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Soil conservation and ecosystem services

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Abstract

Accelerated soil erosion, driven by anthropogenic activities such as conversion of natural ecosystems to agroecosystems and mechanical tillage, has numerous adverse impacts on ecosystem services. In addition to degrading soil quality and reducing agronomic/biomass productivity on-site through a decrease in use-efficiency of inputs, off-site impacts of accelerated erosion include eutrophication and contamination, sedimentation of reservoirs and waterways, and emissions of greenhouse gases (e.g., CO_2, CH_4 and N_2O). While advancing food and nutritional security, adoption of restorative land use and recommended management practices are important to strengthening numerous ecosystem services such as improving water quality and renewability, increasing below and above-ground biodiversity, enhancing soil resilience to climate change and extreme events, and mitigating climate change by sequestering C in soil and reducing the emission of CO_2, CH_4 and N_2O. An effective control of accelerated erosion is essential to sustainable development and improving the environment.

Key Words: Gaseous emission, Climate change mitigation, Sustainable development, Accelerated soil erosion, Geologic erosion, Food security, Eutrophication, Sedimentation, Water quality, Biodiversity

1 Introduction

Natural or geological soil erosion is a constructive process with numerous ecological functions: formation of alluvial and Aeolian (loess) soils, weathering of alumino silicates and sequestration of atmospheric CO_2, formation and evolution of the landscape with distinct soil types in relation to landscape position, biogeochemical recycling, etc. Some of the world's most fertile soils (e.g., Indo-Gangetic Plains; the Nile Delta; U.S. Great Plains) have been formed through the slow rate of geologic erosion by water, wind and other agents. However, anthropogenic perturbations have drastically accelerated the process leading to severe negative effects on ecosystem functions and services and adverse transformation/dissection of the landscape.Being a work function, as defined by the product of force (kinetic energy of water and/or wind) and the distance over which the soil is transported, the soil impacted by erosion-induced work is subject to several processes. These include: i) detachment of particles from aggregates or soil mass, ii) entrainment of detached particles, iii) redistribution of soil over the landscape, iv) sedimentation and deposition (or burial) of soil in depressional sites following Stoke's law (settling velocity $\alpha\ r^2$, where r is the radius of the particles), and v) long distance transport of fine particles (colloidal material) and the light (low-density) fraction such as soil organic carbon (SOC) and fine clay. In view of these five processes, soil erosion is a reverse of aggregation (Eq. 1):

$$\begin{tikzcd}
\text{Clay} \arrow[r, shift left, "\text{Aggr.}"] & \text{Domain} \arrow[l, shift left, "\text{Erosion}"] \arrow[r, shift left, "\text{Aggr.}"] & \text{Micro-aggregates} \arrow[l, shift left, "\text{Erosion}"] \arrow[r, shift left, "\text{Aggr.}"] & \text{Macro-aggregates} \arrow[l, shift left, "\text{Erosion}"] \arrow[l, bend right=40, "\text{Stabilization}"']
\end{tikzcd} \tag{1}$$

Where Aggr. refers to aggregation involving flocculation, cementation, and stabilization of floccules into micro and macro-aggregates.

Formation of stable micro-aggregates, according to the hierarchy model (Tisdall and Oades, 1982),

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encapsulates SOC and other soil organic matter (SOM) within it and physically protects it from microbial/ enzymatic attack. In contrast, slaking or disruption of an aggregate exposes hitherto protected SOC/SOM to microbial/enzymatic processes and aggravates the rate of decomposition leading to emission of CO_2 (oxidizing or aerobic conditions), CH_4 (reducing or anaerobic conditions) and N_2O (nitrification/denitrification reactions).

Thus, the objectives of this review article is to describe multi-functions and numerous ecosystem services provisioned and strengthened through adoption of conservation effective measures and restoration of eroded and degraded landscapes.

2 On-site and off-site effects of accelerated erosion

Being a complex transformational process, accelerated soil erosion has numerous on-site and off-site impacts. On-site impacts are those that occur at the site of erosion. In contrast, off-site impacts are those that occur where sediments (eroded material) are being carried to and deposited (Fig. 1).

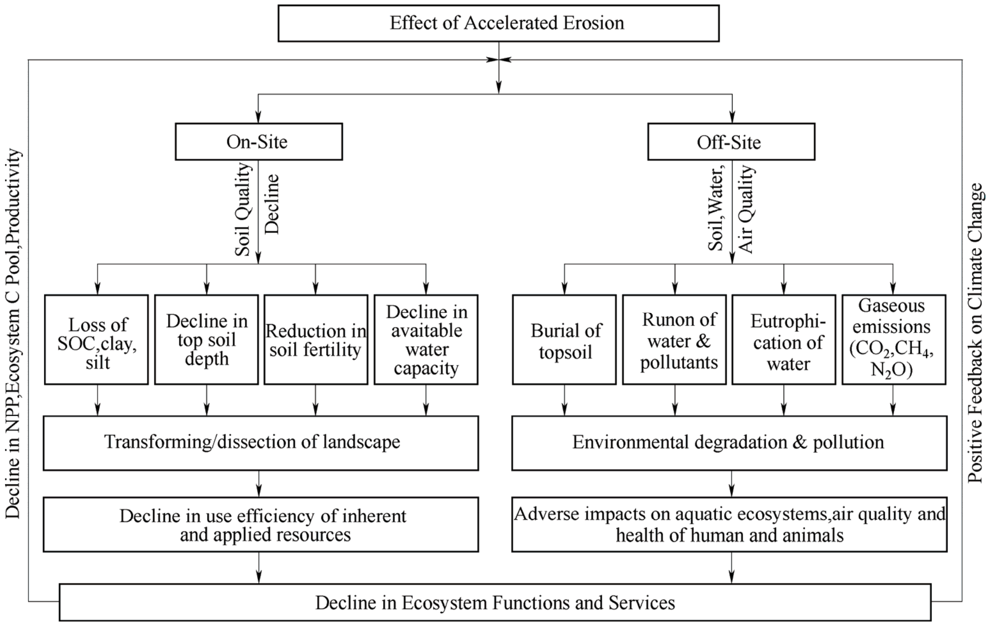

Fig. 1 Adverse effects of accelerated erosion on ecosystem functions and services

Principal among on-site impacts are decline in soil quality because of the loss of key soil constituents (e.g., SOC, clay, and silt), reduction in available water capacity and nutrient reserves, truncation of soil profile and shallowing of topsoil depth, decline of use-efficiency of inherent and applied resources and depletion of ecosystem C pool. Among off-site impacts are burial of topsoil, runon of agricultural chemicals, contamination/eutrophication of natural waters, inundation, anaerobiosis and emission of greenhouse gases (GHGs). Combined, on-site and off-site impacts of accelerated erosion curtail ecosystem functions and services, reduce biomass/agronomic productivity, and create positive feedback to climate change by aggravating emissions of CO_2, CH_4, and N_2O. While some sediment-born C may be buried and protected (Van Ooste et al., 2007), the net effect is increase in the gaseous emission with positive feedback to climate change (Lal, 2003). Numerous goods and services provided by soil (Blum et al., 2004) are severely curtailed when soil is prone to accelerated erosion. In contrast, therefore, adoption of conservation-effective measures has numerous ecological benefits by improving ecosystem functions and services.

2.1 *Accelerated erosion and fate of soil carbon*

Erosion-induced transport and redistribution of C over the landscape disrupt the C cycle at multiple scales (Table 1; Ito, 2007; Kuhn et al., 2009). Transport, redistribution and deposition affect SOC dynamics (Cheng et al., 2010; Haring et al., 2013a; Harper et al., 2010; Nie et al., 2013; Page et al., 2004; Wiaux et al., 2014; Zhang and Li, 2013; Ran et al., 2014).However, some of it is buried (Chaopriche and Marin-Spiotta, 2014; Hoffman et al., 2013; Ran et al., 2014) and is partially protected against decompositional processes.

Table 1 **Soil erosional impacts on carbon cycle**

	Processes	Reference
1	Erosion, sedimentation and the C cycle	Kuhn et al. (2012)
2	Erosion impact on the global C budget	Lal (2003)
3	Accelerated export of C from landscape	Glandell and Brazier (2014)
4	Soil erosion from agricultural lands and the global C cycle	Kuhn et al. (2009)
5	Agricultural soil erosion and the C cycle	Van Oost et al. (2007)
6	Erosion and C balance of continental China	Gao(2007); Hu et al. (2004)
7	Implications of soil erosion on C cycle over 2 centuries (1901 – 2100)	Ito (2007)
8	Erosion/deposition impacts on C dynamics (1870 – 1997)	Liu et al. (2003)

One of the consequences of burial and redistribution is the increase in spatial variability in SOC concentration in the surface layer (Chaplot et al., 2009) and the attendant impacts on biogeochemical and microbial properties (Park et al., 2014). Erosion-induced transport of SOC over the eroding landscape can accentuate gaseous flux (Page et al., 2004; Smith et al., 2007) with an attendant loss of SOC pool (Boix-Fayos et al., 2009); Glendaell and Brazier, 2014; Hancock et al., 2010; Liang et al., 2009; Korup and Rixen, 2014; Martinez-Mena et al., 2008; Quinton et al., 2006; Yan et al., 2005). Thus, it is argued by pedologist and agronomist, that landscapes subjected to accelerated soil erosion are a major source of GHGs (Fig. 2; Table 2; Chappell et al., 2013; Lal, 2013; Lal and Pimentel, 2008) with a strong adverse impact on the C cycle (Ito, 2007; Lal, 2003; Kuhn et al., 2009) and ecosystem C budget (Gao, 2007; Lal, 2003).

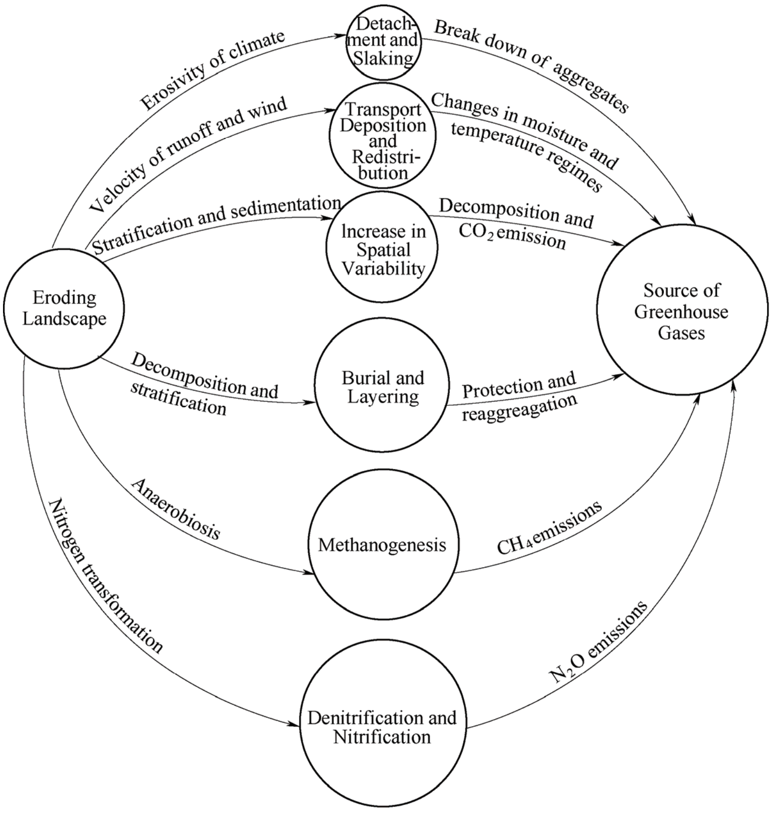

Fig. 2 Processes making eroding landscape as a source of greenhouse gases with accelerated emissions of CO_2, CH_4, and N_2O

Similar losses of SOC pool are also observed in landscapes subject to wind erosion (Table 3; Wang et al., 2006). Therefore, specific methodologies have been developed to detect soil C degradation during erosion (Alwell et al., 2009) including the use of $\delta^{13}C$ and $\delta^{15}N$ (Bellanger et al., 2004), use of the vis-NIR spectroscopy and geomorphological analysis (Conforti et al., 2013; Jouqueta et al., 2010) and by modeling studies (Yadav and Malanson, 2009; Yoo et al., 2005) (Table 4).

Table 2 Soil erosion as a source of carbon

	Erosion as source/sink of CO_2	Country/Region	Ecosystem	Reference
1	Released to the atmosphere	USA, Illinois	Timberland, cropland, Pastureland	Olson et al. (2014)
2	Snow-caused erosion	Europe, Alps	Cryosphere, wet snow avalanches	Korup and Rixon (2014)
3	Released to the atmosphere	China	Yellow River	Ran et al. (2014)
4	Erosion-induced source	Global	Modeling	Lal (2003)
5	Removal of C	Ecuador	Rio Chimbo/ Andean Andisols	Henry et al. (2013)

Table 3 Examples of the effects of wind erosion on soil carbon dynamics

	Soil C impact	Region/County	Ecosystem/Biome	Reference
1	Erosion impacts soil C pool	Shelihu Lake Basin/ China	Desertification regions	Lian at al. (2013)
2	Dust as a source of C and the net loss from ecosystems	Australia	Rangelands	Chapell et al. (2013)
3	Erosion caused loss of 3% of soil C pool to 1-m depth (3.6 Mg/ha)	Western Australia	Dryland farming systems	Harper et al. (2010)
4	Loss of soil C and nutrients	Northern China	Dust storms	Wang et al. (2006)
5	Loss of 75 Tg C/yr by wind erosion	China	Wind erosion at national level	Yan et al. (2005)

Table 4 Techniques and approaches of addressing coupled transport of carbon and sediments by erosional processes

	Technique	Country	Biome/Region	References
1	Geochemical approaches	Czech Republic	Loess-covered sub-catchment	De Baets et al. (2013)
2	$Cs^{137}(Pb^{210})$	Japan	Run-off plots under forests	Teramage(2013)
	Cs^{137}	China	Tibetan Plateau	Nie et al. (2010)
	Cs^{137}	Switzerland	Central Alps	Alewell et al. (2009)
	Cs^{137}	China	Yangtze River	Wei et al. (2008)
	Cs^{137}	U.K.	Point and field scale	Quine and Van Oost (2007)
	Cs^{137}	Northeast China	Black soil region	Fang et al. (2012)
3	Black Carbon	Cypres	Mediterranean island	Brauneck et al. (2012)
4	Vis-NIR spectroscopy	Italy	Mediterranean Belt	Conforti et al. (2013)
5	δC^{13}	China	Three Gorges Reservoir	Haring et al. (2013b)
	δC^{13} (N^{15})	Venezuela	Andean region	Bellanger et al. (2004)
6	Near infrared reflectance spectroscopy	Northern Vietnam	Steep slope ecosystems	Jouqueta et al. (2010)
7	Vertical profile of soil carbon	Northeast China	Black soils	Liang et al. (2009)
8	Modeling	U.K.	Bedfordshire	Quinton (2006)
	Modeling (Erosion-Deposition carbon model)	USA	Mississippi	Liu et al. (2003)

The slow process of geological erosion, however, can lead to C sequestration in sediments, aquatic ecosystems and oceans over the millennial and short-term temporal scale. Indeed, SOC buried in depressional sites and transported into aquatic ecosystems (e.g., lakes and oceans) is taken out of the C cycle. However, this fraction (20% of the total transported according to some estimates; Lal, 2003) cannot be technically termed “sequestration” (Olson et al., 2014; Bernoux et al., 2006). Because it is taken out of the C cycle, it is termed by some as a “C sink” (Table 5; Obame et al., 2014; Quine and Van Oost, 2007; Van Oost et al., 2005, 2007, 2009). Yet, even the “sink hypothesis” is questionable because of the assumption based on “dynamic replacement of C” at the eroding site. A severe decline in soil quality reduces agronomic productivity and decreases the input of biomass C, which can be replaced on a decadal scale under restoration landuse and best management practices.

Table 5 Soil erosion and carbon storage on land as a sink

	Experimental Approach	Region/Country	Ecosystem/Biome	Reference
1	Inland river sediments	Central Europe	Riverine systems	Hoffman (2013)
2	Literature synthesis	Global	–	McPherson (2009)
3	Discussion/comments	Global	–	Van Oost et al. (2008)
4	Modeling	Africa	Sahelian Lakes	Obame et al. (2014)
5	Soil C burial in deep horizons	Global soil burial by volcanic, Aeolian, alluvial, colluvial and glacial processes	Paleosols	Chaopricha and Marin-Spiotta (2014)

3 Soil conservation for carbon sequestration

In contrast to accelerated soil erosion, adoption of conservation-effective measures on eroded landscape would reverse the degradation trends and increase soil and ecosystem C pools. In this context, soil conservation must be viewed in an ecosystem perspective. It implies maintaining pedological processes, reducing losses of soil and water, and strengthening cycling of C and other elements (e.g., N, P, S) especially the coupled cycling of elements including that of C and the hydrologic cycle (H_2O). Thus, conversion to a restorative land use and adoption of conservation-effective measures would sustain/ improve soil and ecosystem C pools, enhance soil quality, and increase net primary productivity (NPP), among numerous ecological benefits (Fig.3). Over and above the beneficial impacts on water quality, a principal ecological benefit of soil conservation and restoration is the increase in the C pool in the soil and the terrestrial biosphere with the attendant negative feedback on climate change. Improvement in soil quality would enhance resilience against climate change by dampening the effects of extreme events, moderating fluctuations in microclimate, reducing diurnal/annual variations in soil temperature and moisture, and mitigating the climate change (Fig. 3).

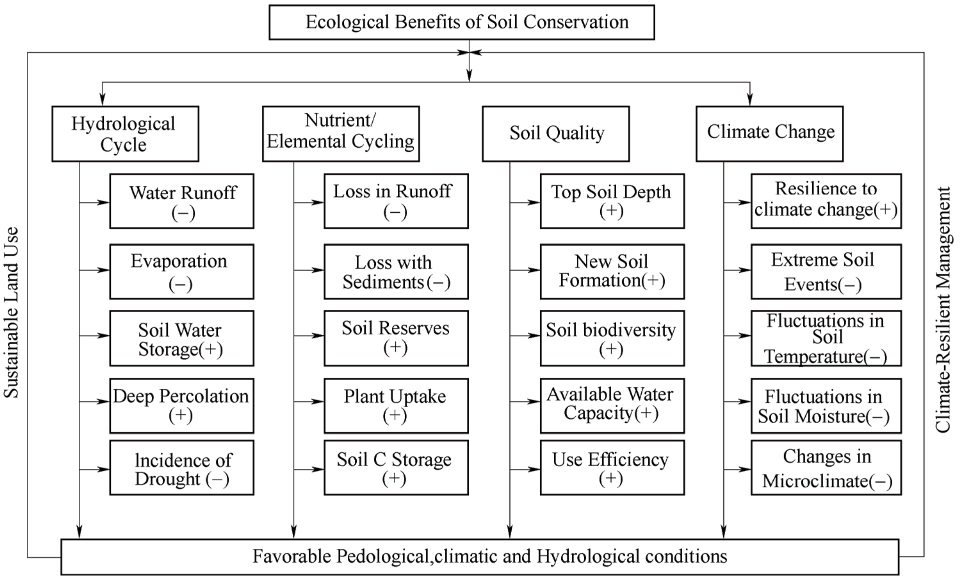

Fig. 3 Ecological benefits of soil conservation

Impacts of conservation-effective measures on climate change mitigation stem from an increase in quantity and quality of SOC and ecosystem C pools. Specific benefits of these are those related to restoration of drastically disturbed/ degraded/ desertified lands, cycling of C and other elements along with H_2O, enhancing ecosystem functions and services, increasing biodiversity and creating plant-soil feedback with positive impact on the biosphere (Table 6).

Table 6 Ecological benefits of soil carbon enhancement and sequestration

	Parameter	Ecosystem	Reference
1	Restoration of drastically disturbed lands	Mined Soil	Bodlak et al. (2012)
2	Biodiversity	Arid/semi-arid rangelands	Witt et al. (2011)
3	Soil restoration	Atlantic Forest Ecosystem-Brazil	Nogueira, Jr. et al. (2011)
4	Land restoration	Mountainous terrain, NW China	An et al. (2010)
5	Combat desertification	Communal grazing land, Ethiopia	Mekuria et al. (2011)
6	Sustainable wetlands management	Tropical African wetlands	Saunders et al. (2012)
7	Sustainable agriculture	South Africa's degraded rangelands	du Preez et al. (2011)
8	Elemental cycling	Natural and managed ecosystems	Battle-Aguilar et al. (2011)
9	Global carbon cycle	Gulf of Mexico	Hansen and Nestlerode (2014)
10	Ecosystem restoration	Temperate steppe	Jiang et al. (2010)
11	Ecosystem services	Pedosphere	Otte et al. (2012)
12	Plant-soil feedback	Global	Van der Putten et al. (2013)

4 Soil carbon cycling within the biosphere

Pedospheric processes, strongly impacted by soil conservation and restoration, are inter-connected with the atmosphere, biosphere, lithosphere, and hydrosphere (Fig. 4). Pedospheric processes impact biospheric processes such as photosynthesis, respiration, NPP and net biome productivity, and elemental cycling; lithospheric processes including rate of weathering and soil formation as impacted by volcanism and metamorphism; hydrospheric processes including components of the hydrologic cycle, and specifically soil water storage (green water), surface runoff and deep seepage (blue water); and atmospheric processes including temperature, precipitation and extreme events (Fig. 4).

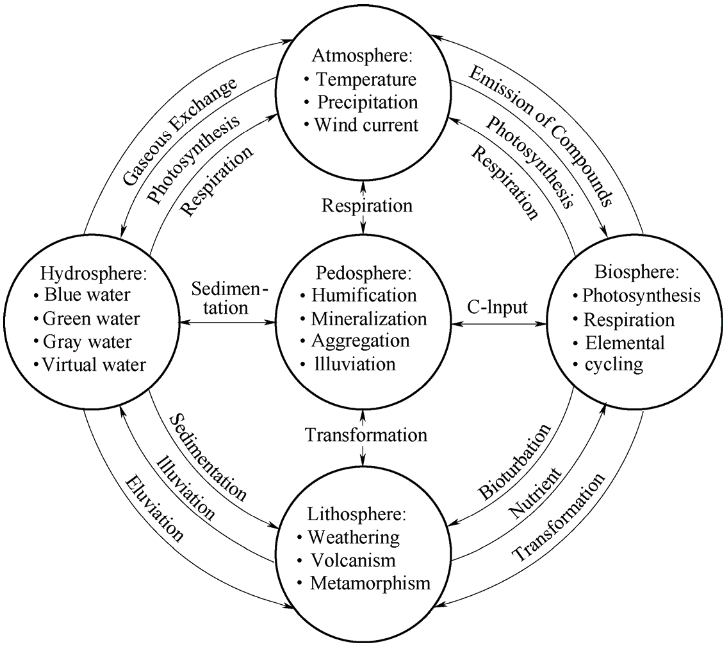

Fig. 4 Soil C cycling within the ecosphere

The SOC pool and its dynamics also impact soil properties and processes (Table 7), with a strong moderatory impact on soil quality and the attendant ecosystem functions and services. Important properties impacted by SOC dynamics include: i) physical (e.g., aggregation, bulk density, surface area, porosity and pore size distribution and continuity, gaseous exchange by mass flow and diffusion, water retention and transmission, thermal conductivity and heat capacity), ii) chemical (e.g., buffering capacity, pH, CEC, exchangeable cations, leaching, nutrient reserves, elemental transformations), iii) biological (e.g., SOC concentration, microbial biomass, activity and species diversity of soil fauna and flora, respiration, enzymatic activity), and iv) ecological (e.g., biogeochemical cycling, ecosystem functions) (Table 7). Optimization of these properties and processes is essential to goods and services provisioned by soils.

Table 7 Processes and properties moderated by soil organic carbon

	Properties/Processes	Ecosystem	Reference
1	Soil hydrological properties	Semi-arid region, Turkey	Yusek and Yusek (2011)
2	Physical/chemical properties	Sodic soil	Singh et al. (2012)
3	Soil aggregation	Eroded lands	Tang et al. (2010)
4	Spatial heterogeneity	Sand dune	Zuo et al. (2008)
5	Soil chemical properties	Arable land	Valtinat et al. (2008)
6	Enzymatic activities	Sodic soil	Singh et al. (2012)
7	Soil physical properties	Grasslands	Yuan et al. (2012)
8	Microbial population	Deserts	Bashan and de-Bashan (2010)

5 Strategies of restoring degraded soils

Reversing degradation trends necessitates identification and implementation of site-specific strategies. There exists neither a panacea nor a silver bullet that has a universal applicability. Thus, choice of strategies depends on biophysical (climate, geology, soil type, drainage patterns, vegetation, land use) and human dimension factors (demography, infrastructure, land tenure, access to credit and market). Examples of a few strategies are outlined in Fig.5. The objective is to: i) minimize losses of water and nutrients out of the ecosystem,ii) create positive ecosystem C, nutrient and water budgets, iii) enhance biodiversity (above and below ground), iv) strengthen plant-soil feedback, and v) minimize soil disturbances.

Restoration of drastically disturbed lands requires specific strategies. Drastically disturbed lands include mined soils, severely dissected gullied land, land prone to sand dune formation etc. Some strategies to reclaim drastically disturbed lands (Table 8) include mechanical land forming to create gentle slope gradients and increasing micro-relief. Increasing SOC pool, by recycling biomass/biosolid carbon (e.g., compost, manure, mulch, sludge, grey/black water after treatment) is always useful to set-in-motion the restorative process. Enhancing available water capacity, deceasing bulk density and soil strength, improving availability of essential nutrients (N, P, K, Zn, B, Cu) and improving bioturbation are generic options of wider applicability.

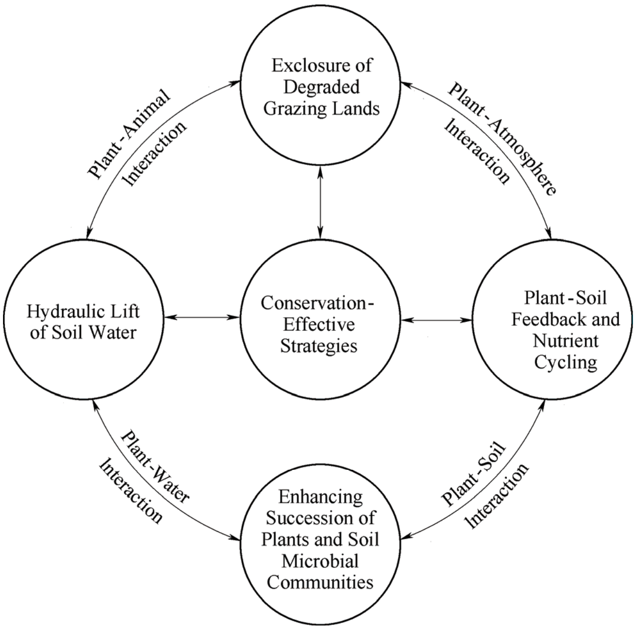

Fig. 5 Approaches to conservation of eroded/degraded soils

Table 8 Strategies of reclaiming severely eroded soils

	Strategy	Reference
1	Mechanical land forming (bulldozers)	Phillips (1998)
2	Bioturbation (earthworms)	Butt (2008)
3	Creating microtopography	Simmons et al. (2011)
4	Local soil knowledge	Lemercier et al. (2012)
5	Enhancing SOC pool	Lal (1977)

6 Towards broadening the scope of soil conservation

Adverse impacts of accelerated erosion on agronomic productivity have long been recognized, and recorded in the literature since the days of Virgil (1 A.D.) in Rome, ancient Greece (Andel and Zangger, 1990; Papnastasis et al., 2010), in Indus Valley (Lal, 2008) and elsewhere. Many once-thriving ancient civilizations collapsed because of the erosion of soil that supported them (Montgomery, 2012). Adverse impacts of erosion on water quality and non-point source pollution were considered major issues during the 1970s (Dinnes, 2004; Johnson et al., 1979; Laflen and Tabatbai, 1984; Seta et al., 1993; Angle et al., 1984). The importance of erosion and SOC sequestration as a source or sink of atmospheric CO_2 emerged as a global issue during the 1990s (Lal et al., 1999).

Soil conservation and restoration of eroded soils/landscape has a wide range of benefits (Table 9).

Table 9 **Benefits of soil conservation and restoration of eroded soils**

Parameter		Beneficial Impact
1	Pedological	Soil Quality, elemental cycling, horizonation
2	Ecological	Ecosystem function and services
3	Hydrological	Reductions in non-point source pollution, component of hydrological cycle
4	Climatological	C sequestration, reduction in gaseous emissions decline in hidden C costs of inputs (fertilizers, pesticides, irrigation)
5	Agronomic	Productivity, sustainability, use-efficiency of input, profitability
6	Sociological	Human well being, land value, aesthetical and moral issues

7 Conclusions

Whereas accelerated soil erosion and erosion-induced degradation have plagued humanity since the dawn of settled agriculture, its importance to environmental and food security issues is more than ever before. Global issues linked to accelerated soil erosion include water quality and renewability events, SOC sequestration to off-set anthropogenic emissions and mitigate global warming, food and nutritional security and biodiversity.Therefore, soil conservation, erosion control and restoration of eroded soils have important policy imperatives. The goal is to incentivize farmers and land managers to adopt to restorative land use and recommended soil/crop/animal management practices for improving soils and the environment.

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