus mauritiana*)	
		(Terminalia Arjuna) Arjuna herb	
IV	**Grasses and Forages**		
	Karnal Grass	(*Leptochloa fusca*)	
	Veliver	(*Vetiveria* spp)	
	Narrow Leaf Lupin	(*Lupinus angustifolius*)	
	Wheat grass	*(Thynopyron ponticum)*	
V	**Crops**		
	Triticale	(*Secale* spp)	
	Bambara groundnut	(*Voandzeia subteranea*)	
	Marama bean	(*Tylosema esculentum*)	
	Tepary bean	(*Phaseolus acutifolius*)	

Table 5. Mean annual biomass yield and carbon sequestration rate of sea-water irrigated halophyte at Puerto Penasco (Adapted from Glenn et al., 1993).

Species	Biomass Yield (t C/ha/y)	C Sequestration Rate (t C/ha/y)
1. Batis maritime	34.0	8.2
2. Atriplex linearis	24.3	6.7
3. Salicornia bigelovii		
• **Year one**	22.4	5.6
• **Year two**	17.7	4.3
4. Suaeda esteroa	17.2	4.3
5. Sesuvium partulacastrum	16.7	4.2

Table 6. Changes in bulk density and organic carbon concentration and pool under *Eucalyptus* plantations after 3 and 6 years of growth in a sodic soil of U.P. India (Recalculated from Mishra et al., 2003).

Treatment	Soil Depth (cm)	SOC Concentration (g/kg)	Bulk density (t/m^3)	SOC Pool (t/ha)	Rate of SOC sequestration (t C/ha/yr)
1. Control					
	0-10 (10)	2.0	1.66	3.32	
	10-30 (20)	1.6	1.59	5.09	
	30-60 (30)	0.9	1.66	4.48	
	60-90 (30)	0.6	1.72	3.10	
	90-120 (30)	0.6	1.74	3.13	
	120-150 (30)	0.3	1.76	1.58	
	Total			20.70	Baseline
2. Three year old Plantation					
	0-10 (10)	3.2	1.39	4.45	
	10-30 (20)	2.2	1.39	6.12	
	30-60 (30)	1.2	1.48	5.33	
	60-90 (30)	0.8	1.56	3.74	
	90-120 (30)	0.7	1.63	3.42	
	120-150 (30)	0.3	1.67	1.50	
	Total			24.56	1.29
3. Six year old Plantation					
	0-10 (10)	4.2	1.27	5.33	
	10-30 (20)	2.8	1.27	7.11	
	30-60 (30)	1.0	1.38	4.14	
	60-90 (30)	0.6	1.45	2.61	
	90-120 (30)	0.7	1.52	3.19	
	120-150 (30)	1.0	1.57	4.71	
	Total			27.09	1.07

Table 7. Technical potential of reclaiming salt-affected soils on SOC sequestration (Lal, 2009).

Land Use	Area (Mha)	C Sequestration Rate (t/ha/yr)		Technical Potential (Mt C/yr)
		Soil	Biomass	
1. Cropland				
a. Irrigated	100	1.0-2.0	-	56-112
b. Rainfed	56	0.5-1.0	-	22-24
2. Perennial Land Use	44	0.5-1.0	0.5-2.0	280-840
Total	280			358-996

Table 8. Potential of desertification control and land restoration to sequester C (GtC/yr) (Recalculated from Lal, 2001).

Process	Range	Mean	% of Total Potential
Restoration of eroded lands	0.2-0.3	0.25	21
Restoration of physically and chemically degraded soils	<0.01	<0.01	1
Reclamation of salt-affected soils	0.4-1.0	0.7	60
Agricultural intensification on undegraded soils	0.01-0.02	0.015	-
Sequestration as secondary carbonates	0.01-0.4	0.2	17
Total	0.62-1.72	1.17	100

These estimates have large uncertainties, the potentials of different strategies may not be additive, and adoption of recommended measures at global scale is a major challenge to humanity.

Table 9. Concepts of science and spiritualism are similar with regards to stewardship and sustainable use of natural resources. It is a matter of interpreting these concepts and principles in the right perspective and context.

Ancient Religions	Importance of Soil/Earth/Nature
Greek	The daughter of Earth goddess "Gaea" named "Themis", was the goddess of law, and a descendent named "Demeter", was the goddess of agriculture and fertility.
Romans	The Earth goddess "Tellus" was related to the goddess of fertility and harvest "Ceres". Fama, the goddess of fame and gossip was the daughter of Tellus.
Hinduism	Vedas (2000 to 1500 BC) state, "upon this handful of soil our survival depends. Husband it and it will grow our food, our fuel, and our shelter and surround us with beauty. Abuse it and the soil will collapse and die taking man with it". Srimad Bhagvatam (500-1000 B.C.) states (10.35) "By the law of Karma, you are in control of your own destiny. It is, therefore, important to care for hills, and cows… and protect the forests rather than worship Lord Indra". Prasna Upanishad stated "kshiti (soil), jal (water), pawak (energy), gagan (Sky), sameera (air), panch (five), tatva (elements), yah (from) adham (made) sharira (humam body). The goddess "Sita", heroine of the epic Ramayana and wife of god "Rama", was born from the womb of mother earth "Dherra or Vasundherra", Sanskrit equivalents of Latin word "Terra".
Buddhism/ Jainism	Mother Earth (Vasundherra, Dherra, Bhumi, Prithvi) and all its life forms are sacred. The word "Ahimsa" (non-violence) is based on the respect for all forms of life nurtured by mother Earth. "It is not enough to live and let live you must help others to live". The "Panch Sila" code of Buddhism states "one should not even break the branch of a tree that has given one shelter" (Petavatthu II, 9,3). Monastic rules prevent the monks from injuring plant life (Vin. IV, 34), and going on a journey during the rainy season because of possible injuries to worms and insects that come to the soil surface during wet weather (Vin. I, 137). *Ficus religiosa* (Bodhi tree) and other huge trees (Vanaspati in Sanskrit and Pali) are objects of great veneration (S. IV, 302; Dh. A. I., 3; D II, 4).
Judaism	The Latin name for "man" (homo) is derived from "humus", the decomposed organic matter in soil which is the essence of all terrestrial life. Through the history of the Israelite kingdom, prophetic messengers warned the people that if their collective obligations were not fulfilled, YHVH could take away the land He had given them and force them into exile (e.g. Amos 3:2, 7:11).
Christianity	The word "Adam" is derived from the Hebrew word "adama" meaning, "earth" or "soil". Similarly, the word "Eve" is derived from "hava", which means "living". Thus, biblical words "Adam and Eve" literally mean "living earth". "Out of earth you were taken, from soil you are and unto soil you shall return"…Genesis 3:19. "God said: Let the earth bring forth every kind of living creature…and all kinds of creeping things of the soil"…(Genesis 1:24-25). "So God created man in his own image, in the image of man created he him; male and female created he them. And God blessed them, and God said unto them, be fruitful and multiply, and replenish the earth, and subdue it: and have dominion over the fish of the sea, and over the fowl of the air, and over every living thing that moveth upon the earth" (Genesis 1: 27-8). "Hurt not the earth, neither the sea, nor the trees..." (Revelation 7:3).
Islam	"Then We made you heirs in the land after them, to see how ye would behave (Quran 10:14). "Verily all things have We created in proportion and measure (Quran 54:49). "There is not an animal (that lives) on the earth nor a being that flies on its wings, but (forms part of) communities like you" (Quran 6:38). "Say: Who hath forbidden the beautiful (gifts) of God, which he has produced for his servants, and the things clean and pure (Which He has provided) for sustenance" (Quran 7:32). "It is He who produces gardens, with trellises and without, and dates, and cultivated land with produce of all kinds, and olives and pomegranates, similar (in kind) and different (in variety): Eat of their fruit in their season, but render the dues that are proper on the day that the harvest is gathered. But waste not by excess: For God loves not the wasteful" (Quran 6:141).

Table 10. Extinction of ancient civilizations by mismanagement of soil and natural resources.

Era	How the Mighty Fell and Survived?
6000 BC	Deforestation leads to collapse of communities in southern Israel/Jordon.
3200-1900 BC	Collapse of the Indus Civilization by 1900 BC caused by deforestation for brick making and accelerated erosion caused by excessive demands on soil and water.
1700 BC	Egyptian civilization survived the invasion by Hyksos because their land was still fertile and productive resource in a changing climate.
1500 BC	Collapse of central American city states because of accelerated soil erosion on sloping lands.
563 BC	Birth of Siddhartha Gautma (Buddha)
600 BC	King Ashoka, who ruled India and preached Buddhism throughout Asia, issued numerous proclamations to protect forests and trees.
600 to 540 BC	Babylon and Mesopotamia vanished because of the erosion of the hills, heavy siltation of irrigation canals, and salinization of cropland soils.
500 BC	Greek coastal cities become landlocked because of erosion and siltation.
427-347 BC	Plato compares hills and mountains of Greece to the bones of a wasted body "All the richer and softer parts have fallen away, and mere skeleton of the land remains".
P. Vergilus Maro (70-19 BC) (Virgil)	Virgil recognized that soil erosion of the sloping land was caused by cultivation up-and-down the slope by "ard" (plow).
180-350 AD	Decline of the Mediterranean civilizations due in large part to bad management of the landscape, and excessive deforestation on hills.
570 AD	Birth of Mohammed.
600 AD	Classic Maya civilization.
874 AD	Norse settlement of Iceland.
971 AD	Mahmud of Ghazni conquers India and causes migration of "Gypsies".
980 AD	Erik the Red colonizes Greenland.
1492 AD	Columbus arrives in the Americas.
1532 AD	Fall of Incas to Francisco Pizzaro
1500 AD	The Mogul emperor Akbar established "Nature's reserves" in India.
1666 AD	Japan's Shogun warns against dangers of erosion, stream siltation and flooding caused by deforestation and urged people to plant trees.
1690 AD	Governor William Penn requires Pennsylvania settlers to preserve one acre of trees for every 5 acres cleared.
1748-1762 AD	Jared Eliot (1635-1763) observed in New England that "water running from a bare hillside was muddy unlike water running from grassy and forested areas".
1778 AD	Bishnois of Rajasthan, India, willingly die to protect Khejri trees.

Table 11. Soil and human survival.

Culture	Worshipping Soil
An Ancient Chinese Proverb	"Man…despite his artistic pretensions and many accomplishments… owes his existence to a 6-inch layer of topsoil and the fact that it rains."
Columella, 1st Century AD	"Not content with the authority of either former or present day husbandmen, we must hand down our own experiences and set ourselves to experiments as yet untried".
American Indians (1852)	"Earth does not belong to the man, man belongs to earth"…Chief Seattle Circa 1852.
W.T. Kelvin (1824-1907)	"To the wise man the whole world's a soil".
Paul Bigelow Sears (1891-1990)	"How far must sufferings and misery go before we see that even in days of vast cities and powerful machines, the good earth is our mother and that if we destroy her, we destroy ourselves".
William Bourke Cockran (1854-1923)	The author of "Earth is a Generous Mother" states that "There is enough for all. The earth is a generous mother; she will provide in a plentiful abundance food for all their children if they will but cultivate her soil in justice and in peace".
Gerald W. Johnson (1939)	"When the land begins to be regarded, not as the primary source of wealth, but as the playthings of gentlemen already rich, the economy of the country is in questionable, if not dangerous condition. England, to be sure had survived in spite of that attitude; but only by becoming the workshop of the world".
Lowermilk (1940)	"Individuals, nations and civilizations write their records on the land…the record that is easy to read by those who understand the simple language of the land".
Alan Paton (1948)	"The grass is rich and matted, you cannot see the soil. It holds the rain and the mist, and they seep into the ground, feeding the streams…It is well-tended, and not too many cattle feed upon it; not too may fires burn it, laying bare the soil. Stand unshod upon it, for the ground is holy, being as it can from the Creator. Keep it, guard it, care for it, for it keeps men, guards men, cares for men. Destroy it and man is destroyed".
Aldo Leopold (1949)	"Ethical criteria have been extended to many fields of conduct, with corresponding shrinkages in those judged by expediency only". "The land ethic simply enlarges the boundaries of the community to include soils, waters, plants, and animals, or collectively: the land". "A land ethic changes the role of *Homo sapiens* from conqueror of the land-community to plain member and citizen of it".
Mitchell et al. (1950)	"The fabric of human life is woven on earthen looms-it everywhere smells of clay".
W.H. Auden (1955)	"A culture is no better than its woods".
Garret Hardin (1968) (Tragedy of the Commons)	"Multiple individuals acting independently in their own self interest can destroy a shared resource even when it is clear that it is not in anyone's long-term interest for this to happen".
Barry Commoner (1971) The Closing Circle)	1. Everything is connected to everything else. 2. Everything must go somewhere. 3. Nature knows best. 4. There is no such thing as a free lunch.
Vernon G. Carter and T. Dale (1974)	"No species of plant could long survive on sloping hill sides unless it helped check soil erosion. No species of animal developed enough intelligence or versatility to survive for long unless it tended to support the continued growth of plant and soil. If a species of plant and animal did evolve that tended to destroy the soil, it usually destroyed itself instead by destroying its primary source of food".
Floyd Looks for Buffalo Hand (1998)	In the book "Learning Journey on the Road" the author notes " Civilized man has marched across the face of the earth and left a desert in his foot prints".
Albert Bartlett (2004) (The Essential Exponential)	1. Land's carrying capacity and the sustainable average standard of living are inversely related to one another". 2. Humans will always depend on agriculture. 3. Starving people don't care about sustainability 4. The spherical earth is finite, but a flat earth can be infinite in depth and lateral extent. 5. It is easy to talk about sustainability but it is difficult to make realistic constructive progress towards it.

Table 12. Some examples of existing policies on conservation and protection of world soil resources.

Region		Title	Reference
Africa		Explaining Agricultural and Agrarian Policies in Developing Countries	Binswanger and Deininger (1997)
Americas	(i)	Payment-in-Kind (PIK)	Furuseth (1984)
	(ii)	Soil Conservation Issues in the U.S.	Wedin (2002)
	(iii)	The Soil Resolution	SR 401, 24 June 2008
Asia	(i)	Now That Your Land is My Land…Does it Matter?	Mukhopadhyay (2005)
Europe	(i)	The Identification of 100 Ecological Questions of High Policy Relevance to U.K.	Sutherland et al. (2006)
	(ii)	Soil Conservation and Protection for Europe	SCAPE (2005)
	(iii)	European Soil Protection Law	Peterson (2008)
	(iv)	EU Strategies and Policies in Soil and Waste Management	Marmo (2008)
	(v)	Legislation and Ecological Quality Assessment of Soil	Rombke et al. (2005)
	(vi)	Strategies in Soil Protection-Mission and Visions	Chaney et al. (2001)
	(vii)	EU Soil Protection-More Than a Memorandum of Understanding	Kördel and Terytze (2004)
World	(i)	Regulatory Decisions For Environmental Protection	Rodrignes et al. (2009)
	(ii)	The Dirt on Intl. Environmental Law Regarding Soils	Wyatt (2008)
	(iii)	Legal and Institutional Frame Work of Sustainable Soils	Hannam and Boer (2002)
	(iv)	Legal Aspects of Sustainable Soils	Boer and Hannam (2003)
	(v)	Entering the Century of the Environment: A New Social Contract for Science	Lubchenco (1998)
	(vi)	Big Questions for a Small Planet	Gallegher et al. (1995)
	(vii)	Soil on the Global Agenda	Hurni (2006)
	(ix)	Can the UN Convention to Combat Desertification Guide Sustainable Use if the World Soils	Stringer (2008)
	(x)	World Soil Character	FAO (1982)

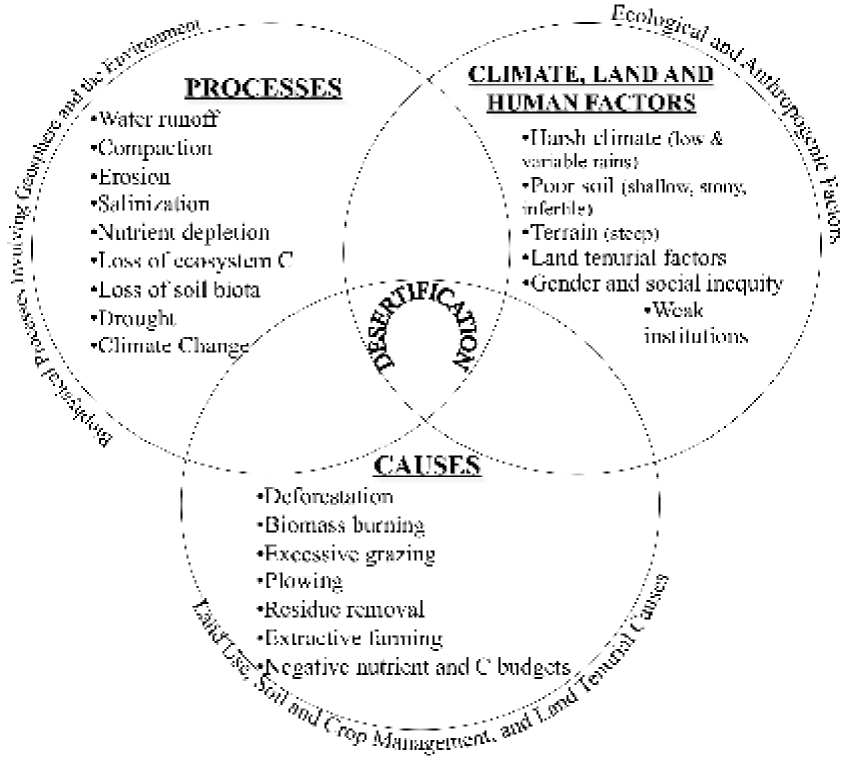

Fig. 1 Desertification is caused by the interactive effects of biophysical factors and the human dimensions issues.

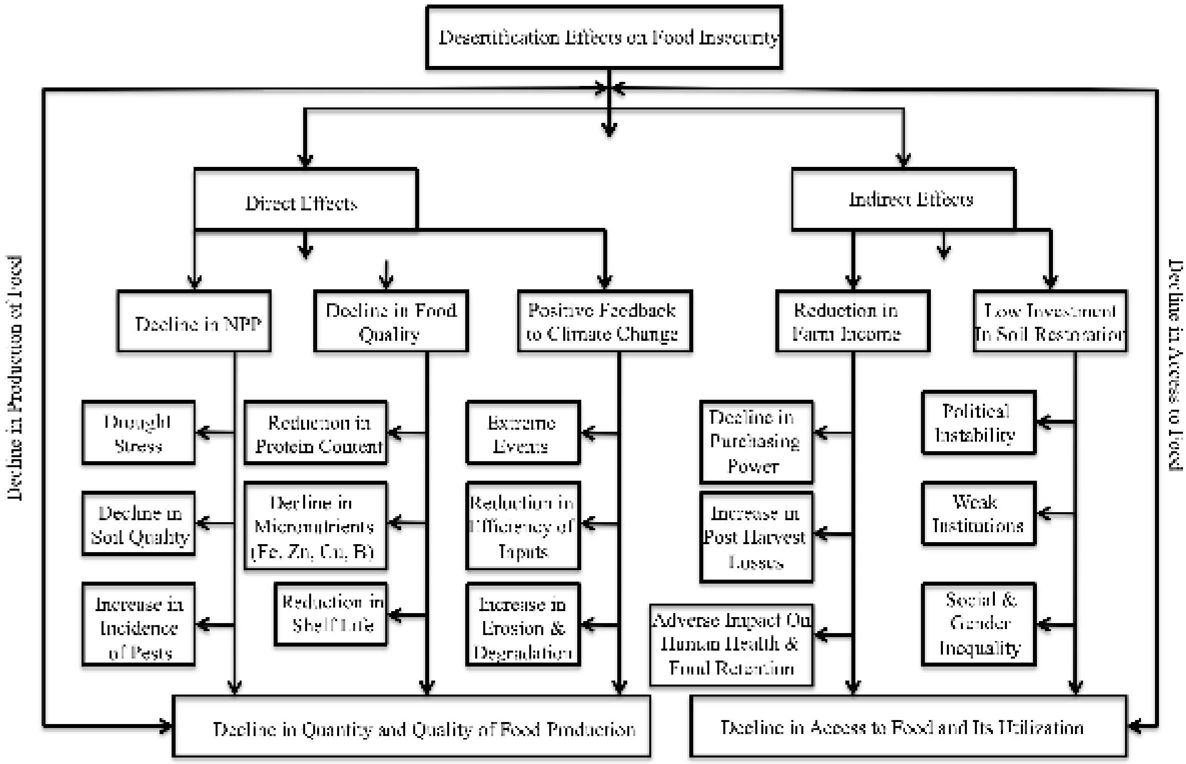

Fig. 2 Direct and indirect effects of desertification on food insecurity.

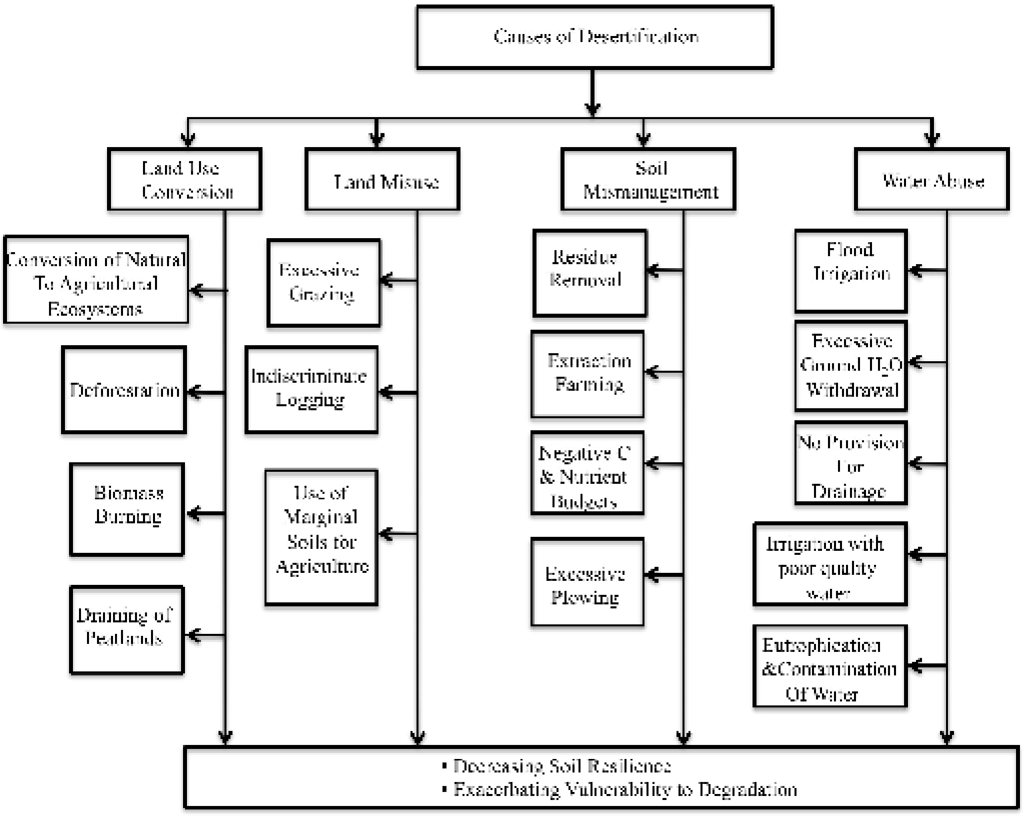

Fig. 3 Human activities that exacerbate the process of soil degradation and desertification

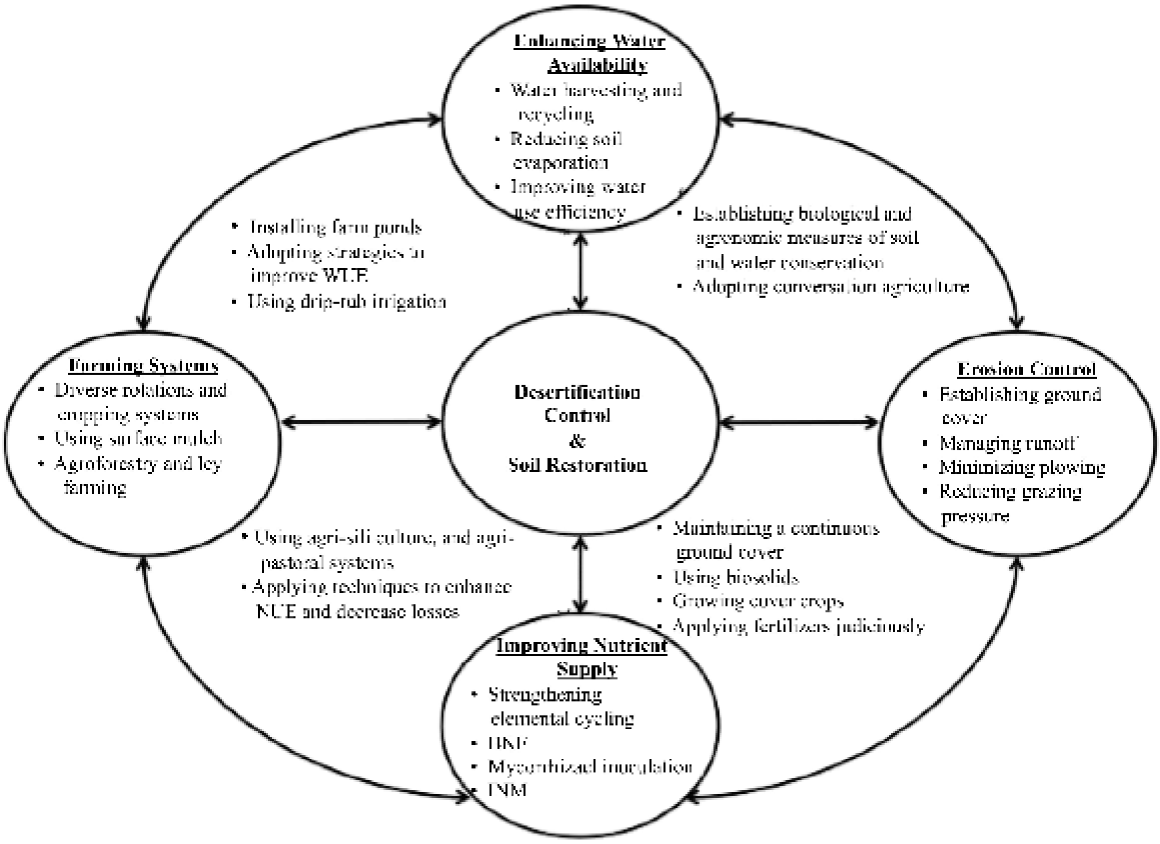

Fig. 4 Strategies for desertification control and improving soil quality for restoring ecosystem functions.

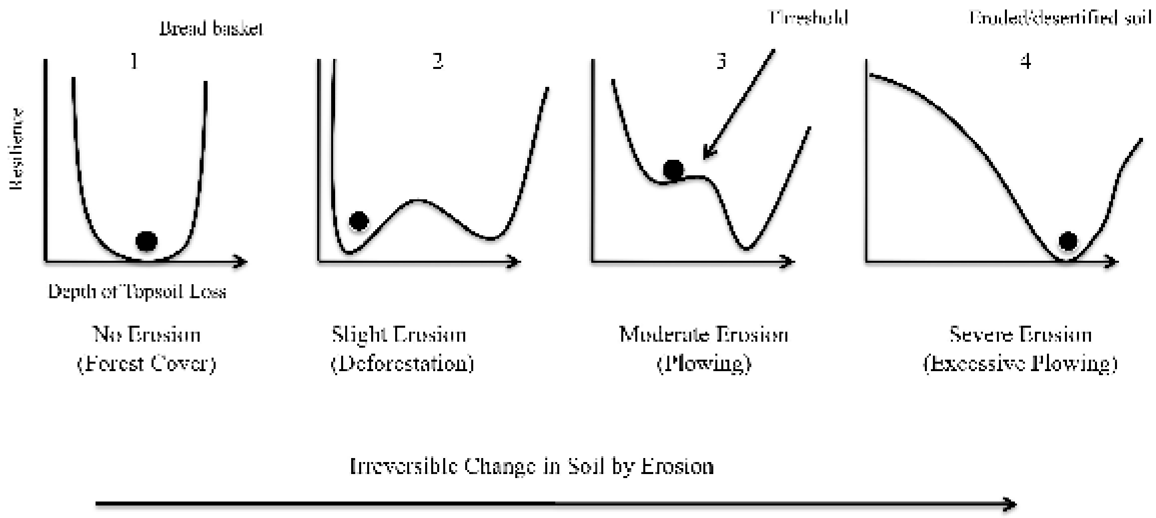

Fig. 5 Regime change in relation to soil degradation (Adapted from Walker et al. 2009; Folke et al., 2004, and Walker and Salt, 2006).

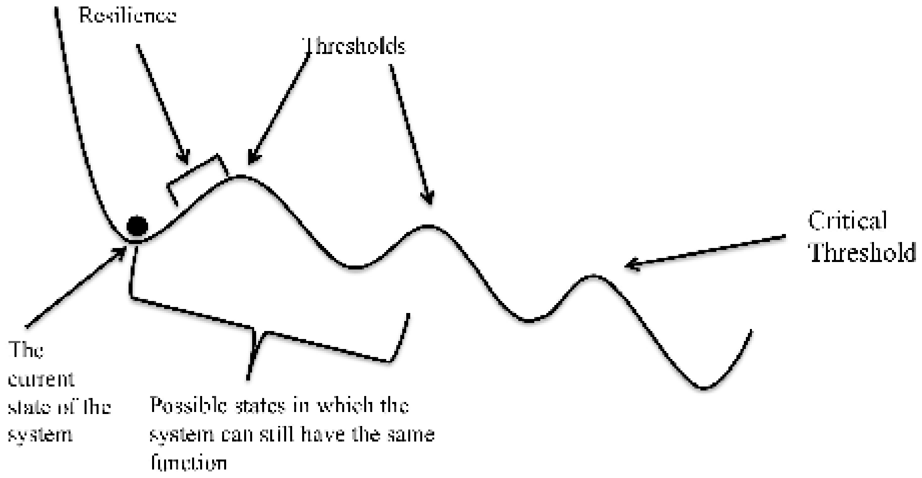

Fig. 6 Soil ecological systems comprise of multiple states separated by thresholds (Modified from Walker et al., 2004; Folke et al., 2004; Walker Folke, 2006).

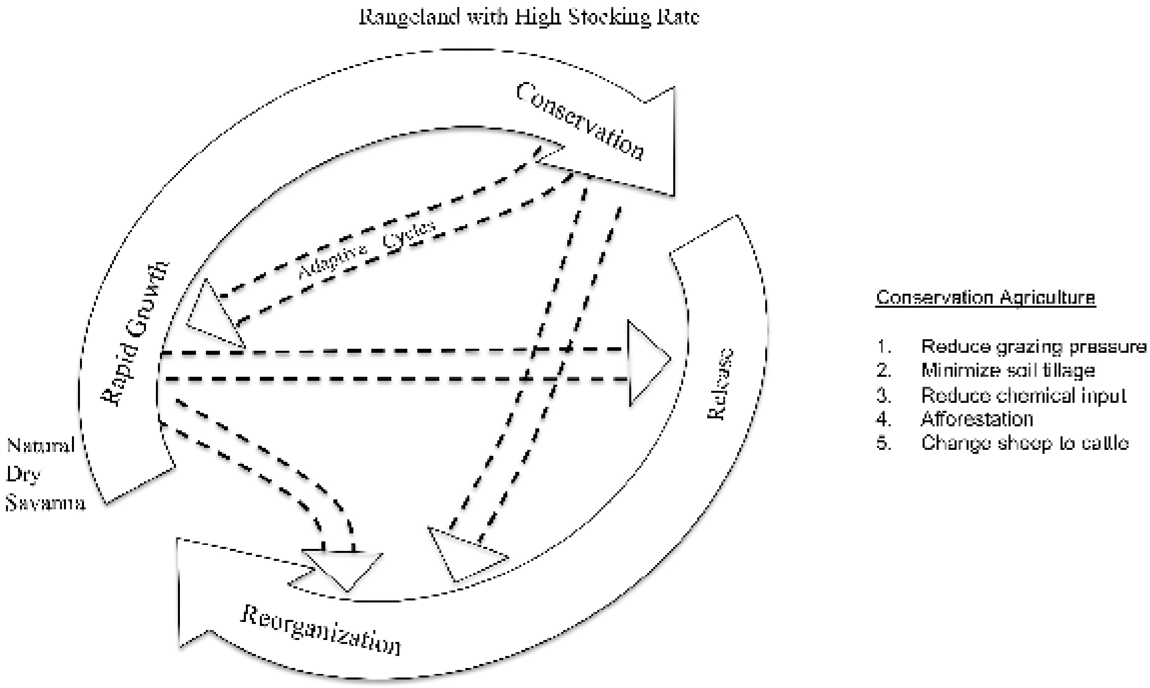

Fig. 7 Adaptive cycle in rangeland management and desertification (Adapted from Gunderson and Holling, 2002)

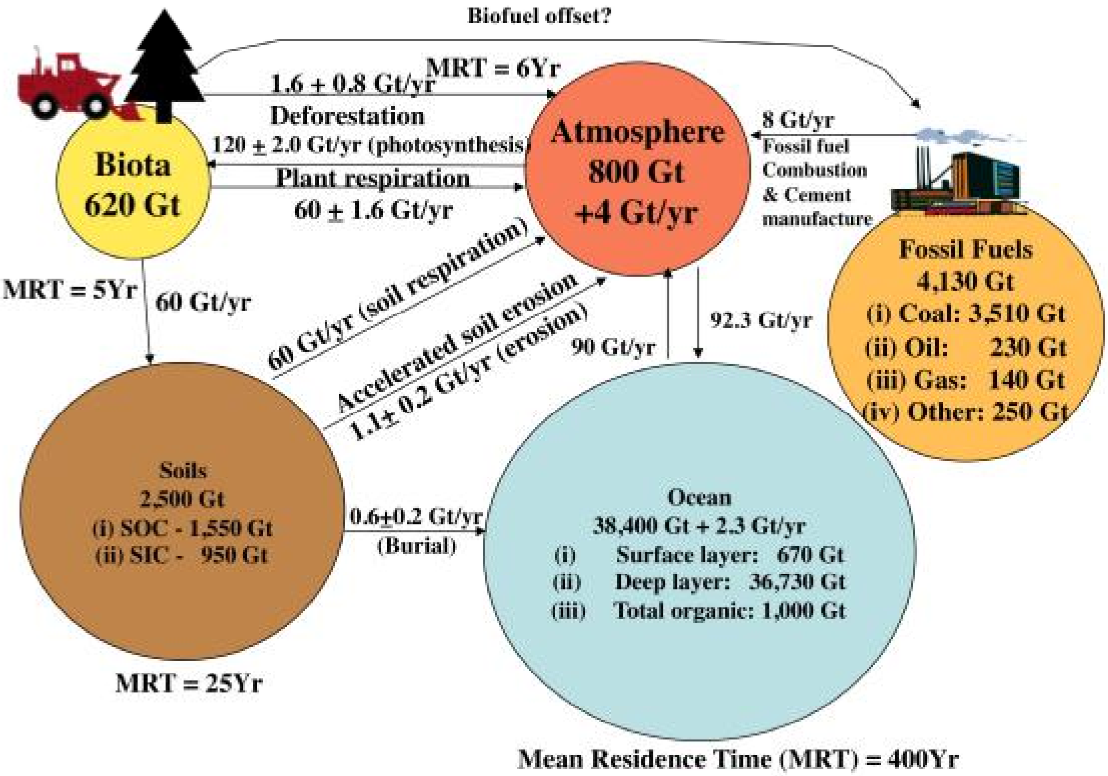

Fig. 8 Global carbon pool and fluxes (Updated from Lal, 2004b).

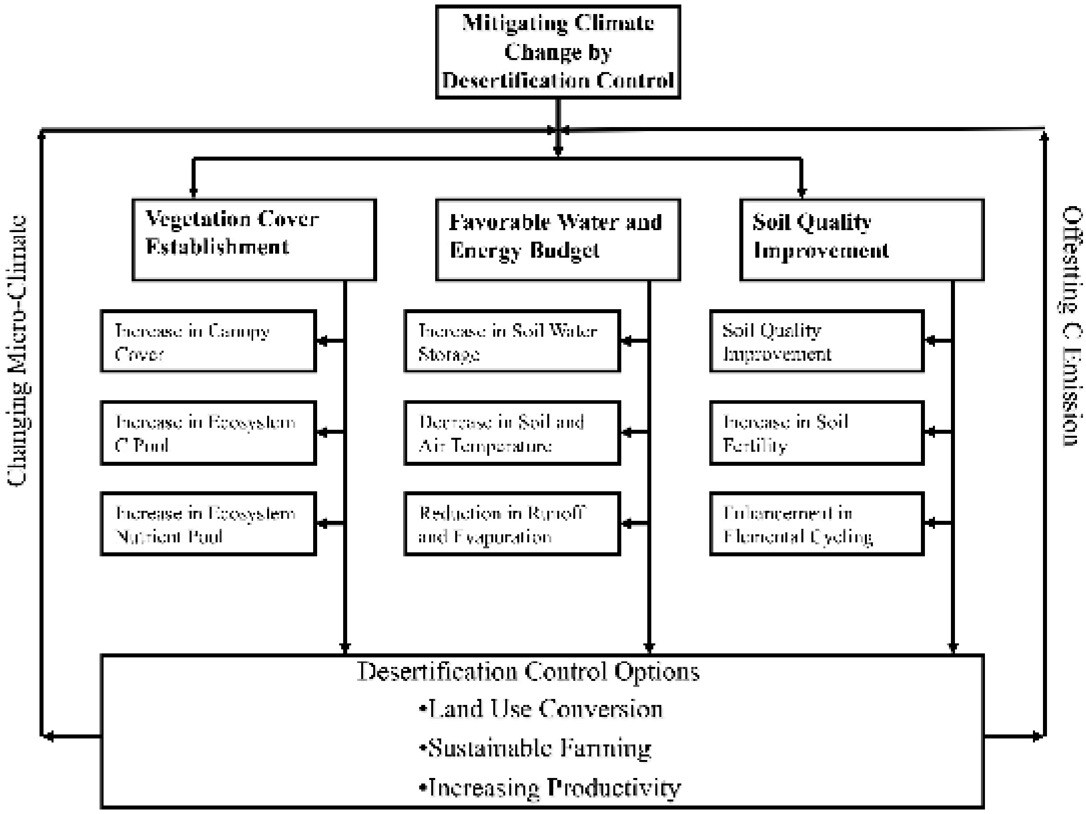

Fig. 9 Mitigating climate change through desertification control.

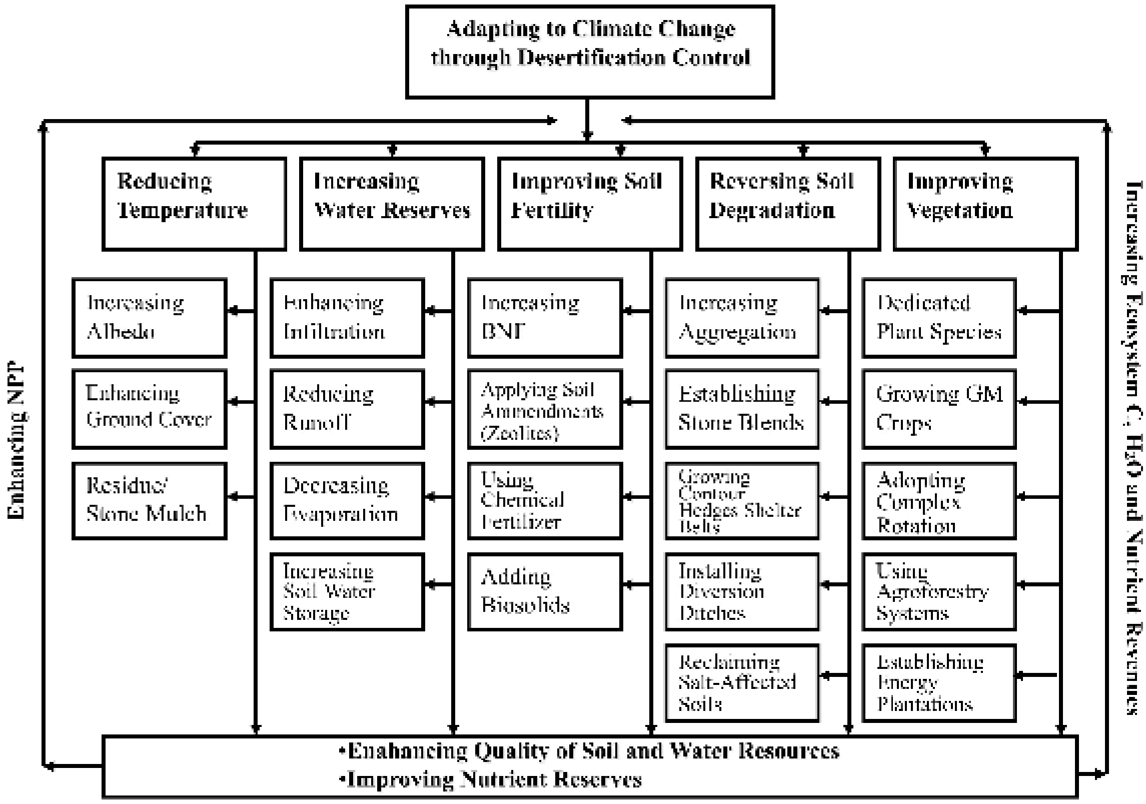

Fig. 10 Conceptual approaches to controlling desertification by adapting to climate change.

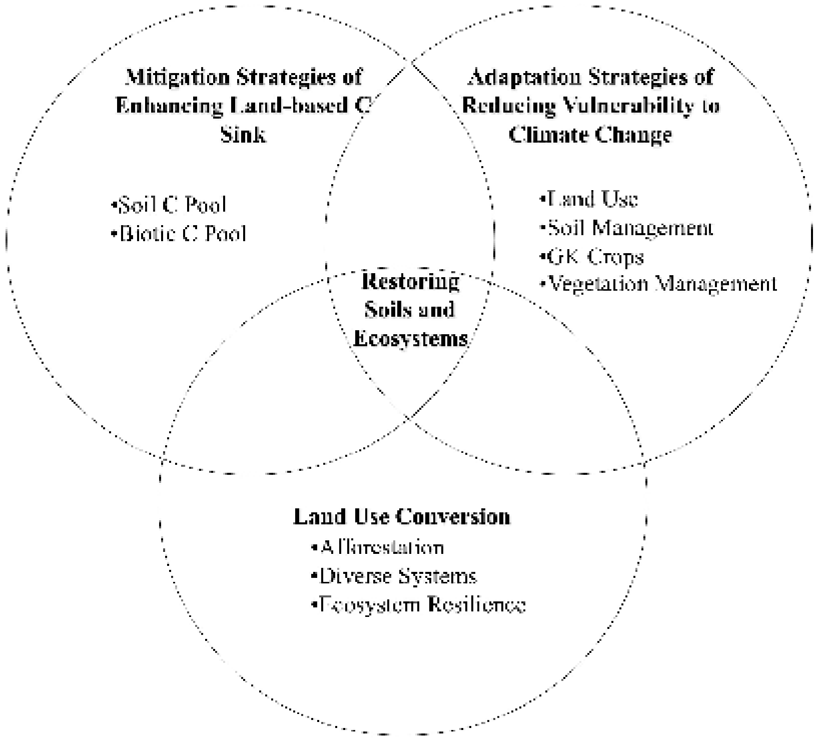

Fig. 11 Synergetic interactions between mitigation and adaptation strategies for climate change to restore degraded soils and desertified ecosystems

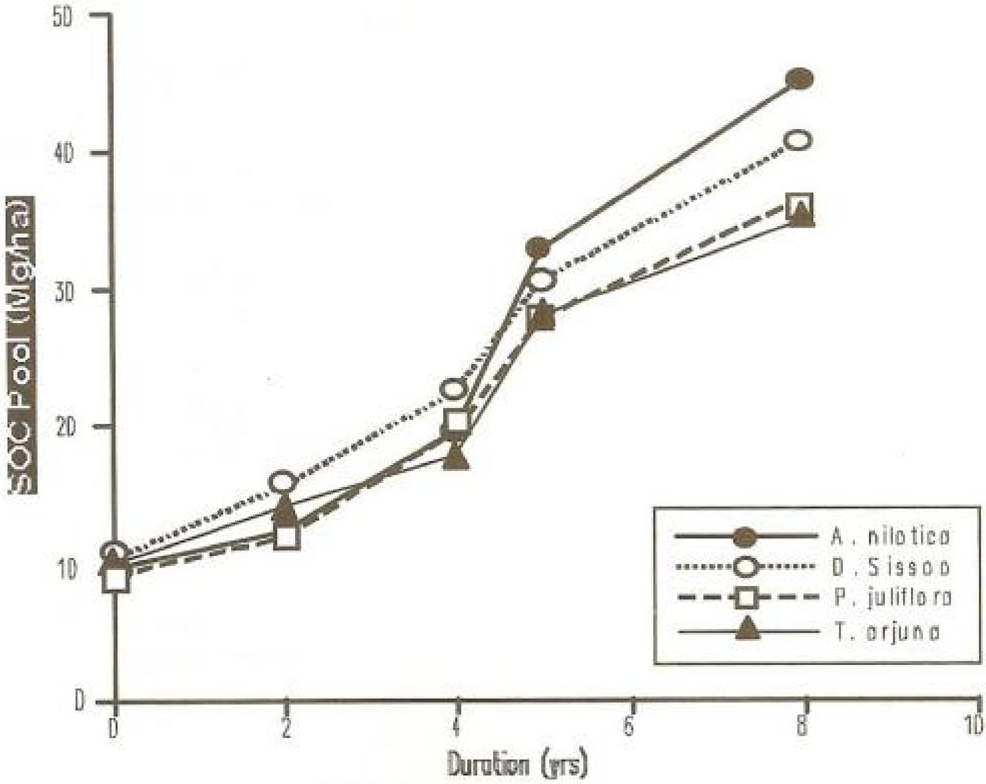

Fig 12. C sequestration through reclamation of salt affected soils in northern India (recalculated from Garg, 1998; Lal et al., 1998).