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Sustainable management of soils under climate change: Mitigation approach

GN Gurjar and Sanjay Swami

Abstract
Climate change also impacts two among principal processes of desertification–erosion and salinization. Soil erosion hazard depends on climatic erosivity, soil erodibility, and land and crop management practices. Climate change can impact all of these parameters and greatly accentuate the erosion hazard. Increase in frequency and intensity of extreme events would enhance rainfall intensity and its kinetic energy, wind velocity and its erosivity, and run-off velocity and its shearing and sediment carrying capacity. Furthermore, erosivity of wind-driven rain and that of shallow overland flow impacted by raindrops is more than that of a rain without wind and of a laminar overland flow. Soil erodibility increases with decrease in aggregation and reduction in aggregate strength caused by increase in slaking due to reduction in SOC concentration. Progressive desertification of the dryland tropics may reduce already low amount of SOC stored in these soils. Furthermore, desertification may also alter the emission of GHGs from these ecologically sensitive and fragile ecosystems. Thus, warming induced decline in SOC pool and aggregation, combined with increase in land conversion to meet the growing human demands, may severely accelerate soil erosion and desertification hazard. Wind erosion hazard, one of the major degradation processes in drylands.

Keywords: Climate change, degradation, desertification, sustainable management

Introduction

Soil, an important component of land, has numerous functions and ecosystem services essential to all terrestrial life. Soil degradation, decline in its capacity to support functions and provide ecosystem services, is caused by accelerated erosion, salinization, elemental imbalance, acidification, depletion of soil organic carbon (SOC), reduction in soil biodiversity, and decline in soil structure and tilth. Desertification, a sub-set of degradation, specifically refers to decline in soil quality and functions in arid climates. Climate change affects and is affected by soil degradation through a positive feedback due to increase in mineralization of SOC pool and the radiative forcing. Desertification may lead to a net increase in temperature despite change in albedo of the denuded surface. Feedbacks and threshold amplify the risks of degradation, and the projected climate change may exacerbate all four types of drought (i.e., meteorological, hydrological, pedagogical, and ecological). The mutually reinforcing positive feedbacks between soil degradation and climate change are strongly influenced by social, economic, political, and cultural factors. There exists a strong link between poverty, desperateness, and societal collapse on soil degradation and climate change. Soil is an important component of land. Soil is a four dimensional body (length, width, depth, and time), at the interface between atmosphere and the lithosphere, and essential to all terrestrial life. Soil degradation implies decline in its capacity to provide ecosystem services (ESs) of interest to humans and useful to nature’s functions. Principal processes of soil degradation are erosion, salinization, nutrient and carbon (C) depletion, drought, decline in soil structure, and tilth. Examples of ESs provided by soil include ecological/supporting (biomass production, nutrient cycling), regulating (water purification and flow, C sequestration, temperature fluctuations), provisional (food, fiber, fuel, and forages), and cultural (aesthetical, spiritual, and cultural). Erosion induced degradation diminishes soil’s capacity to provide ESs, and support ecosystem functions. Desertification refers to land degradation in dry/arid regions, which cover approximately 41% of the continental area [Sterk *et al*., 2001] [40]. It is the diminution or destruction of the biological potential of land, and can lead ultimately to desert-like conditions [Veldman and Putz, 2011] [41]. Thus, desertification is a sub-set of land degradation and specifically refers to decline in quality and functionality of soil, vegetation, water, biota, and climate in dry regions. Soil erosion is one of the processes of desertification. Others include salinization, depletion of plant nutrients and soil organic carbon (SOC) pool, reduction in plant available water capacity (AWC) and the overall decline in net primary production (NPP), and denudation of the vegetation cover. Soil erosion implies physical removal of the soil by tillage, wind, gravity, raindrop splash, surface run-off, stream flow, coastal processes, and chemical dissolution. In the more common forms of water (inter-rill and rill) and wind erosion, the processes comprise of four distinct but inter-related phases: detachment, transport, redistribution, and deposition. The impacts of erosion on soil quality, and ecosystem functions and services depend on the rate (Mg/ ha/year, mm/year) of soil erosion vis-a-vis the rate of soil renewal (mm/century or millennia). The accelerated soil erosion, when the rate of soil removal exceeds that of its renewal, has adverse on- and off-site effects. The on-site adverse effects of severe erosion are due to loss of the effective rooting depth, reduction in plant-AWC, depletion of SOC and plant nutrients, decline in soil structure, and reduction in soil quality.

The Green Revolution and other technologies since mid twentieth century were developed under an assumption of a stable climate. However, current and protected climate change poses severe challenges. Thus, it is pertinent to understand the followings [West *et al*., 2009] [43]: (i) climate impacts to soil and ecosystem processes, (ii) relation between land use/ management and soil/ecosystem resilience, (iii) opportunities for successful implementation of adaptation and mitigation strategies, and (iv) the process of feasible decision making with consideration of scale and thresholds. The terrestrial biosphere and soils have been the source of GHGs, (i.e., CO_2, CH_4, and N_2O) for thousands of years as a result of agriculture and the attendant deforestation, biomass burning, soil tillage, cultivation of paddy rice (Oryza sativa), and domestication of livestock. Ruddiman [2003; 2007] [30, 31] argued that cyclic variations in CO_2 and CH_4 caused by Earth's orbital changes caused decreases in atmospheric concentrations of these GHGs throughout the Holocene. However, increase in atmospheric concentration of CO_2 around 8,000 years ago and that of CH_4 around 5,000 years ago corresponded with the onset of early agriculture in Eurasia and of rice cultivation in Asia, respectively. This hypothesis is supported by the argument that despite the low population density, early per capita land use was large because of extensive or extractive farming [Ruddiman *et al*., 2009] [32]. It is also argued that warming caused by these early gaseous emissions, estimated at 320 Pg C during the pre-industrial era compared with 160 Pg C since 1750, reached a global mean value of 0.8 C [Ruddiman, 2003; Ruddiman, 2007] [30, 31]. Soils of most agro-ecosystems may have lost 30–50% of the antecedent SOC pool in temperate regions and 50–75% in the tropics [Lal, 2004] [16, 17, 19]. Total emissions from world soils have been estimated at 60–80 Pg C. The magnitude of SOC depletion is exacerbated in soils prone to degradation by accelerated erosion, decline in structure, depletion of nutrients, and reduction in plant-AWC. Indeed, there exists a strong link between desertification, accelerated erosion, and climate change. There are several important aspects of the climate change in the context of drylands. These are: (i) decrease in annual rainfall amount, (ii) change in duration of rainfall events, (iii) increase in interval between the rainfall events, (iv) increase in temperature-induced evaporation, (v) increase in water run-off, and (vi) decrease in soil water storage. Increase in frequency of extreme events has been already reported in Africa. Thus, climate-induced effects on water resources and availability to plants are highly complex.

Climate Change and Soil Degradation and Desertification

Desertification is defined as the irreversible extension of desert landforms and landscapes to areas where they did not occur in a recent past [Le, 2002] [23]. Over and above any possible impacts of climate change, soil degradation, and desertification are also caused by long-lasting and perpetual mismanagement by extractive practices. Perpetual mismanagement can replace the climax vegetation in a specific biome because of soil degradation. It has been reported that changes in land-uses, fire regimes, and climate change are replacing the tropical humid forest by a savanna (grass) vegetation in the Amazon Basin [Veldman and Putz, 2011] [41]. As many as 100 countries are prone to desertification. Estimates of global land area affected by land degradation and desertification [Oldeman, 1994] [27] vary widely because of the lack of credible data based on ground truthing, and thus reliance on proxy methods. Therefore, there is a strong need of strengthening the scientific basis for dryland ecosystems. Similarly, there also exist major challenges in establishing the direct cause-effect relationship between climate change and desertification/erosion. Increase in the land use under hyper-arid (50.7 Mha or 1.5%) and arid (3.1 Mha or 0.1%) regions between 1931–1960 and 1961–1990 has been linked to climate change. Despite the widespread belief in strong interaction between climate and desertification [Shivkumar, 2007] [38], it is difficult to state that climate change has caused desertification because of major uncertainties in obtaining credible site-specific data for both independent (climate change) and dependent (desertification, erosion) parameters at the desired temporal and spatial scales. On the contrary, some have hypothesized that desertification (independent variable) may have increased the temperature (dependent variable) of the desertified lands. It is also believed that dryland ecosystems are more resilient to climate variability than hitherto presumed probably because of the combination of an opportunistic response of some of its species and prevalence of a wide range of buffering mechanisms.

Drought and Desertification

Rather than the total endowment of the global renewable water resources, important factors affecting drought and desertification are the hydrologic fluxes and their spatial and temporal variability [Oki, 2006] [26]. Water resources are already scarce in arid/dry lands [Gischler, 1979] [13], and in the Arab countries [Shahin, 1996] [37]. Increasing water scarcity caused by ever growing population and its demands (Seckler *et al*., 1998) [36] may be accentuated further by global warming. Drylands (with 42% of the world population and 41% of the land area) are already the most vulnerable regions with regards to risks of desertification and drought. Yet, these regions are also likely to be even more adversely affected by the projected climate change, along with potential changes in agriculture and forestry in the arid and semi-arid tropics [Shivkumar *et al*., 2005] [39]. Life in some of these regions is already on the edge [Dixon *et al*., 2003] [9] because of widespread poverty, inequitable land distribution, environmental degradation, over exploitation of natural resources, and dependence on rainfed agriculture managed by extractive farming practices.

Technological Options for Sustainable Management

Protection of soils and natural resources is critical to maintaining ecosystem services (ESs) essential for human well-being and other functions [Bardshaw *et al*., 2010] [5]. Successful adaptation to climate change implies strong understanding of processes and properties of soils and the related natural resources, but also the response of the community. Engaging the natural resource management community [Bardsley and Rogers, 2011] [4] is important to promoting adoption of recommended management practices (RMPs), strengthening science/ public dialogue, and enhancing the awareness. Despite availability of a large amount of scientific data toward sustainable management of soils and natural resources since 1950s, about 1.4 billion resource-poor farmers located in risk-prone regions remain untouched by modern agricultural innovations. It is surmised by some that application of the principles of agroecology can provide the needed scientific basis to development and adoption of new management systems fine-tuned to highly variable and diverse farming conditions. The strategy is to replace what is removed; wisely restore what is altered, and predict and manage what can happen to soil (and natural) resources by anthropogenic and natural perturbations. The ecosystem and soil C poo mechanisms, minimizing losses, and creating positive C and nutrient (N, P, K, S, and Zn) budgets. ls are critical attributes which affect soil quality and soil/ecosystem resilience. Thus, an important strategy is to enhance the soil and ecosystem C pool by strengthening recycling.

Soil Carbon and Nutrient Management

Major RMPs include those involving soil and water conservation, conversion from plow till to no-till (NT) farming in conjunction with crop residue mulch and complex crop rotations grown with integrated nutrient management (INM), and use of biomass-C (i.e., manure, compost, mulch, and cover crop) needed to create a positive C budget, While the benefits of NT farming are widely known for upland production systems, the techniques is also being recommended and fine-tuned for ricebased systems [Lal *et al*., 2004] [16, 17, 19]. The rice–wheat system, practiced on some 14 Mha of cropland in South Asia, provides the staple food grains to 8% of the world population. In South Asia, (Pakistan, India, Nepal, Bangladesh, Bhutan), the decline or stagnation of the productivity of rice–wheat system since 1990s may be attributed to soil degradation, severe depletion of the SOC reserves, and nutrient imbalance/depletion. Therefore, conversion to mulch farming and NT for wheat, along with direct seeding of aerobic rice in an unpuddled soil in conjunction with a judicious combination of INM strategies and adequate weed control, can reverse the degradation trend, improve soil quality and enhance, and sustain agronomic productivity [Lal *et al*., 2004; Lal *et al*., 2010] [16, 17, 19, 18]. Furthermore, present farm yields are low and hardly 40–60% of the attainable yield potential [Dobermann and Cassman, 2002] [10] and even lower (20%) in degraded soils and marginal ecosystems. Such a large yield gap can be narrowed by adoption of INM strategies, which are also useful to enhance the SOC pool of degraded and depleted soils [Lal, 2004] [16, 17, 19]. There is a widespread problem of nutrient imbalance, caused by an excessive use of highly subsidized N but not of expensive P, and deficiency of micronutrients (Zn, Fe, etc.). A judicious combination of inorganic fertilizers and organic amendments (compost, manure, and sludge) can alleviate this problem. Similar to eroded and physically degraded soils, there is a large soil/ecosystem C sink capacity of chemically degraded soils. Important among these are salinized soils in arid and semi-arid ecosystems. In addition to enhancing agronomic productivity, reclamation of salt affected soils also has a high soil C sink capacity to off-set anthropogenic emissions [Lal, 2010] [18].

Water Management

There is a close link between C, N (P, S), and water, and understanding and managing this link is important to improving soil quality and resilience. Water deficit, already a serious problem even in humid regions because of poor distribution, is likely to be exacerbated by the changing and uncertain climate with increase in frequency of extreme events. The drastic situations of water deficit in harsh environments of Middle Eastern regions [Abu *et al*., 2001] [1] have led to some drastic measures such as changing texture of sandy soils by mixing clay to enhance water retention [Al-Omran *et al*., 2004] [2]. Sustainable waste water management, especially for small communities, in Middle East and elsewhere in arid and semi-arid regions, can be useful to improve agronomic production [Bakir *et al*., 2001] [3]. Another strategy is to explore the nexus between integrated natural resource management (NRM) and integrated water resource management because of the co-cycling within an ecosystem/watershed. The strategy is to redirect blue water issues to green water issues and vice versa [Falhenmark and Rockstro, 2008] [12]. Indeed, sound water management requires a better understanding of the opportunity cost of water and greater coordination of sectoral strategies, especially among agriculture, industry, and urban uses [Lal *et al*., 2004] [16, 17, 19]. In the final analyses, the significance of the judicious NRM within a watershed (especially in semi-arid and arid regions) cannot be over emphasized. Indeed, the integrated use of soil and water conservation practices with balanced plant nutrition is an important basis of enhancing the water productivity and resource use efficiency [Sahrawat *et al*., 2010] [33]. The goal is to effectively manage the precipitation [Peterson and Westfall, 2004] [28] to obtain more crops per drop of water. Then, there is also an important issue of wetland and their management, because wetland ecosystems are a natural resource of global significance [Verhaeven *et al*., 2006] [42]. Wetlands, as kidneys of the ecosystem, provide protection against floods and non-point sources pollution, and are also a major source of fresh water. Wetlands have numerous ESs (e.g., biodiversity, C sequestration, water purification and decontamination, aquaculture, and wetland restoration) and can enhance these ESs, especially the C sink capacity to off-set anthropogenic emissions [Lal *et al*., 2012] [20]. In this regards, it is important to realize that wetlands are prone to drainage and degradation especially in arid regions. Eutrophication is a major threat to hydrophytic and other hydric species [Daoud *et al*., 2011] [8], and policy interventions are needed to protect and restore these valuable resources.

Forest Management

A judicious management of the humid tropical forests (spanning *5 N and S of the equator) is important to numerous ESs of global significance. Given the significance to global C and water cycles and conservation of biodiversity, tropical forest resources must be protected and restored. Forest management, and integration of trees with crops and livestock through appropriate agroforestry systems, can also conserve and improve soil and ecosystem C pools. Phat *et al*.

[2007] reported that between 1990 and 2000 in Southeast Asia, about 2.3 Mha of forest were cleared every year and emitted 46.5 Tg of C into the atmosphere (*29% of the global net C release by deforestation). Thus, there is a strong need to develop policy for reforestation and afforestation of the previously deforested land. Scatena [2001] [35] advocated the use of ecological rhythms in the management of endangered species and water resources in the Caribbean. Such a dynamic management is a challenging task. However, integrating ecological rhythms into management options is an important strategy for both tropical and temperate environments. Similarly, a judicious management of plantation forests is an opportunity and a challenge. Implications for biodiversity of the intensively managed plantations are a major issue. Although natural forests are a better habitat for biodiversity, judicious management of plantation forests can provide a valuable habitat [Brockerhoff *et al*., 2009], while also creating other ESs. During the early stages of tree development, agroforestry techniques can be adapted to enhance productivity and biodiversity [Mc Neely and Schroth, 2009].

New Research techniques

Strong scientific understanding is the basis for identifying technological options to be implemented for sustainable NRM. The knowledge base improvement requires credible data from long-term hypothesis based research to establish the cause-effect relationship [Haven and Aumen, 2000] [14]. In addition, innovative experimental techniques can improve the data procurement, analyses and synthesis. Remote sensing and the geographic information system (GIS) are useful tools to assess ecosystem characteristics and functions [Junge *et al*., 2010] [15]. These techniques can be used to study the change in land-use/cover and soil degradation in diverse ecoregions. There are also several modeling techniques to study biophysical processes, and also assess the anthropogenic interactions or the human dimensions of ecosystems. Nautiyal and Kaechele [2009] [25] used modeling approach to understanding how human behavior is changing under shifting political, socioeconomic, and environmental conditions in the Indian Himalayas. There are also decision support system (DSS) for soils and water conservation within a watershed. Saragni *et al*. (2004) [34] used DSS for generating alternative decision support scenarios to facilitate integrated watershed management concepts in an interactive and holistic manner.

Conclusion

Sustainable management must also be linked to sustainable governance of natural resources. Sustainable governance is essential to place the politically neutralizing discourse of management in the context of a wider social debate to discuss and negotiate the norms, rules, etc., of NRM and sustainable development. Thus, there is a need for the judicious governance of natural resources. The goal is to move from strategic action to communicative action. An important among NRM techniques is the assessment of the environmental impacts of developmental/land use/ cover options. The strategy is to assess the ecological footprint by conducting life cycle analyses (LCA). The environmental protection and conservation being critical to maintaining ESs. There exists a close link between soil erosion/degradation, climate change, and poverty. Soil degradation creates a positive feedback attributed to emission of radiatively active gases depletion of soil organic carbon and nutrient pools, denudation of vegetation cover, and reduction in net primary productivity, increase in frequency and intensity of droughts. There is a strong need for prudent management of soil, vegetation, water, and other natural resources. Restoration of degraded soils can increase the ecosystem C pool provided that available water and plant nutrients are adequate.

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