Journal of Agriculture and Environmental Sciences
June 2024, Volume 13, pp. 16-34
ISSN: 2372-5060 (Print), 2372-5079 (Online)

Published byThe Brooklyn Research and Publishing Institute
DOI: 10.15640/ijhs.v13a2
URL: https://doi.org/10.15640/ijhs.v13a2

Soil Degradation: Contributing Factors and Extensive Impacts on Agricultural Practices and Ecological Systems- Systematic Review

Adugna Bayata[1]

Abstract

Soil degradation is a significant issue that has extensive impacts on agricultural productivity, ecosystem health, and global food security. This systematic review explores the contributing factors of soil degradation, including both natural processes and human-induced activities. Key drivers such as deforestation, overgrazing, industrial activity, unsustainable agricultural practices, and climate change are examined. Soil degradation manifests in various forms, including erosion, loss of organic matter, salinization, compaction, acidification and contamination; each affecting soil structure, fertility, and water retention capacity. The consequences of soil degradation are far-reaching, threatening agricultural sustainability and leading to declining crop yields and reduced soil reliance. Additionally, soil degradation disrupts ecological systems, diminishing biodiversity, changing nutrient cycles, and contributing to increased greenhouse gas emissions. The review also highlights the economic impacts of soil degradation, particularly, on smallholder farmers in vulnerable regions who are heavily dependent on agriculture. Different findings underscore the urgent need for integrated soil management strategies that promote sustainable land use and agricultural practices. Various solutions, such as conservation agriculture, agroforestry, crop rotation, cover cropping, and soil amendments with organic materials were discussed as potential strategies to mitigate soil degradation and restore.The findings underscore the urgent need for integrated soil management strategies that promote sustainable land use and agricultural practice soil health and increase crop productivity. This review emphasizes that addressing soil degradation requires a coordinatedglobal efforts involving policy makers, researchers, and practitioners to ensure the long-term viability of agricultural systems and the preservation of ecological balance.

Key words: degradation, erosion, food security, soil erosion, soil structure, fertility, sustainable

Introduction

Globally, land degradation may be attributed to soil erosion (Guo et al., 2019). Soil erosion has been estimated to degrade about 32% of the total land area in the USA, 16% in Africa, 31% in China, 17% in Europe, and 45% in India (Singh et al., 2020). The annual average soil erosion rates reported in the literature vary drastically. Natural or geological erosion occurs in the natural environment due to the action of water, wind, gravity, and glaciers. It occurs silently and often continues unnoticed. However, it is usually of little concern because its rate is low, and soil loss is naturally compensated by soil formation. Thus, geological erosion includes soil-forming and soil-eroding processes, which maintain the soil in a favorable balance, suitable for plant growth. Geological erosion is responsible for forming the present topographical features such as canyons, stream channels, and valleys.By dispersing the weathered materials created by geomorphic processes, erosion of soil from catchments which involves the process of soil detachment from the soil surface and its transportation by rainfall and runoff has been largely responsible for shaping the physical landscape of today.

---

[1] Jimma Agricultural Research Center/JARC, Ethiopian Institute of Agricultural Research/EIAR, Ethiopia
Email: adubay2013@gmail.com, bayata_af13@yahoo.com
ORCID: https://orcid.org/0009-0009-6927-8530

"Accelerated soil erosion" is defined as "Soil erosion, as a result of anthropogenic activity, in excess of accepted rates of natural soil formation, causing a deterioration or loss of one or more soil functions" (VAN et al., 2004). This type of erosion is a threat to soil. Soil erosion has many causes and involves several mechanisms. Soil erosion by water occurs through rills, inter-rills and gullies, as a result of rainfall, snowmelt and slumping of banks alongside rivers and lakes.

According to (Hurni et al., 2010), land degradation is any process that reduces the ability of land resources to provide crucial ecosystem services. This is brought on by two interconnected complex systems: the natural ecosystem and the human social system. The success or failure of resource management is determined by interactions between the two systems (L. Berry et al., 2003). The main causes of land degradation are erosion by water and wind, chemical degradation (acidification, salinization, fertility depletion, and decrease in cation retention capacity), physical degradation (crusting, compaction, hardening, etc.), and biological degradation (reduction in total and biomass carbon, and decline in land biodiversity) (Abebaw, 2019)).

It is a continual process that, nonetheless, has grown to be a significant issue affecting food security, national prosperity, and practically everyone's ability to survive (Tefera et al., 2000). In terms of natural resources, Ethiopia is one of Sub-Saharan Africa's wealthier nations (Zeleke et al., 2006). However, Ethiopia has seen a long history of natural resource degradation (Hurni et al., 2010). (J. W. Berry, 2003), similarly noted that Ethiopia's loss of land resource productivity is a significant issue, and Berry predicted that as the country's population grows, the issue will likely become much more significant. Rapid population growth, severe soil erosion, deforestation, low vegetative cover, and uneven agricultural and livestock output are the main factors contributing to land degradation in Ethiopia (Girma, 2001). In addition to topography, soil types, and agro-ecological parameters, man-induced degradation processes are also significantly influenced by additional elements (Girma, 2001). In the middle of the 1970s, the Ethiopian government started a significant soil conservation effort to fight land degradation (Hawando, 1997). "Think globally, act locally" was a slogan used by the environmental movement in the 1980s and 1990s, however it was unsuccessful. Additionally, throughout the past 30 years, efforts for conservation and afforestation have been implemented (Bishaw, 2001).

Table 1 Global Extent of Soil Erosion by Water and Winds

Continent	**Water erosion**	**Wind erosion**
	Million ha	
Africa	227	186
Asia	441	222
South America	123	42
Central America	46	5
North America	60	35
Europe	144	42
Oceania	83	16
World total	1094	548

Source: (Oldeman, 1992)

Water erosion

On global scale, water induced erosion represents the most critical form of soil degradation resulting in a sediment flux of 28 Gtyear^{-}(Quinton et al., 2010). Research done in India depicted water erosion impacts 68.4% of the overall land coverage(Mandal & Sharda, 2013),leading to an annual loss of 13.4 Mt in cereal, pulse, and oil seeds production (Sharda et al., 2010). The process of soil erosion entails soil detachment initiated by raindrop impact or flowing water, with subsequent transport occurring via surface runoff.

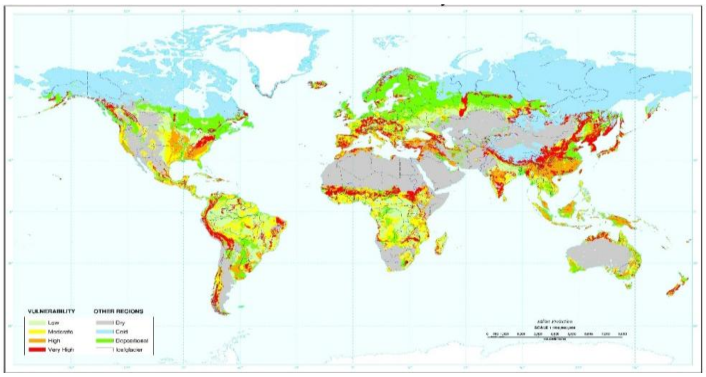


Figure 1 World erosion severity

Wind erosion

Wind erosion is a widespread phenomenon impacting about 28% of the global land (Borrelli et al., 2017). In wind erosion, soil detachment and transportation are caused by wind. Wind erosion is a severe environmental hazard as it causes air pollution and adversely affects human health. It also influences the climate by altering the global radiation budget due to the dust particle concentration in the atmosphere. It occurs extensively in the arid and semiarid regions worldwide, which have inadequate precipitation and little or no vegetation cover. The agricultural lands subject to wind erosion are in Asia, North Africa, Australia, and parts of North and South America (Shepherd et al., 2016)

Modeling Soil Loss

Modeling soil erosion by water, vital to understanding the soil erosion processes and predicting soil erosion rates, started in the 1930's when the first research study was published. Since then, numerous empirical and process-based models of varying complexities and prediction capabilities have been developed for evaluating soil erosion. Although, process-based models like WEPP and EUROSEM have been developed in the recent past, the empirical models, like USLE and RUSLE, are extensively used globally because of their simplicity and wider acceptability.

Revised Universal Soil Loss Equation (RUSLE)

The USLE was revised during the 1990s to the RUSLE by including process-based components and improved procedures to estimate various factors involved (Kenneth et al., 1997). The basic multiplicative structure of USLE is, however, preserved in RUSLE. RUSLE provides an updated procedure for estimating the erosivity factor (R) using the following relationship:

$$R = \frac{1}{n} \sum_{J=1}^{n} \sum_{k=1}^{m_j} (EI)_k$$

Where, n = number of years of record (usually more than 20 years); mj= number of events causing erosion during year j; and EI = rainfall erosion index for rainfall event k,MJmmha^{-1} h^{-1}.

$$EI = \left(\sum_{r=1}^{m} e_r v_r \right) I_{30}$$

Whereer= unit rainfall energy, MJ ha−1 mm−1; vr= rainfall depth for the time interval r of the hyetograph, which has been divided into r = 1, 2, …,m subintervals, mm.

The unit rainfall energy is given by the following relationship (McGregor & Mutchler, 1976).

$$e_r = 0.29\left(1 - 0.72\, e^{-0.082\, I}\right)$$

RUSLE typically uses the erodibility monograph, developed for estimating the soil erodibility factor, K. It guides the user in identifying the soils for which the monograph is not applicable and then suggests alternative methods for estimating K. RUSLE also includes variability of K over different seasons by considering freezing and thawing. Equations relating K to the annual R for the frost-free period are used to estimate K, and the seasonal variability is taken into account by considering weights proportional to EI for a 15-day interval.

RUSLE provides improved relationships to estimate the slope length-gradient factor, LS, for complex topographies by considering the upslope contributing area and flow accumulation. RUSLE removes the dominance of slope steepness and gives more even weightage to length and steepness. It considers ponding over the surface area and adjusts soil loss accordingly.

RUSLE is available as a computer model, with RUSLE1.06c being its last version (Benavidez et al., 2018). RUSLE2 (Foster et al., 2003)is the advanced version of RUSLE that provides a user-friendly computer interface and uses a hybrid approach to model soil loss. It includes empirical equations to compute sheet and rill erosion due to rainfall erosivity and process-based equations to compute the detachment, transport, and deposition of sediments due to runoff.

What factors and policies improve soil conservation?

There exist two distinct approaches that can yield advantageous outcomes for soil conservation. The first pertains to the subsidization of fertilizers. In various nations like Nigeria and Ghana, governmental bodies procure fertilizers and distribute them to agricultural producers at reduced prices. In principle the application of fertilizers is anticipated to facilitate optimal crop development and mitigate the risks associated with soil erosion.

The second policy that exhibits potentially advantageous implication for soil conservation involves governmental promotions of the establishment of plantation and the cultivation of export-oriented crops. Perennial crops, encompassing plantation of coffee, rubber, palm oil and other arboreal species, contribute to the provision of a protective vegetative cover. Tree crops are particularly well-adopted to forested regions and serve to shield the soil from the impacts of intense rainfall.The degree of soil erosion observed in areas cultivated with tree crops is generally less than that of encountered in regions designated for food crop production. Efforts have been also undertaken to formulate legislation at prohibiting practices such as burning, uncontrolled grazing, and the cultivation of steep terrains. These legislative measures, however, have been ineffective.

Table 2 Loss (in kg/ha/year) of soil organic matter content and plant nutrients in eroded soil from afield of10% slope (Lai, 1976). T = trace

				Exchangeable cations		
Treatment	Organic C	Total N	Bray-P	Ca	Mg	K
Bare fallow	3632	310	20	223	19	28
Maize-maize (mulch)	T	T	T	T	T	T
Maize-maize (plow-till)	168	14	1	10	4	1
Maize-cowpea (no-till)	T	T	T	T	T	T
Cowpea-maize	175	14	0.4	17	1	2

Table 3 Nutrient loss (kg/ha/year) in water runoff from a field of 10%slope (Lai, 1976)

	Nutrient loss				
Treatment	NO_3-N	PO_3-P	K	Ca	Mg
Bare fallow	11.5	3.7	18.2	33.9	7.0
Maize-maize (mulch)	0.6	1.0	1.4	0.8	0.3

Maize-maize (plow-till)	1.6	0.6	4.3	5.8	1.3
Maize-cowpea (no-till)	0.6	0.2	2.5	1.1	0.3
Cowpea-maize	1.3	0.8	5.3	5.0	1.3

Table 4 Relation between soil properties indicative of the degree of soil erosion and growth and yield of maize grown on an eroded Alfisol in West Nigeria (unpublished data of Miller and Lai, 1985), + = positive correlation, – = negative correlation

Variable	Above-ground biomass	Average height	Harvest index	Plant lodged	Plants stand	Shelling (%)	Slope (%)
Soil color	–	–	–	–	–	–	+/–
Gravel (0–10cm) %	–	–	–	–	–	–	+
Gravel on surface (%)	–	–	+	–	–	–	+
Depth to gravel	+	+	+	+	+	+	–
Surface soil thickness	+	+	+		+	+	–
Slope	+	+	+	–	+	–	

Man-made ecological degradation and rehabilitation

In Ethiopia, a significant proportion of population ~ 88%,alongside 60% of the livestock, and 90% of the agriculturally suitable area is predominantly situated within the highland regions, which were characterized by elevations exceeding 1500 m above sea level (Constable, 1985).The remarkable concentration of demographics contributed to the favorable conditions of climate, ecology, soil quality, and environmental health, a phenomenon that is notably unique within the African context. For example, the total population of Ethiopia, being over 45 million people, exceeds the total population of all other countries in the Sahel belt (Keay, 1987). The advantageous environmental conditions were instrumental in attracting early human inhabitants to these expansive mountainous complexes, led to the gradual occupation of the majority of agriculturally sustainable terrains, including marginal lands situated on slopes that were particularly vulnerable to soil erosion. These transformative processes commenced with the advent of agriculture several millennia ago, indicating that they were far from being recent occurrences

Initially, deforestation was undertaken to clear lands for agricultural purposes and convert wildlife habitats into areas designated for livestock. Subsequently, as forest resources became increasingly depleted, the demand for fuel wood began to surpass the natural regeneration capabilities of the remaining forest remnants. In contemporary times, Ethiopia's forest resources were confined to minuscule fraction of the land area (3% of the country), predominantly located in the western highland regions. In many other areas, the residual trees fail to provide sufficient fuel wood for domestic consumptions. The wildlife that historically depended on forest as their primary habitat has been eradicated alongside the forests themselves. In contrast to prevalent beliefs, evidence substantiates that deforestation has its origins several thousand years (Hurni, 1985b). By that time, a substantial portion of Ethiopia had experienced significant deforestation, and the cultivation of Eucalyptus trees offered a critical source of fuel wood for the burgeoning urban centers.

Soil erosion, instigated by precipitation and surface runoff represents a phenomenon that has persisted throughout the entirety of agricultural history in Ethiopia. In the Northern regions, where agricultural practices were in detail, significant degradation has transpired, characterized by the potential total soil removal from inclines, alongside its subsequent deposition in valley floors. In areas such as Welo, Tigray, Gonder, and Eritrea, as well as Hararge, Gojam, Wallaga, Shewa, and Sidama, the prevalence of shallow soil is notable; these soils were primarily utilized for grazing purposes, while deeper soils were designated for cultivation. Shallow soils which exhibit lower fertility and reduced vegetative cover, demonstrated higher vulnerability to erosion, with their capability for water retention diminishing in correlation with declining soil depth. Consequently, reduced agricultural yields are expected from such soil, which in turn exacerbates further degradation. A detrimental cycle is initiated if chronic soil erosion remains un-mitigated. Degraded soils and vegetation contribute to direct runoff rates reaching as high as 80% of total rainfall, whereas vegetated soils characterized by long grasses and trees retain in excess of 90% of the rainfall. Taking 60 cm of soil depth as a cropland average in the highlands, the annual loss of 4 mm of soil depth on average means that within 150 years most current cropland soils in Ethiopia would be eroded (except for gentle slopes below 1% gradients). From this, an annual reduction of soil productivity of 1-2% must be assumed, and has been verified in test areas (Hurni, 1987).

The biological of soil constitutes an additional prevalent process within Ethiopia agricultural frameworks. As a result, there is a marked decrease in organic matter, leading to diminished soil fertility and productivity; thereby adversely affecting agricultural yields and other outputs. Such biological degradation can culminate in annual reduction of soil productivity of as much as 1%.

Table 5 Estimated rates of soil loss on slopes in Ethiopia dependent on land cover (Hurni, 1987).

		Estimated soil loss	
Land cover (from LUPRD)	Area (%)	t/ha/year	Mt/year
cropland	13.1	42	672
Perennial crops	1.7	8	17
Grazing and browsing land	51.0	5	312
Totally degraded	3.8	70	325
Currently uncultivated	18.7	5	114
Forests	3.6	1	4
Wood and bush land	8.1	5	49
Total country	100.0	12	1493

Impact of Land Degradation

Land degradation exerts a profound influence on agricultural output, biodiversity, and ecosystem services; presenting urgent challenge on a global scale. On global scale, it undermines ecological integrity, resulting in habitat destruction, diminished biodiversity, and heightened susceptibility to climate change (Ekka et al., 2023). Moreover, the degradation of soil adversely impacts the health of flora, fauna, and humans by disrupting critical ecosystem functions such as nutrient cycling and hydrological regulations (Sprunger Christine, 2023).Numerous signs of land degradation include decreasing vegetation, drying waterways, prickly weeds taking over once-rich pastures, footpaths turning into gullies, and thin, stony soils. All of these manifestations have the potential to have negative effects on the environment, land users, and people who depend on the products of a healthy landscape for their livelihood (L. Berry et al., 2003). In Ethiopia, the ramifications encompasses food insecurity and poverty, exacerbated by phenomenon such as soil erosion and deforestation (Estefanos Shanko, 2023).

Socio-Economic Impact of Land Degradation

Land degradation impacts socio-economic conditions, particularly agricultural communities. Numerous scholarly investigations underscore the complex and multifaceted nature of these repercussions, thereby accentuating the imperative for sustainable land management strategies aimed at alleviating degradation and improving livelihoods (Slayi et al., 2024). Food security is under risk for many of the poorest and most food insecure people living in Asia, Africa, and Latin America due to land and water degradation. Additionally, it makes an ecosystem less resilient and reduces the provision of environmental services (Bossio et al., 2004). Additionally, environmental decline brought on by land degradation has a negative impact on people's health, happiness, and possibilities for employment (Vivian, 1994); (Scherr & Yadav, 1996)(Pender et al., 2012). Since the middle of the 1980s, land degradation has caused Africa as a whole to become a net importer of food. However, because 65% of people in Sub-Saharan Africa live in rural areas and nearly 90% of them depend on agriculture for their primary source of income, the economic effects of land degradation there are extremely severe (Critchley et al., 2023). Soil erosion is the most significant issue with Ethiopia's land resources. According to, the country loses billions of birr each year due to soil, nutrient, water, and agro-biodiversity losses.

Rural communities are therefore more likely to experience poverty and food insecurity (Abebaw, 2019) Estimates vary widely, but in Ethiopia, direct productivity losses due to land degradation account for little more than 3% of the country's agricultural GDP (L. Berry et al., 2003). Deforestation and degraded soils in the Ethiopian highlands have depleted the resource base and exacerbated the ongoing food shortages brought on by drought (Amede et al., 2001).

Increased runoff and decreased infiltration as a result of land degradation contribute to the flooding issue (Bezuayehu et al., 2002). Deforestation and desertification have a negative impact on agricultural output, human and animal health, and economic activities like ecotourism. Land degradation can directly cause poverty by lowering the supply of other essential goods and services for low-income households (such as fuel wood, building supplies, wild foods, and medicinal plants) and by raising the labor requirements for foraging for these goods.

Ecological Impact of Land Degradation

A variety of direct and indirect processes that have an impact on a wide range of ecosystem functions and services result in the varied and complex effects of land degradation on the global environment (Stocking, 2006). The main environmental effects of land degradation include a quick loss of habitat and biodiversity, changes to water flows, and sedimentation of reservoirs and coastal areas (Nizam Kamaruzzaman & Marinie Ahmad Zawawi, 2010). The ecological effects of land degradation in Ethiopia include loss of soil's chemical, physical, and/or biological properties, which directly affects the type of plants that can be grown there, decreased surface water volume, depletion of aquifers from lack of recharge, and loss of biodiversity (L. Berry et al., 2003). Similarly, (Lemenih, 2004)also described that land degradation is threatening biological resources and agricultural productivity.

Mechanisms to Prevent Land Degradation and Restore Degraded Lands

Depending on the type and extent of the degradation, there are many ways to prevent it. By replenishing nutrient-depleted soil with nutrients, rebuilding topsoil through soil amendments, reestablishing vegetation, or buffering soil acidity, most types of soil degradation can be avoided or reversed (Scherr & Yadav, 1996). However, some aspects of land degradation are more difficult to reverse than others. For instance, gully erosion, total topsoil loss through erosion, the eradication of native soil fauna, or surface sealing and crusting are more irreversible than a negative nutrient balance. Parallel to this, (Scherr, 2000)provided evidence that some types of land degradation are, in all likelihood, irreversible. Examples include severe gulling and extensive salinization. Although the depth and quality of the remaining soil will determine the long-term effects on the ability to produce, soil displacement (also known as erosion) is irreversible.

In general, land degradation can be prevented, reduced, or even reversed if it is used wisely, all of the land's functions are considered, and long-term interests of all human groups take precedence over short-term vested interests of privileged groups locally, globally, and naturally (Getachew 2005). Scherr and Yadav (1996) have noted that the cost of restoring degraded landscapes depends on the expected value of the output or environmental benefits. Physical conservation buildings have traditionally been the focus of attempts to stop land degradation in Ethiopia (Woldeamlak 2003). Temesgen et al. (2014c) noted that farmers in DeraWoreda, Ethiopia rely primarily on physical soil conservation systems. Vegetative methods are, however, only occasionally used. It is generally accepted, though, that different types of land degradation require different approaches.

Table 6 Component of degradation, type of degradation and ways of improving degraded land (Scherr and Yadav 1996)

Component	Degradation	Improvement
Physical soil management	Crusting	Soil conservation barriers
	Compaction	Terracing
	Sealing	Revegetation of denuded lands
	Water erosion	Tree protection
	Wind erosion	Soil decomposition
	Devegetation	Breaking up of pans
	Over tillage	Cover crops
		Wind breaks
		Soil deposition
		Improved tillage methods
Soil water management	Impeded drainage	Irrigation
	Water logging	Water harvesting
	Reduced water holding capacity	Field drainage
	Reduced infiltration	Draining of water logging areas
	Salinization	Filter strips
Soil nutrient and organic matter management	Alkalization	Fertilization
	Acidification	Composting
	Nutrient leaching	Green manuring
	Removal of organic matter	Animal manuring
	Burning of vegetative residues	Flushing of saline alkaline soils
	Nutrient depletion	Liming acid soils
Soil biology management	Over application of agrichemicals	Introduction of biotic organisms
	Industrial contamination	Nitrogen fixing micro organisms
Vegetation management	Decline in vegetative cover	Increased vegetation cover
	Decline in biodiversity	Increased species diversity
	Decline in species composition	Improved species composition
	Decline in availability of valued species	Improved availability of valued species

Tillage, soil leveling, root crop harvesting, and animal trampling or burrowing all contribute to disturbance or translocation erosion. Strong air currents that transport exposed soil particles into the wind and waves erode the coast, respectively. Other notable erosion processes include landslides and debris flows. A hidden type of erosion occurs when subsurface water flows dissolve mostly carbonate soil minerals. In order for an indicator to be helpful for environmental protection, it must be quantitative, objectively calculated, validated against measurements, and evaluated by experts, according to the Environmental Assessment of Soil for Monitoring (ENVASSO) Project, which identified and evaluated the performance of a number of soil erosion indicators.

However, policymakers urge the mapping of soil erosion risk areas under current land use and climate so that appropriate measures to control erosion can be taken within the legal and social context of natural resource management (Jetten et al. 1999). They also call for an overall assessment of the soil erosion in geographical areas of interest. Local, national, and European authorities should be able to provide answers to the questions "where, how much, by what means, and when erosion occurs" based on such information, subject to data availability and reliability (Boardman 2006).

According to (Pimentel et al. 1995), soil erosion has quite serious social repercussions and costs the USA $44 billion annually. According to estimates from SOER (2010) and Kibblewhite et al. (2012), 115 million acres in Europe are affected by erosion. The European Soil Data Centre (ESDAC) has been established at the Joint Research Centre, Ispra (I), in response to recent developments in soil policy at the European level (Panagos et al. 2012), to provide a mechanism for reporting crucial information on soil in the Member States of the European Union (EU).

Soil Erosion Impact

Soil erosion exerts considerable influence on environmental integrity, agricultural efficiency, and the quality of aquatic systems, this phenomenon propelled by elements including climatic change, rigorous agricultural approaches and modifications in land utilizations, resulting in a series of ecological repercussions. It plays a pivotal role in in the depletion of topsoil,which is essential for vegetative development, subsequently resulting in diminished agricultural productivity (Weslati & Serbaji, 2023).The eroded soil transport vital nutrients in to aquatic system, thereby impairing water quality and adversely affecting aquatic biomes (Slayi et al., 2024). The escalations of sediment deposition can hider watercourses, impacting infrastructures such as reservoirs, and irrigation networks, consequently leading to reduction in agricultural yields.Climate change intensifies soil erosion through augmented precipitation intensity and frequency, which exacerbates soil depletion (Mandal & Roy, 2024). The depletion of soil carbon due to intensified erosion further accelerates climate change, as the eroded soil liberates sequestered carbon into the atmosphere. The implementation of regenerative agriculture strategies, including cover cropping and agroforestry, has the potential to alleviate soil erosion while simultaneously improving soil fertility (Kodaparthi et al., 2024). Comprehensive management frameworks are imperative for safeguarding biodiversity and ensuring sustainable land utilization (Moutaoikil et al., 2024). In contrast, while soil erosion presents considerable obstacles, it concurrently offers prospects for innovation in land management strategies. The embrace of sustainable agricultural practices cannot only address erosion challenges but also enhance overall ecosystem resilience and productivity.

Soil Erosion Impacts on Nutrient Mobilization

Soil erosion exerts a huge influence on the mobilization of nutrients, thereby affecting both soil fertility and the overall health of the ecosystems. The processes associated with soil erosion results in the depletion of vital nutrients such as nitrogen, phosphorus, and potassium which are essential for the optimal growth of plants. Water erosion can precipitate considerable losses of mineral nitrogen alongside bioavailable phosphorus and potassium, particularly in slope terrains(Kuncheva & Dimitrov, 2020). Stream bank failures plays a significant role in in the mobilization of sediments and nutrients with augmented sediments loads being directly associated with elevated concentration of nutrients specially, phosphorus (Ramos et al., 2022). A notable loss of phosphorus fraction occurs in particulate matter during runoff events, underscoring the pivotal role of erosion in the transportation of nutrients (Mardamootoo et al., 2015). Erosion has the capacity to modify the spatial distribution of soil organic carbon (SOC); impacting the cycling of nutrients. The burial of soils induced by erosion served to stabilize nutrient reservoirs, thereby enhancing primary productivity (Quinton et al., 2010). Although soil erosion is frequently perceived negatively due to the resultant nutrient depletion, it also promotes the redistributions of nutrients potentially augmenting soil fertility under specific circumstances. A comprehensive understanding of these dynamics is essential for the formulation of effective land management strategies.

The annual fluxes of 2.1–3.9 Tg of organic phosphorus and 12.5-22.5 Tg of inorganic phosphorus are attributed to soil erosion. These estimates are unsure, nevertheless, due to the scant availability of data on global soil phosphorus. However, they are comparable in size to crop intake (14 Tg/yr) and fertilizer phosphorus inputs to agricultural land (18 Tg/yr). Global mean phosphorus fluxes are significantly lower than the 40 Pg of phosphorus retained in soils globally (Smil, V 2002).

Soil Erosion Impact on Nutrient Cycles

Prior studies on how erosion affects nitrogen and phosphorus cycling have mainly examined how nutrients are mobilized and delivered to aquatic ecosystems. Less is understood about how erosion affects the cycling of phosphorus and nitrogen in terrestrial settings. Large amounts of nitrogen and phosphorus are present in soil organic matter. As a result, increased soil mineralization brought on by soil mobilization will result in a relative rise in dissolved nitrogen and phosphorus (Jacinthe, P. A. et al. 2002). The biota will have easier access to these dissolved forms than to particulate or organic forms. The stabilization of organic nitrogen, on the other hand, will result from the burial and preservation of deposited carbon. The rate of carbon mineralization largely determines how stable nitrogen is in depositional environments, where it may be high. This may explain why topsoil C:N ratios are surprisingly stable within a specific biological setting and why palaeosol investigations show C:N values that are comparable to those found in modern soils (Inoue, Y., et al., 2009). Nitrogen will stabilize in eroding sites as a result of dynamic replenishment of carbon. In some situations, nitrogen availability may directly limit biomass output and consequently dynamic replacement (Van Groenigen, K.-J. et al. 2006), suggesting that nitrogen may also regulate carbon cycle.

In fact, erosion is a key mechanism for the longer-term fall in soil phosphorus levels (Filippelli, G. M. 2008). This is caused by a combination of physical phosphorus removal, exposure of lower phosphorus-containing subsoil, and the interaction between erosion rates and chemical weathering. The phosphorus in the soil profile shifts from a mixture of mineral, occluded, non-occluded, and organic forms to a mixture that is predominately organic and occluded as phosphorus levels fall over time (Filippelli, G. M. 2008). Sediment can be a significant source of phosphorus in depositional areas. Dust deposition, for instance, in Hawaii can help to some extent with the phosphorus limitation of forest growth on old soils (Chadwick, O. et al. 1999).

Soil Erosion Implications for Soil Function

According to Woodward, F. I., et al. (2009) and Reay, D., et al. (2008), alterations brought on by erosion have an impact on a variety of soil processes. For instance, variations in the relative availability of carbon and nitrogen in soil organic matter were a key determinant of the dynamics of microbial nitrogen mineralization and immobilization, and consequently, the supply of nitrogen to plants (Kaye, J. P. and Hart, S. C. 1997; Bardgett, R. D. 2005). According to research done by Wardle, D. A., et al. (2004) and Wardle, D. A., et al. (2009), changes in the N:P ratio of soil organic matter had a major impact on nutrient cycling, plant output, and decomposition. These feedbacks are probably most important in nutrient-poor environments, such as the nutrient-poor soils of Africa and Australia. In certain areas, soil erosion brought on by diminished plant cover and the loss of soil carbon can cause catastrophic transitions to a severely degraded condition (Berhe, A., et al., 2007). By speeding up erosion through these mechanisms, land use change may result (Bakker, M. M. et al., 2005), which in turn alters the rate of biogeochemical cycling and affects atmospheric composition and climate change (Feddema, J. J. et al., 2005), further disrupting the cycling of carbon, nitrogen, and phosphorus.

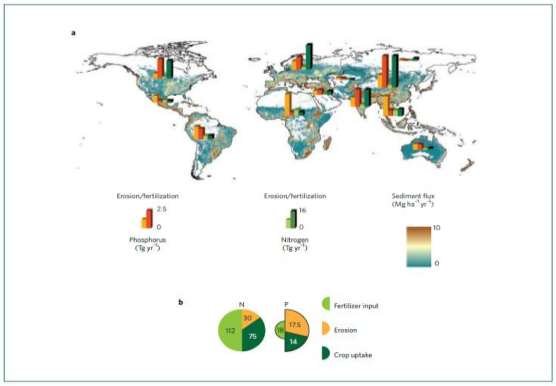


Figure 2 Global fluxes of sediment, nitrogen and phosphorus

a, Shaded areas show the global distribution of sediment fluxes derived using methods described in Supplementary Information S2. Bars show the continental fluxes of nitrogen and phosphorus by water and tillage erosion compared with fertilizer use. **b**, Global fluxes of nitrogen and phosphorus ($Tgyr^{-1}$) due to fertilizer input, erosion and crop uptake

Impact of Soil Erosion on Agriculture

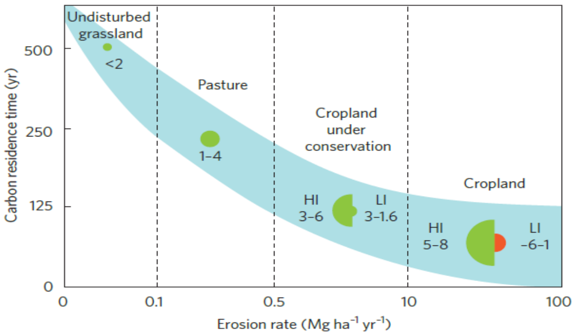
According to (M. Kouli et al., 2009), water-induced soil erosion is a serious environmental problem that negatively affects the character of top soil, depletes essential minerals, and lowers agricultural productivity (M. Jothimani et al., 2022). This problem is especially prevalent in developing countries like Ethiopia, where agriculture serves as the backbone of the economy (Bufebo & Elias, 2020). Rural land use systems claim that issues with soil disintegration, sedimentation, and cleansing were persistent environmental issues in a particular region of Ethiopia (Moisa et al., 2022). Agricultural soil sustainability, which accounts for approximately 95% of the world's food security, determines the standard of life for humans (Duguma, 2022). An empirical model called the revised universal soil loss equation (RUSLE) has been applied globally to prioritize conservation efforts and forecast soil erosion loss using GIS in high-erosional areas (Hurni, 1985a). Poor management caused soil erosion, which harmed over 65% of the soil in Sub-Saharan African countries. According to ((Tessema& Simane, 2019), Ethiopia is exceptionally vulnerable to climate change, which directly affects soil characteristics, especially in the highlands of the research region. Horo district, one of Ethiopia's highlands, is at risk of soil disintegration due to human causes brought on by population increase and other variables that depend on the soil and the surrounding environment. These regions are susceptible to crevasse formation and sheet erosion due to the steep slopes that are there and the sensitive character of the area that recently formed on steep upper inclines. This provides unequivocal proof that soil efficiency for agricultural production and other services is negatively impacted by excessive levels of soil erosion. Land, however, is attracting more and more interest (Olika & Iticha, 2019). The biggest contributor to soil degradation in Ethiopia's highlands is often agricultural practices (Moisa et al., 2022).

The amount of soil erosion in Ethiopia varies depending on the environmental conditions like the slope of the land, temperature, rainfall amount and frequency, soil type, and human influence. Research conducted in the Anger River sub-basin showed that 43.6% and 8.4% of soil loss was very severe and severe, respectively (Moisa et al., 2022). A similar study in the Kulfo river catchment showed that 30% and 27% of the total area had very severe and very light soil loss, respectively. To prevent such sedimentation, a lot of money is needed, as shown in the Fincha'a watershed, where the mean annual soil loss rate was 33.66ton/ha/yr. In the Gudar sub-watershed, the mean annual soil eroded was 25.23ton/ha/yr, and near the study area in Fincha'a watershed, annual soil loss was categorized into four ranges, with the highest range being higher than 75 ton/ha/yr(Duguma, 2022); (Tamiru & Wagari, 2021). So it's clear that the severity of soil loss in the country varies from place to place (Jothimani et al., 2022).

Consequences of soil erosion on Carbon Cycle

Mobilization, transport, and deposition of soil detachments are all included in soil erosion. Considering each of these stages is necessary to comprehend how erosion affects the carbon cycle. The soil structure is at least partially affected when soil material is mobilized. The rate of soil organic carbon (SOC) mineralization may significantly increase during or shortly after sediment mobilization, according to laboratory research, which might result in the loss of over 20% of the total SOC as carbon dioxide (Lal, 2003).

The fate of SOC that is delivered to rivers should be distinguished from SOC that is transported over a relatively small distance (500 m) by water or tillage over a short period of time (1 day) and deposits in a local depositional store. Field observations suggest that the additional SOC mineralization that happens during soil transport over land is comparatively insignificant; erosion-deposition simulations based on 137Cs inventories reveal that the carbon inventory found at depositional sites is incompatible with significant mineralization during the transport (Van Oost et al., 2009). Additionally, recent field measurements indicated that SOC losses from soil that is re-deposited after a brief transport phase are relatively insignificant for the global carbon budget (Van Hemelryck et al., 2009), coming in at only 2.5% of eroded SOC. However, a significant quantity of SOC that is discharged into rivers was mineralized there (Cole et al., 2007).



Erosion rate (Mg ha^{-1}yr^{-1}

Figure 3 interplay between soil erosion, land use/soil management and carbon cycling at sites of erosion.

The blue shaded area reflects possible combinations of carbon residence time (1/decomposition rate) and erosion rates as a function of land use/management. The numbers (g C m^{-2}yr^{-1}) and size of the circles represents the maximum size of the carbon sink (positive, green) or source (negative, red). For croplands, the data represent high input systems (HI, low sensitivity of yield decline to erosion, 4% per 0.1 m erosion) and low-input systems (LI, high sensitivity of yield decline to erosion, 15% per 0.1 m erosion).

Erosion causes the instantaneous release of carbon dioxide by disrupting the soil's structural integrity. Increased emissions over extended periods of time are linked to a decrease in the ability of eroded soils to support plant development (van de Koppel et al., 1997), which led to a reduction in the carbon input from plant and root matter (Berhe et al., 2007). Erosion causes the ploughed layer to get mixed with carbon-poor subsoil. If the recently exposed mineral surfaces bind organic materials, soil carbon stocks could rise. Because sediment is buried in depositional environments, the encouragement of carbon sequestration by erosion depends on lower rates of SOC breakdown. Although the mechanisms that contribute to the decrease in decomposition at depth (Rosenbloom et al., 2006), had recently come to light, the burial of pedogenic carbon at sites of deposition had repeatedly been shown to stabilize soil carbon over timescales of several decades, resulting in decreased emissions of carbon dioxide (Van Oost et al., 2007). In addition, in depositional settings where net primary output exceeds that in the source regions, mineralization can be deliberately controlled. By reducing the concentration of soil carbon, the inflow of low-carbon sediments into wetlands and lowland valley bottoms, encourage net carbon sequestration ((Stallard, 1998). Overall, the amount of the depositional accumulation dynamically replaced by freshly created plant-derived soil carbon at eroding locations determines how much mobilization and deposition lead to carbon storage (Harden et al., 1999).

Fate of Soil Organic Carbon on Erosion

In agricultural landscapes, erosion and deposition redistribute significant amounts of mineral soil and soil organic carbon (SOC) and erosion rates are one to two orders of magnitude higher than in areas with native vegetation (Quinton et al., 2010). In the context of the global carbon cycle, the relationship between sedimentary processes, the fate of eroded SOC, and its replacement at the site of erosion are of special interest; (Quinton et al., 2010). A key information gap in our understanding of the global carbon cycle is the exchanged of carbon between agricultural soils and the atmosphere, which resulted in sequestration or emission (source or sink of CO_2) (Berhe et al., 2007). Alternatively the land use carbon source has the largest uncertainties in the global carbon budget, as stated by (Menon et al., 2007). The soil carbon pool is larger than both the biotic/vegetational and atmospheric pools by 4.1 and 3.3 times, respectively, and is predicted to be 2300 Gt C with 1500 Gt of organic C (Berhe et al., 2007); (Lal, 2010). 4% of the total SOC pool is released annually, which is 10 times the emission from fossil fuels (Lal, 2003). Agricultural soils can act as a net source or sink of atmospheric CO_2; a positive balance indicates sequestration by SOC buildup (sink), whereas a negative balance indicates CO_2 emission (source). Recent rapidly rising atmospheric CO_2 concentrations have sparked particular interest in agricultural land's ability to store carbon through a combination of reduced emission and expanded, long-term SOC storage (Gregorich, Rochette, et al., 1998); (Post et al., 2004). Despite this, the dynamics of the SOC pool are complicated and heterogeneous, making it difficult to estimate the effects of erosion, transport, deposition, and agricultural disturbances on lateral and vertical SOC fluxes (Smith et al., 2001); (Doetterl et al., 2012). According to Liu et al. (2003), increasing levels of physicochemical protection are found among various soil fractions (differentiated by density fractionation), and SOC, a significant portion of soil organic matter (SOM), has a variety of characteristics that can affect mineralization.

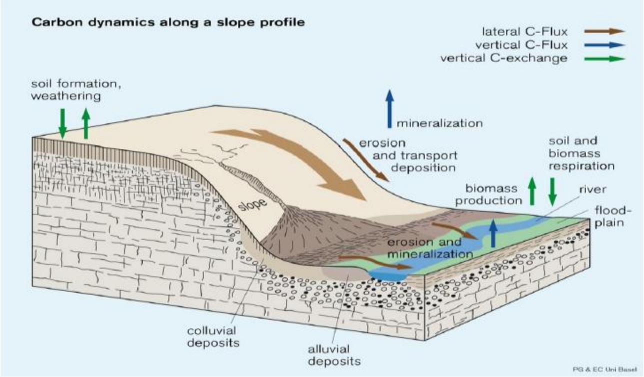


Figure 4 Carbon dynamics along a slope profile

Itshows interactions between biomass production, soil formation, erosion and deposition processes and their effects on lateral and vertical carbon fluxes on landscape scale in a terrestrial system with an adjacent aquatic environment**.**

Tillage Effects on Soil Erosion and SOC Dynamics

Since the advent of mechanized agriculture (Van Oost et al., 2005), tillage-induced erosion has been recognized as the major process on cropped fields, accounting for significant soil redistribution. According to (Quinton et al., 2006), different tillage techniques have an impact on the rates of carbon mobilization by tillage erosion. While other researchers (Van Hemelryck et al., 2009), observed more significant contributions from water erosion, possibly because of different soil properties, (Van Oost et al., 2005), ascribed over 80% of soil redistribution on agricultural land to tillage erosion. SOC and sediment losses from convexities (crests and divergent shoulders) and accumulation in concavities (valleys and foot slopes) are typical characteristics of redistribution patterns caused by tillage (Van Oost et al., 2006). However, they differ from the topographic signature caused by water erosion (Doetterl et al., 2012), and are difficult to identify from natural, diffusive geomorphologic processes.

The tillage process has both positive and negative effects on SOC dynamics. Tillage improves mineralization by bringing organic carbon to the surface and fostering conditions for decomposition, but it also reduces the amount of SOC in the topsoil by mixing passive and active SOC in the subsurface (Renwick et al., 2004). Despite the significant amounts that tillage and tillage erosion mix and transfer the net impact on soil-atmosphere exchange and the carbon budget is still poorly understood. This interpretation is disputed by (Van Oost et al., 2005), who view tilled land as a sink on a landscape scale with a net uptake of 3 4 g C m^{2}due to soil admixture, rapid carbon fixation (dynamic replacement), and burial, which produce significant carbon stocks at depositional sites. With source perspective, it is stated that switching to non-tillage farming reduces carbon emissions by 3–3.5 g C m^{2}, increasing on-site SOC storage. However, the trade-off between tillage and non-tillage management requires detailed knowledge of the magnitude and dynamics of tillage-induced SOC redistribution (Van Oost et al., 2004).

Dynamic Replacement and Mineralization at Eroding Sites

In particular, the non-linear relationship between soil erosion and net primary output makes the dynamic replacement of SOC by biomass production at eroding sites a contentious topic (Gregorich, Greer, et al., 1998). According to (Lal & Pimentel, 2008), erosion leads to the deterioration of soil properties (such as loss of nutrients, soil structure, and water retention capacity), which results in low agronomic productivity even when fertilizers are used. According to the theory, the lower carbon returns have an aggravating feedback effect, causing the carbon stock to decline when carbon replacement rates fall below erosion rates. In contrast, some researchers discovered that in agricultural systems, eroded SOC is restored by net primary production, leading to dynamic loss and replacement of carbon (Smith et al., 2001). Low to moderate erosion rates can encourage carbon sequestration because they stimulate carbon uptake by continually removing a portion of SOC that can be supplemented by increased plant input.

Dynamic replacement and mineralization occurring at sites undergoing erosion entails intricate interaction among soil processes, vegetation and transformation of minerals. The process of erosion has the potential resulted in considerable losses of carbon, which is estimated that nearly 100 % of the prehistoric soils carbon was depleted over a span of 127 years characterized by intensive agricultural practices (Harden et al., 1999). The ultimate fate of eroded carbon is paramount importance as it can either exacerbate carbon dioxide emission or contribute carbon sequestration, contingent upon the rates of decomposition occurring in various landscape positions (Harden et al., 1999). Areas experiencing erosion are characterized by elevated levels of mineral nitrogen and enhanced rates of net mineralization when compared to zones of deposition, with notable seasonal fluctuations (Kong et al., 2022). The removal of vegetation resulted in increased concentration of soil mineral nitrogen; however it does not substantially influence the rates of net nitrogen mineralization, underscoring the predominant role of soil characteristics over the effects of vegetation (Kong et al., 2022).

Conversely, while the process of erosion facilitates the increased rates of mineralization, it also has the potential to induce-long term degradation of soil quality, thereby underscoring the necessity for the implementation of sustainable land management practices aimed at reconciling these dynamic interactions.

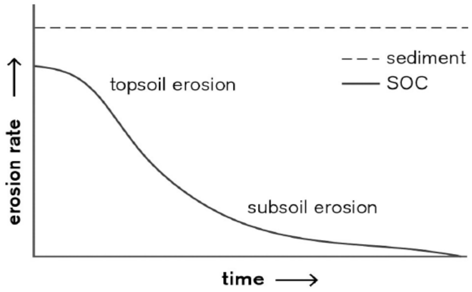


Figure 5 Conceptual relation of the discrepancy between sediment and SOC erosion

SOC erosion on temporal scale, showing a decline in SOC erosion over time owing to the differential depth distribution of carbon quantity and quality within the soil profile, while sediment erosion is constant

Transport of soil and SOC along hill slopes

The connection between depositional and eroding zones is the transport channel. The carbon budget on hill slope and landscape scale is impacted by transport on eroded SOC ((Quinton et al., 2010); (Kuhn et al., 2009). The transport of SOC can lead to mineralization, deposition on an eroded or intact depositional site, in an aquatic environment, or to a net C flux to the atmosphere. The carrying capacity of the transporting agent determines the type of movement (Jacinthe et al., 2001). Clays and labile SOC are two examples of the light fractions that are carried more preferentially over longer distances (Starr et al., 2000). Differentiation takes place along the way depending on the mode of transportation, resulting in the enrichment of SOC in sediments after water erosion and increasing with distance from the source area, resulting in high SOC levels in suspended sediments ((Van Oost et al., 2007); (Wang et al., 2010). According to Kuhn et al. (2009), the degree of enrichment is positively connected with the hydraulic nature (roughness) of the landscape.

Mineralization during Transport

A significant problem with significant effects on the carbon balance on a landscape scale is the mineralizationof SOC during transit. By assuming that 20% of the eroded SOC will be released, and his colleagues presuppose a substantial source (Lal, 2003); (Jacinthe et al., 2002).(Renwick et al., 2004) and Smith et al. (2005) doubt the validity of this assumption. Notably, this results indirectly from the finding that hardly much SOC is exported to the ocean. However, this assumption can be disputed because sediment and SOC are temporarily stored in a catchment as its size increases (Trimble, 1983), which leads to a discrepancy between on-site erosion and the amount of sediment delivered to areas downstream (Chaplot & Poesen, 2012)

Towards Clarification of The Sink/Source Controversy

Agreement among scholars has not been achieved (yet) about the fate of soil organic carbon in agricultural landscapes. Research on soil erosion in agricultural settings has traditionally concentrated on on-site quality loss and decreased crop yield, as well as off-site effects associated to sediment loading and deposition (Morgan, 2009)

It is impossible to overstate the significance of SOC's fate and its lateral and vertical fluxes when examining the consequences for carbon cycling, though. In addition to the sink/source debate, the estimated strength of the sink and source indicates that researcher' assessments of the scale and directions of the major processes vary.

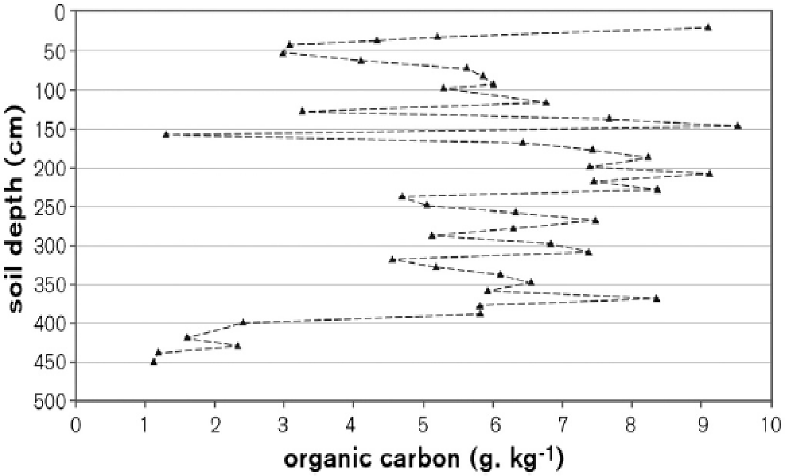


Figure 8

Example of a soil profile showing highly variable SOC contents over depth, reflecting a very dynamic spatio-temporal input of SOC in sediment behind a small retention dam (Upper Lorca basin, SE Spain) on marl and calcareous substratum, deposited in about 60 years.

To determine the fate of SOC, it is essential to conduct eco-geomorphological research, as well as geomorphological, pedological, and biological studies in conjunction with an analysis of SOC dynamics at large spatiotemporal scales. This study should concentrate on eroding sites to determine the extent of dynamic replacement, the length of time it was subject to erosion, and the effects on mineralization, transport processes to comprehend patterns of redistribution and mineralization during transport, and depositional sites to record erosion processes and determine the effects of deep burial. An eco-geomorphologic strategy that incorporates cutting-edge field, laboratory, and modeling techniques can make a significant contribution to the resolution of these urgent concerns. This offers pertinent guidelines for future study in conjunction with a thorough assessment of present constraints.

Conclusions

Soil degradation poses profound challenges to agricultural productivity and ecological balance, influenced by interplay of anthropogenic and natural determinants. Practices that are unsustainable in agriculture, along with deforestation, urban expansion, over grazing and industrial operations, markedly exacerbates the deterioration of soil quality. Such activities interfere with the structural integrity of soil, diminish organic matter content, and precipitate phenomena such as erosion, salinization, and nutrient depletion. The repercussion of soil degradation are extensive, encompassing reduced agricultural yields, heightened susceptibility to climate change, diminished biodiversity, and the disruption of vital ecosystem services, including water purification and carbon sequestration. These consequences jeopardize food security and the economic stability of millions worldwide, especially in areas that are heavily dependent on agricultural activities. Strategies for mitigation, which enclose the adoption of sustainable agricultural approaches, reforestation initiatives soil conservation practices, and pertinent policy reforms, are imperative for the restoration of soil health and the prevention of further degradation. Cooperative endeavors among governmental bodies, communities and various stakeholders are vital to the establishment of the resilient agricultural system and the preservation of ecological integration for future generations. Tackling soil degradation transcends mere environmental necessity; it serves as a fundamental element for sustainable development and the overall well-being of the global community.

References

Abebaw, W. A. (2019). Review on impacts of land degradation on agricultural production in Ethiopia. *J. Resour. Dev. Manag*, *57*.

Amede, T., Belachew, T., & Geta, E. (2001). Reversing the degradation of arable land in the Ethiopian Highlands. *Managing Africa's Soils; No. 23*.

Benavidez, R., Jackson, B., Maxwell, D., & Norton, K. (2018). A review of the (Revised) Universal Soil Loss Equation ((R) USLE): With a view to increasing its global applicability and improving soil loss estimates. *Hydrology and Earth System Sciences*, *22*(11), 6059–6086.

Berhe, A. A., Harte, J., Harden, J. W., & Torn, M. S. (2007). The significance of the erosion-induced terrestrial carbon sink. *BioScience*, *57*(4), 337–346.

Berry, J. W. (2003). Conceptual approaches to acculturation. *Acculturation: Advances in Theory, Measurement, and Applied Research/American Psychological Association*.

Berry, L., Olson, J., & Campbell, D. (2003). Assessing the extent, cost and impact of land degradation at the national level: findings and lessons learned from seven pilots. *World Bank*.

Bezuayehu, T., Gezahegn, A., Yigezu, A., Jabbar, M. A., & Paulos, D. (2002). Nature and causes of land degradation in the Oromiya Region: A review. *Socio-Economics and Policy Research Working Paper*, *36*, 34.

Bishaw, B. (2001). Deforestation and land degradation in the Ethiopian highlands: a strategy for physical recovery. *Northeast African Studies*, 7–25.

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., & Ferro, V. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, *8*(1), 1–13.

Bossio, D., Noble, A., Pretty, J., & Penning de Vries, F. (2004). Reversing land and water degradation: trends and 'bright spot'opportunities. *SIWI/CA Seminar, Stockholm, Sweden*, *21*.

Bufebo, B., & Elias, E. (2020). Effects of land use/land cover changes on selected soil physical and chemical properties in Shenkolla watershed, south Central Ethiopia. *Advances in Agriculture*, *2020*(1), 5145483.

Chaplot, V., & Poesen, J. (2012). Sediment, soil organic carbon and runoff delivery at various spatial scales. *Catena*, *88*(1), 46–56.

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., & Middelburg, J. J. (2007). Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. *Ecosystems*, *10*, 172–185.

Constable, M. (1985). Ethiopian Highlands Reclamation Study (EHRS): Summary EHRS. *FAO/MoA Joint Project, Addis Ababa*.

Critchley, W., Harari, N., Mollee, E., Mekdaschi-Studer, R., & Eichenberger, J. (2023). Sustainable land management and climate change adaptation for small-scale land users in Sub-Saharan Africa. *Land*, *12*(6), 1206.

Doetterl, S., Van Oost, K., & Six, J. (2012). Towards constraining the magnitude of global agricultural sediment and soil organic carbon fluxes. *Earth Surface Processes and Landforms*, *37*(6), 642–655.

Duguma, T. A. (2022). Soil erosion risk assessment and treatment priority classification: A case study on guder watersheds, Abay river basin, Oromia, Ethiopia. *Heliyon*, *8*(8).

Ekka, P., Patra, S., Upreti, M., Kumar, G., Kumar, A., & Saikia, P. (2023). Land Degradation and its impacts on Biodiversity and Ecosystem services. *Land and Environmental Management through Forestry*, 77–101.

Estefanos Shanko, E. (2023). Land Degradation Causes, Consequences and Sustainability of the Restoration Efforts: The Case of Soro Wereda, Hadiya Zone, Southern Ethiopia. *International Journal of Sustainable Development Research*, *9*(2), 18–27. https://doi.org/10.11648/j.ijsdr.20230902.11

Foster, G. R., Toy, T. E., & Renard, K. G. (2003). Comparison of the USLE, RUSLE1. 06c, and RUSLE2 for application to highly disturbed lands. *First Interagency Conference on Research in Watersheds*, *27*(30), 154–160.

Girma, T. (2001). *Land Degradation A Challenge to Ethiopia International Livestock Research institute Environmental Management Vol. 27, No. 6*. Springer Verlag New York Inc.

Gregorich, E. G., Greer, K. J., Anderson, D. W., & Liang, B. C. (1998). Carbon distribution and losses: erosion and deposition effects. *Soil and Tillage Research*, *47*(3–4), 291–302.

Gregorich, E. G., Rochette, P., McGuire, S., Liang, B. C., & Lessard, R. (1998). *Soluble organic carbon and carbon dioxide fluxes in maize fields receiving spring- applied manure*. Wiley Online Library.

Guo, M., Zhang, T., Li, Z., & Xu, G. (2019). Investigation of runoff and sediment yields under different crop and tillage conditions by field artificial rainfall experiments. *Water*, *11*(5), 1019.

Harden, J. W., Sharpe, J. M., Parton, W. J., Ojima, D. S., Fries, T. L., Huntington, T. G., & Dabney, S. M. (1999). Dynamic replacement and loss of soil carbon on eroding cropland. *Global Biogeochemical Cycles*, *13*(4), 885–901.

Hawando, T. (1997). Desertification in Ethiopian highlands. *Rala Report*, *200*.

Hurni, H. (1985a). An ecosystem approach to soil conservation. *Soil Erosion and Conservation*, *73*, 759–771.

Hurni, H. (1985b). *Erosion-productivity-conservation systems in Ethiopia*.

Hurni, H. (1987). *Ethiopia Northern Shewa Administrative Zone: Programme document: Merhabete Integrated Conservation and Development Programme (ICDP): First 5-year phase*.

Hurni, H., Abate, S., Bantider, A., Debele, B., Ludi, E., Portner, B., Yitaferu, B., & Zeleke, G. (2010). *Land degradation and sustainable land management in the highlands of Ethiopia*.

Jacinthe, P.-A., Lal, R., & Kimble, J. M. (2002). Carbon dioxide evolution in runoff from simulated rainfall on long-term no-till and plowed soils in southwestern Ohio. *Soil and Tillage Research*, *66*(1), 23–33.

Jothimani, M., Getahun, E., & Abebe, A. (2022). *Remote sensing, GIS, and RUSLE in soil loss estimation in the Kulfo river catchment, Rift Valley, Southern Ethiopia*.

Keay, R. W. J. (1987). The IUCN Sahel Report: A Long-term Strategy for Environmental Rehabilitation. International Union for Conservation of Nature and Natural Resources, World Conservation Centre, Avenue-du Mont-Blanc, CH-1196, Gland, Switzerland: 80 pp., illustr., 29.25× 21× . *Environmental Conservation*, *14*(4), 379.

Kenneth, G. R., George, R. F., Glenn, A. W., & Jeffrey, P. P. (1997). RUSLE: Revised universal soil loss equation. *J. Soil Water Conserv*, *46*, 30–33.

Kodaparthi, A., Ranjit, P., Deepu, P. G., Kaushik, D. M., Valli, L. A., Ashrutha, P., Harihara, J., & Chepuri, K. (2024). Impact of Regenerative Agriculture on Soil Erosion. In *Prospects for Soil Regeneration and Its Impact on Environmental Protection* (pp. 269–295). Springer.

Kong, W., Yao, Y., Hou, L., Wang, X., & Wei, X. (2022). Site and landscape position-dependent effects of vegetation removal on soil nitrogen mineralization across five sites on China's Loess Plateau. *Catena*, *215*, 106336.

Kuhn, N. J., Hoffmann, T., Schwanghart, W., & Dotterweich, M. (2009). Agricultural soil erosion and global carbon cycle: controversy over? *Earth Surface Processes and Landforms*, *34*(7), 1033–1038.

Kuncheva, G. S., & Dimitrov, P. D. (2020). Loss of nutrients by soil water erosion. *2020 7th International Conference on Energy Efficiency and Agricultural Engineering (EE&AE)*, 1–5.

Lal, R. (2003). Soil erosion and the global carbon budget. *Environment International*, *29*(4), 437–450.

Lal, R. (2010). Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *BioScience*, *60*(9), 708–721.

Lal, R., & Pimentel, D. (2008). Soil erosion: a carbon sink or source? *Science*, *319*(5866), 1040–1042.

Lemenih, M. (2004). *Effects of land use changes on soil quality and native flora degradation and restoration in the highlands of Ethiopia: Implications for sustainable land management* (Issue 306).

Mandal, D., & Roy, T. (2024). Climate Change Impact on Soil Erosion and Land Degradation. In *Climate Change Impacts on Soil-Plant-Atmosphere Continuum* (pp. 139–161). Springer.

Mandal, D., & Sharda, V. N. (2013). Appraisal of soil erosion risk in the Eastern Himalayan region of India for soil conservation planning. *Land Degradation & Development*, *24*(5), 430–437.

Mardamootoo, T., du Preez, C. C., & Sharpley, A. N. (2015). Phosphorus mobilization from sugarcane soils in the tropical environment of Mauritius under simulated rainfall. *Nutrient Cycling in Agroecosystems*, *103*, 29–43.

McGregor, K. C., & Mutchler, C. K. (1976). Status of the R factor in northern Mississippi. *Soil Erosion: Prediction and Control, Soil Conservation Soc. Amer*, 135–142.

Menon, S., Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C., & Holland, E. (2007). *Couplings between changes in the climate system and biogeochemistry*. Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).

Moisa, M. B., Dejene, I. N., Merga, B. B., & Gemeda, D. O. (2022). Impacts of land use/land cover dynamics on land surface temperature using geospatial techniques in Anger River Sub-basin, Western Ethiopia. *Environmental Earth Sciences*, *81*(3), 99.

Morgan, R. P. C. (2009). *Soil erosion and conservation*. John Wiley & Sons.

Moutaoikil, N., Benzougagh, B., Mastere, M., El Fellah, B., & Lamrani, H. (2024). The impact of soil erosion on environments: A case study of the Oued Beht Watershed (Morocco). *BIO Web of Conferences*, *115*, 1006.

Nizam Kamaruzzaman, S., & Marinie Ahmad Zawawi, E. (2010). Development of facilities management in Malaysia. *Journal of Facilities Management*, *8*(1), 75–81.

Oldeman, L. R. (1992). Global extent of soil degradation. In *Bi-annual report 1991-1992/ISRIC* (pp. 19–36). ISRIC.

Olika, G., & Iticha, B. (2019). Assessment of soil erosion using RUSLE and GIS techniques: A case of Fincha'a Watershed, Western Ethiopia. *American-Eurasian Journal of Agricultural & Environmental Sciences*, *19*(1), 31–36.

Pender, J. L., Hagos, F., & Gebreselassie, N. (2012). *Land degradation in the highlands of Tigray and strategies for sustainable land management.*

Post, W. M., Izaurralde, R. C., Jastrow, J. D., McCarl, B. A., Amonette, J. E., Bailey, V. L., Jardine, P. M., West, T. O., & Zhou, J. (2004). Enhancement of carbon sequestration in US soils. *Bioscience*, *54*(10), 895–908.

Quinton, J. N., Catt, J. A., Wood, G. A., & Steer, J. (2006). Soil carbon losses by water erosion: experimentation and modeling at field and national scales in the UK. *Agriculture, Ecosystems & Environment*, *112*(1), 87–102.

Quinton, J. N., Govers, G., Van Oost, K., & Bardgett, R. D. (2010). The impact of agricultural soil erosion on biogeochemical cycling. *Nature Geoscience*, *3*(5), 311–314.

Ramos, M. C., Lizaga, I., Gaspar, L., & Navas, A. (2022). *P mobilization by an extreme rainfall event and its spatial variability in an agroforestry South-Pyrenean catchment.* Copernicus Meetings.

Renwick, W. H., Smith, S. V, Sleezer, R. O., & Buddemeier, R. W. (2004). Comment on" managing soil carbon"(ii). *Science*, *305*(5690), 1567.

Rosenbloom, N. A., Harden, J. W., Neff, J. C., & Schimel, D. S. (2006). Geomorphic control of landscape carbon accumulation. *Journal of Geophysical Research: Biogeosciences*, *111*(G1).

Scherr, S. J. (2000). A downward spiral? Research evidence on the relationship between poverty and natural resource degradation. *Food Policy*, *25*(4), 479–498.

Scherr, S. J., & Yadav, S. N. (1996). *Land degradation in the developing world: Implications for food, agriculture, and the environment to 2020.*

Sharda, V. N., Dogra, P., & Prakash, C. (2010). Assessment of production losses due to water erosion in rainfed areas of India. *Journal of Soil and Water Conservation*, *65*(2), 79–91.

Shepherd, G., Terradellas, E., Baklanov, A., Kang, U., Sprigg, W., Nickovic, S., Darvishi Boloorani, A., Al-Dousari, A., Basart, S., & Benedetti, A. (2016). *Global assessment of sand and dust storms.*

Singh, R. K., Chaudhary, R. S., Somasundaram, J., Sinha, N. K., Mohanty, M., Hati, K. M., Rashmi, I., Patra, A. K., Chaudhari, S. K., & Lal, R. (2020). Soil and nutrients losses under different crop covers in vertisols of Central India. *Journal of Soils and Sediments*, *20*, 609–620.

Slayi, M., Zhou, L., Dzvene, A. R., & Mpanyaro, Z. (2024). Drivers and Consequences of Land Degradation on Livestock Productivity in Sub-Saharan Africa: A Systematic Literature Review. *Land*, *13*(9), 1402.

Smith, S. V, Renwick, W. H., Buddemeier, R. W., & Crossland, C. J. (2001). Budgets of soil erosion and deposition for sediments and sedimentary organic carbon across the conterminous United States. *Global Biogeochemical Cycles*, *15*(3), 697–707.

Sprunger Christine. (2023). *The effect of soil degradation on human, animal and plant health openaccessgovernment.org Dr. Christine Sprunger, soil scientist and ecologist at W.K. Kellogg Biological Station (KBS) and the Department of Plant, Soil, and Microbial Sciences at Michigan S. June*, 1–3.

Stallard, R. F. (1998). Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial. *Global Biogeochemical Cycles*, *12*(2), 231–257.

Stocking, M. (2006). Land Degradation as a Global Environmental Issue: A Synthesis of Three Studies Commissioned by The Global Environment Facility to Strengthen the Knowledge Base to Support The Land Degradation Focal Area. *Report for GEF Council (Report Prepared for Scientific and Technical Advisory Panel, Global Environment Facility, Washington DC).*

Tamiru, H., & Wagari, M. (2021). *Spatio-temporal Analysis of sediment yield estimation using integrated RUSLE and GIS technique: case of Nashe Dam Reservoir, Abay Basin, Ethiopia.*

Tefera, B., Ayele, G., Atnafe, Y., Dubaleb, P., & Jabbarc, M. A. (2000). Nature and causes of land degradation in the Oromiya region: A review of literature. *Policies for Sustainable Land Management in the Highlands of Ethiopia*, 34.

Tessema, I., & Simane, B. (2019). Vulnerability analysis of smallholder farmers to climate variability and change: an agro-ecological system-based approach in the Fincha'a sub-basin of the upper Blue Nile Basin of Ethiopia. *Ecological Processes*, *8*, 1–18.

VAN, C., GENTILE, A.-R., BUJARRABAL, B., JONES, R., MONTANARELLA, L., OLAZABAL, C., & SELVARADJOU, S. K. (2004). (n.d.). *Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection. (2004) Vol. VI: Research, Sealing and Cross-Cutting Issues.*

van de Koppel, J., Rietkerk, M., & Weissing, F. J. (1997). Catastrophic vegetation shifts and soil degradation in terrestrial grazing systems. *Trends in Ecology & Evolution*, *12*(9), 352–356.

Van Hemelryck, H., Fiener, P., Van Oost, K., & Govers, G. (2009). The effect of soil redistribution on soil organic carbon: an experimental study. *Biogeosciences Discussions*, *6*(3).

Van Oost, K., Beuselinck, L., Hairsine, P. B., & Govers, G. (2004). Spatial evaluation of a multi‐ class sediment transport and deposition model. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *29*(8), 1027–1044.

Van Oost, K., Cerdan, O., & Quine, T. A. (2009). Accelerated sediment fluxes by water and tillage erosion on European agricultural land. *Earth Surface Processes and Landforms*, *34*(12), 1625–1634.

Van Oost, K., Govers, G. d, De Alba, S., & Quine, T. A. (2006). Tillage erosion: a review of controlling factors and implications for soil quality. *Progress in Physical Geography*, *30*(4), 443–466.

Van Oost, K., Govers, G., Quine, T. A., Heckrath, G., Olesen, J. E., De Gryze, S., & Merckx, R. (2005). Landscape‐ scale modeling of carbon cycling under the impact of soil redistribution: The role of tillage erosion. *Global Biogeochemical Cycles*, *19*(4).

Van Oost, K., Quine, T. A., Govers, G., De Gryze, S., Six, J., Harden, J. W., Ritchie, J. C., McCarty, G. W., Heckrath, G., & Kosmas, C. (2007). The impact of agricultural soil erosion on the global carbon cycle. *Science*, *318*(5850), 626–629.

Vivian, J. (1994). *Environmental degradation and social integration*.

Wang, Z., Govers, G., Steegen, A., Clymans, W., Van den Putte, A., Langhans, C., Merckx, R., & Van Oost, K. (2010). Catchment-scale carbon redistribution and delivery by water erosion in an intensively cultivated area. *Geomorphology*, *124*(1–2), 65–74.

Weslati, O., & Serbaji, M.-M. (2023). *Spatial Assessment of Soil Erosion Using RUSLE Model, Remote Sensing and GIS: A Case Study of Mellegue Watershed, Algeria-Tunisia*.

Zeleke, G., Kassie, M., Pender, J., & Yesuf, M. (2006). SECOND DRAFT Stakeholder Analysis for Sustainable Land Management (SLM) in Ethiopia: Assessment of Opportunities, Strategic Constraints, Information Needs, and Knowledge Gaps. *Environmental Economics Policy Forum for Ethiopia (EEPFE), Addis Ababa*, *96*.