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Assessing the Impacts of Desertification on Soil Organic Carbon: Insights from a Systematic Literature Review

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Abstract
Soil organic carbon (SOC) is a critical component of soil health, ecosystem productivity, and global carbon regulation, yet it is increasingly threatened by desertification processes in dryland environments. This systematic review aims to: (1) assess the impact of desertification on SOC levels, (2) examine the associated environmental and agricultural consequences of SOC decline, and (3) identify sustainable land management (SLM) practices that enhance SOC stocks. A comprehensive literature search and screening process resulted in the inclusion of 90 peer-reviewed studies, significantly expanding the evidence base compared to earlier assessments. The findings reveal a consistently negative relationship between desertification and SOC, with reported SOC losses frequently exceeding 30-50% under conditions of vegetation degradation, soil erosion, and land-use change. Strong statistical associations were identified, including positive relationships between SOC and vegetation indices and negative relationships between SOC and erosion intensity and desertification indices. The review further highlights threshold dynamics, in which SOC depletion beyond critical thresholds reduces soil resilience and accelerates land degradation. Sustainable land management practices, including vegetation restoration, conservation tillage, controlled grazing, and erosion control, were found to significantly enhance SOC, although their effectiveness varies across ecological contexts. Overall, the study underscores the central role of SOC in desertification processes and its importance in achieving Land Degradation Neutrality (LDN). The findings provide critical insights for developing integrated land management strategies to restore SOC, improve soil health, and strengthen climate resilience in dryland ecosystems.

Keywords
Soil organic carbon (SOC); Desertification; Land degradation neutrality (LDN); Soil erosion; Land-use change; Dryland ecosystems

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1. Introduction

The demand for global land resources is increasing as a growing population drives greater demand for food, feed, fibre, biofuels, and other land-based resources (Maggio et al., 2016; D'Odorico et al., 2018). By 2050, the global population is projected to reach 9.7 billion, placing immense pressure on land resources, particularly arable land, which is increasingly being converted to non-agricultural uses such as urban expansion (Sharma et al., 2017). Climate change further exacerbates instability in agricultural systems by reducing the resilience of agro-ecosystems and increasing the frequency and intensity of extreme weather events, thereby threatening global food security (FAO, 2022; Zhou et al., 2019). Together, these pressures accelerate land degradation, a process characterised by a decline in land productivity and the capacity of land to support biodiversity, agriculture, and economic activities (Ajeye, 2014; FAO, 2022). Land degradation is particularly acute in drylands, where desertification poses a significant threat to sustainable land management. Defined by the UNCCD as land degradation in arid, semi-arid, and dry sub-humid areas caused by climatic variations and human activities, desertification is driven by factors such as overgrazing, deforestation, unsustainable agricultural practices, and poor water management (Tsyganko et al., 2024). These processes are especially severe in regions vulnerable to climate-induced stresses, such as sub-Saharan Africa, where declining land productivity has intensified food insecurity, migration, and socio-economic instability (Connolly-Boutin & Smit, 2015; Osborne et al., 2018). Globally, an estimated 2 billion hectares, approximately 25% of total land area, are degraded, affecting the livelihoods of over 5 billion people (AbdelRahman, 2023).

The effects of desertification extend beyond land productivity to critical ecosystem functions, including carbon sequestration, groundwater recharge, and nutrient cycling. Global land conversion trends indicate that approximately 60 million hectares of arable and forested land have been transformed into urban and built-up areas over the past two decades (Mustard et al., 2012; Aycrigg et al., 2022). Similarly, global forest cover declined by 178 million hectares between 1990 and 2020 due to agricultural expansion and urbanisation, reducing the Earth's natural carbon sequestration capacity (FAO, 2020). The interaction between climate change and land degradation not only accelerates desertification but also undermines long-term land productivity, with immediate consequences for water availability, soil health, and crop yields (IPCC, 2023). Soil is one of the most complex and vital components of terrestrial ecosystems, comprising mineral particles, organic matter, water, air, and diverse biological communities. It plays a central role in supporting vegetation, filtering water, recycling nutrients, and storing carbon (Abdalla et al., 2020). The global carbon cycle is heavily dependent on soil organic carbon (SOC), with soils storing approximately 1,500 petagrams of organic carbon - nearly twice the amount present in the atmosphere and three times that in vegetation (Reichstein et al., 2013; Smith, 2008). Desertification severely impacts SOC levels by promoting soil erosion, reducing vegetation-derived carbon inputs, and accelerating the microbial decomposition of organic matter, ultimately releasing greenhouse gases such as CO_2 into the atmosphere and further exacerbating climate change (Ramesh et al., 2019).

At the mechanistic level, desertification alters SOC dynamics through interconnected biological, physical, and chemical processes. Reduced vegetation cover limits the input of organic residues into the soil, thereby decreasing carbon replenishment (Lal, 2004; Ramesh et al., 2019). Simultaneously, increased soil temperature and exposure enhance microbial respiration, accelerating the mineralisation of soil organic matter and the release of CO_2 (Davidson & Janssens, 2006; Conant et al., 2011). Soil disturbance associated with land degradation further exposes previously stabilised organic carbon fractions to oxidation, while wind and water erosion physically remove SOC-rich topsoil layers (Lal, 2003; Six et al., 2002). These combined processes transform soils from stable carbon sinks into net carbon sources, reinforcing atmospheric carbon accumulation and amplifying climate change feedback mechanisms (Schlesinger & Andrews, 2000; Reichstein et al., 2013). The loss of SOC resulting from desertification not only contributes to rising atmospheric CO2 levels but also degrades soil structure, reduces water retention capacity, and diminishes biodiversity, thereby limiting the soil's ability to sustain crops and other vegetation. This challenge is particularly urgent in dryland regions, where approximately one billion hectares in Africa alone are at high risk of desertification (Reshaping the Terrain Forest and Landscape Restoration in Burkina Faso). In arid and semi-arid zones, limited precipitation, high evaporation rates, and fragile soil systems make land degradation more difficult to reverse. Regions such as the Sahel and parts of Asia are projected to become increasingly water-scarce by 2050, underscoring the need for urgent and effective sustainable land management interventions (Alvaro-Fuentes et al., 2014; Li et al., 2017).

The critical role of SOC in mitigating desertification and sustaining soil fertility underscores the importance of adopting practices that preserve or restore carbon stocks. Sustainable land management approaches, such as agroforestry, conservation tillage, cover cropping, and integrated soil management, have demonstrated significant potential to enhance SOC levels and improve overall soil health (Jinger et al., 2023). However, despite the growing body of research on SOC dynamics and land degradation, existing studies remain fragmented, often focusing on isolated drivers or localised case studies without providing a comprehensive synthesis of how desertification processes collectively influence SOC at broader spatial and temporal scales. Furthermore, the interactions between biophysical processes, ecosystem responses, and management interventions are not yet fully integrated within the literature, limiting the ability to develop coherent and scalable mitigation strategies. Without a consolidated understanding of these interrelationships, ongoing land degradation trends are likely to result in severe environmental and socio-economic consequences. It is estimated that land degradation currently imposes economic losses of approximately US$44 trillion annually, representing nearly 40% of global GDP (Eswaran et al., 2019). This highlights an urgent need for evidence-based synthesis to inform policy and practice. Given these gaps, this systematic review aims to examine the impacts of desertification on soil organic carbon (SOC) by synthesising evidence from recent studies. Specifically, the objectives are to: (1) assess how desertification influences SOC levels, (2) examine the broader environmental and agricultural consequences of SOC decline, and (3) identify sustainable land management practices that enhance SOC stocks. By providing an integrated synthesis of current knowledge, this study contributes to global efforts to promote sustainable land management and strengthen climate resilience amid accelerating desertification.

2. Methodology

2.1 Study Design

A systematic literature review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. The systematic review is defined as an 'evidence-based review on multiple questions about a study area or topic, made in order to identify and critique relevant research and to analyse data from multiple studies' (Booth et al., 2010). A systematic review must also be replicable and present the effects, interventions, and gaps in knowledge about the researched topic. This review aimed to investigate the effects of desertification on SOC levels using a meticulous and transparent methodology. The following sub-sections outline the search strategy, study selection criteria, data extraction procedures, quality evaluation, and data synthesis adopted to ensure the review is detailed and replicable.

2.2 Search Strategy

A comprehensive search strategy was employed to identify relevant studies on the impacts of desertification on soil organic carbon. The search was conducted across multiple databases, including Google Scholar, ScienceDirect, ResearchGate, and ProQuest, from 6th September 2024 to 30th September 2024. The search strategy involved pairing primary keywords such as 'Desertification', 'Soil organic carbon', 'Land degradation', 'Soil carbon', 'Semi-arid', 'Arid', 'Impact', 'Effect', and 'Loss'. These keywords were used to form search strings using the Boolean operators 'AND' and 'OR' for each database consulted. The search terms and results for each database are detailed in Table 1.

Table 1. Search terms and results from the databases consulted

Database	Search String	Results
Google Scholar	("soil organic carbon" OR "SOC") AND ("desertification" OR "Forest loss" OR "Vegetation loss") AND ("Soil loss" OR "Soil decline" OR "Soil depletion")	9,890
Science Direct	("soil organic carbon" OR "SOC") AND ("desertification" OR "Forest loss" OR "Vegetation loss") AND ("Soil loss" OR "Soil decline" OR "Soil depletion")	739
ResearchGate	("soil organic carbon" OR "SOC") AND ("desertification" OR "Forest loss" OR "Vegetation loss") AND ("Soil loss" OR "Soil decline" OR "Soil depletion")	100
ProQuest	("soil organic carbon" OR "SOC") AND ("desertification" OR "Forest loss" OR "Vegetation loss") AND ("Soil loss" OR "Soil decline" OR "Soil depletion")	5,174

2.3 Study Selection Criteria

Inclusion and exclusion criteria were established prior to the search. The criteria were designed in line with the objectives of the review and were applied during the eligibility screening process to eliminate papers that did not meet the required standards. Table 2 summarises the inclusion and exclusion criteria used to select documents for the study.

Table 2. Document selection criteria

Criteria	Inclusion	Exclusion
Study Focus	Studies that directly investigate the relationship between desertification and soil organic carbon (SOC) levels	Studies that do not address desertification or SOC specifically
Type of Degradation	Articles examining land degradation processes linked to desertification, such as soil erosion, vegetation loss, and reduced productivity	Research not associated with land degradation, desertification, SOC loss, and in non-arid areas.
Study Methodology	Studies that utilise GIS, remote sensing, soil sampling, empirical data, or modelling approaches to assess SOC levels	Studies lacking empirical data or robust methodology
Publication DateStudies published from 2000 to the present	Studies published before 2000	Studies published before 2014.
Language	Studies published in English	Studies published in languages other than English

2.4 Study Selection Process

Using the PRISMA framework (Figure 1), 18,021 potential documents considered relevant to the study were identified through the database search. Of these, 17,808 documents were discarded due to irrelevant titles and abstracts. A total of 143 documents were considered for full-text screening, from which 8 duplicate papers were identified and removed. The remaining 135 papers were subjected to full-text review, during which the content of each paper was assessed against the established eligibility criteria. A further 45 papers were excluded after full-text screening. In total, 90 papers met the inclusion criteria and were included in the synthesis.

3. Results

3.1 Temporal and Spatial Distribution of Studies

The geographic distribution of studies indicates a strong concentration of research in specific countries and regions (Figure 3). China accounted for the highest number of studies (n = 25), representing approximately 27.8% of the total dataset. This was followed by global-scale studies (n = 10; 11.1%), and India and Ethiopia (n = 8 each; 8.9% each). Spain contributed 6 studies (6.7%), while other countries, such as South Africa, Algeria, Argentina, and Ghana, were represented by fewer studies. The remaining studies were distributed across multiple countries with limited representation. Overall, the results indicate that research on SOC and desertification has increased significantly in recent years, with a noticeable geographic concentration in Asia and selected parts of Africa.

3.2 Methods for Measuring Soil Organic Carbon (SOC)

The analysis of the reviewed studies indicates that a variety of methodological approaches were employed to assess SOC (Figure 4), with a clear dominance of field-based techniques. Field and laboratory-based methods accounted for the largest proportion of studies (n = 44), involving soil sampling at different depths and subsequent laboratory analysis to determine SOC content. These approaches were predominantly used in localised studies because they provide direct and accurate measurements of SOC stocks.

Remote sensing techniques were also widely used, comprising 16 studies in the dataset. These methods primarily used satellite imagery to monitor land-use and land-cover changes associated with SOC dynamics at larger spatial scales. Remote sensing approaches were particularly useful in capturing spatial variability and temporal changes in SOC in desertified landscapes. A smaller proportion of studies employed review-based approaches (n = 6), synthesising existing data to assess SOC trends. Modelling and GIS-based techniques were identified in a limited number of studies (n = 3), whereas spectroscopic methods, such as near-infrared reflectance spectroscopy, were rarely used (n = 1). Additionally, a notable number of studies (n =

20) utilised mixed or less clearly defined methodological approaches, reflecting the diversity of techniques applied in SOC assessment. Overall, while traditional field-based methods remain dominant, there is a growing integration of remote sensing and analytical techniques for assessing SOC dynamics in desertification contexts.

3.3 Main Drivers of Desertification

The main drivers of desertification identified across the reviewed studies are summarised in Table 3. The results indicate that desertification is influenced by a combination of climatic and anthropogenic factors, often interacting to accelerate land degradation and SOC loss. Climate change and variability emerged as dominant drivers, characterised by fluctuations in precipitation, rising temperatures, droughts, and extreme weather events. These conditions contribute to reduced vegetation cover and increased soil exposure, thereby influencing SOC dynamics.

Table 3. Summary of main drivers of desertification and their effects on soil organic carbon

#	Driver Category	Description of Driver	Effect on SOC Dynamics
1	Climate Change/Variability	Changes in temperature, precipitation variability, and increased frequency of droughts and extreme weather events	Reduces vegetation cover, increases soil temperature, and accelerates SOC decomposition and loss
2	Agricultural Practices	Intensive cultivation, poor soil management, and unsustainable farming techniques	Depletes soil nutrients, reduces organic matter input, and lowers SOC storage capacity
3	Overgrazing	Excessive livestock pressure leading to vegetation removal and soil exposure	Reduces plant biomass input and increases susceptibility to erosion, leading to SOC decline
4	Deforestation	Conversion of forested areas into agricultural or degraded lands	Reduces organic carbon inputs from vegetation and disrupts soil structure
5	Land Use Change	Transformation of natural ecosystems into agricultural or urban land	Alters carbon balance and reduces SOC sequestration potential
6	Soil Erosion	Removal of topsoil by wind and water processes	Leads to direct loss of SOC-rich topsoil and decreases soil fertility
7	Mixed/Other Drivers	A combination of multiple interacting factors	Produces compounded effects on SOC through interacting degradation processes

Among anthropogenic drivers, agricultural practices were frequently identified, including intensive cultivation and poor soil management practices. These activities contribute to the depletion of soil nutrients and reduce the capacity of soils to retain organic carbon. Land-use change, particularly the conversion of natural ecosystems to agricultural or degraded land, was also widely reported as a key driver of SOC dynamics. Soil erosion was another prominent driver, involving the removal of nutrient-rich topsoil by wind and water, which leads to a direct loss of SOC and a reduction in overall soil fertility. Deforestation and overgrazing were also identified, albeit to a lesser extent, as contributing to vegetation loss and increased soil vulnerability to degradation. Several studies reported the combined effects of multiple interacting drivers, highlighting the complexity of desertification processes across different environmental contexts.

4. Correlation Between Desertification and Soil Organic Carbon

The relationship between desertification and SOC across the reviewed studies is established through quantified changes in SOC stocks, percentage losses, threshold responses, and depth-dependent variations (Table 4). The extracted evidence demonstrates a consistent pattern of SOC decline associated with land degradation and desertification processes. Several studies reported substantial SOC losses following land-use change and degradation. SOC reductions of approximately 30% were observed after a decade of forest conversion to cropland, while degraded soils exhibited average carbon losses of 49%-54%, depending on soil type. In more severely degraded systems, SOC depletion reached up to 89%, indicating extreme sensitivity of soil carbon to prolonged disturbance. At broader scales, total SOC losses were quantified at approximately 3.89 Tg under land-use change scenarios, with an estimated global loss of approximately 3.1 Pg C, highlighting the magnitude of carbon depletion associated with desertification.

Threshold-based relationships were also identified, with SOC levels below approximately 20 g kg^1 associated with sharp declines in soil functional capacity. These findings suggest that once SOC falls below critical thresholds, soil resilience and ecosystem functioning are significantly compromised. Depth-dependent variations in SOC were consistently reported, with higher SOC concentrations observed in surface soils and significant declines with increasing depth across different land-use systems. This pattern reflects the vulnerability of topsoil carbon to erosion and degradation processes. Several studies reported nonlinear responses of SOC to desertification, with temporary increases during light-to-moderate degradation stages followed by substantial declines as degradation intensifies. Spatial variability in SOC was also observed, influenced by land-use type, topography, and erosion processes.

Table 4. Summary of quantitative relationships between desertification and soil organic carbon (SOC)

Relationship Type	Quantitative Evidence Reported	Implication for SOC Dynamics
SOC loss due to land-use change	∼30% SOC loss after forest conversion to cropland over 10 years	Land-use change significantly reduces SOC stocks
SOC depletion under degradation	49–54% SOC loss in degraded soils; up to 89% in severely degraded systems	Severe desertification leads to substantial SOC depletion
Large-scale SOC loss	∼3.89 Tg SOC loss under land-use change; ∼3.1 Pg C global loss	Desertification contributes to large-scale carbon loss
Threshold effects	SOC < 20 g kg^{-1} is associated with a sharp decline in soil function	Critical SOC thresholds determine soil resilience
Depth-related variation	SOC consistently decreases with soil depth across land-use systems	Topsoil is more vulnerable to degradation and SOC loss
Land-use differences	Forests and grasslands store significantly higher SOC than croplands	Natural ecosystems maintain higher SOC levels
Nonlinear SOC response	SOC may increase under light degradation before declining at severe stages	The SOC response to desertification is not always linear
Erosion-driven SOC loss	Up to ∼50% reduction in topsoil SOC due to erosion processes	Erosion is a major mechanism of SOC removal
Spatial variability	SOC varies with topography, land use, and environmental conditions	SOC distribution is heterogeneous across landscapes

4.1 Indicators Used to Assess Desertification and Its Impact on Soil Organic Carbon

The reviewed studies employed a wide range of quantitative indicators to assess desertification processes and their impacts on SOC. These indicators encompass direct measurements of SOC, associated soil properties, environmental variables, and composite land degradation metrics. SOC-specific indicators were the most consistently applied, including SOC stock, SOC density (SOCD), and SOC concentration. Several studies also utilised different SOC fractions, such as particulate organic carbon (POC), mineral-associated organic carbon (MAOC), and dissolved organic carbon (DOC), thereby providing more detailed insights into carbon pool dynamics. In addition, carbon-related indices such as the Carbon Management Index (CMI) and SOC stratification ratios were used to evaluate soil quality and carbon stability.

Soil physicochemical properties were frequently used alongside SOC indicators, including bulk density, soil moisture, pH, cation exchange capacity, and nutrient concentrations. These variables are essential for interpreting SOC dynamics under varying environmental and management conditions. Erosion-related indicators, such as soil loss rates, sediment-associated carbon loss, and runoff, were widely used to quantify the physical processes that contribute to SOC redistribution and depletion. Similarly, vegetation-based indicators, including vegetation cover, biomass, and normalised difference vegetation index (NDVI), were used to assess ecosystem productivity and its relationship with SOC inputs.

Climate variables, such as precipitation, temperature, and aridity indices, were also commonly integrated into

Table 5. Summary of indicators used to assess desertification and soil organic carbon (SOC)

Indicator Category	Indicators Reported in Studies
SOC Metrics	SOC stock, SOC density (SOCD), SOC concentration (%), carbon storage, SOC flux
SOC Fractions	Particulate organic carbon (POC), mineral-associated organic carbon (MAOC), dissolved organic carbon (DOC)
Soil Properties	Bulk density, soil moisture, pH, cation exchange capacity, nutrient concentrations
Erosion Indicators	Soil loss, erosion rates, sediment-associated SOC loss, and runoff
Vegetation Indicators	Vegetation cover, biomass, NDVI, land-use/land-cover change
Climate Indicators	Rainfall, temperature, aridity index, evapotranspiration
Spatial/Model Indicators	Kriging outputs, model accuracy (e.g., MAE), spatial variability, and mapping uncertainty
Composite Indicators	Land productivity, land cover, SOC (LDN framework indicators)

SOC assessments, particularly in dryland environments where climatic variability strongly influences both vegetation and soil processes. Several studies applied spatial and modelling indicators, including geostatistical measures, kriging uncertainty, and model accuracy metrics, to evaluate the spatial distribution and prediction of SOC.

4.2 Sustainable Land Management Practices for Mitigating SOC Loss

The reviewed studies identified a range of sustainable land management practices to mitigate SOC loss and improve soil resilience under desertification conditions (Table 6). These practices primarily focus on enhancing vegetation cover, reducing soil disturbance, and minimising erosion. Vegetation-based approaches were among the most frequently reported, including afforestation, reforestation, agroforestry, and vegetation restoration. These practices increase organic matter inputs into the soil and improve soil structure, thereby supporting SOC accumulation.

Table 6. Summary of sustainable land management practices for mitigating SOC loss

Practice Category	Practices Identified in Studies
Vegetation Restoration	Afforestation, reforestation, agroforestry, grassland restoration
Soil Management	Conservation tillage, reduced tillage, and organic amendments
Erosion Control	Terracing, contour farming, and vegetation barriers
Grazing Management	Controlled grazing, exclosures, rotational grazing
Integrated Approaches	Combined vegetation restoration, soil conservation, and land-use management

Soil management practices were also widely applied, including conservation tillage, reduced tillage, and organic amendments. These approaches maintain soil structure, reduce carbon losses associated with soil disturbance, and enhance SOC stabilisation. Erosion control measures were commonly reported, such as the use of terraces, contour farming, and vegetation barriers. These practices reduce soil loss and limit the removal of SOC-rich topsoil, thereby contributing to carbon retention in degraded landscapes. Grazing management practices, including controlled grazing and exclosure systems, were identified as important strategies for reducing vegetation degradation and promoting SOC recovery in rangeland systems.

4.3 Effects of Soil Organic Carbon Loss on Ecosystem Services

The reviewed studies indicate that SOC loss associated with desertification has measurable impacts across multiple ecosystem service domains, particularly affecting soil quality, productivity, carbon dynamics, and ecosystem stability. SOC depletion was consistently associated with declines in soil fertility and productivity, including reductions in nutrient availability, soil quality, and agricultural output (Table 7). These changes reflect SOC's role as a key determinant of soil function and its capacity to support plant growth.

Table 7. Effects of soil organic carbon (SOC) loss on ecosystem services

Ecosystem Service Domain	Reported Effects of SOC Loss
Soil Fertility and Productivity	Reduced nutrient availability, lower soil fertility, decreased crop productivity.
Carbon Regulation	Reduced carbon sequestration, shift from carbon sink to carbon source.
Soil Physical Properties	Reduced aggregate stability, lower water retention, and increased erosion
Ecosystem Stability	Reduced resilience, increased degradation risk, weaker recovery capacity
Biodiversity and Functioning	Reduced microbial activity, lower biodiversity support
Hydrological Regulation	Reduced infiltration, increased runoff, weakened water retention.

In terms of carbon dynamics, SOC loss was linked to reduced carbon sequestration capacity and a shift in soils from carbon sinks to carbon sources. This transition has implications for climate regulation, as declining SOC reduces soils' capacity to store carbon and contributes to atmospheric carbon accumulation. SOC loss was also associated with deterioration in soil physical properties, including reduced aggregate stability, lower water retention capacity, and increased susceptibility to erosion. These changes further accelerate land degradation and reinforce desertification processes. At the ecosystem level, declining SOC was associated with reduced resilience and stability, including a lower capacity for recovery and increased vulnerability to environmental stress. SOC loss was further associated with reduced biodiversity support, particularly affecting soil microbial activity and ecosystem functioning.

5. Discussion

5.1 Desertification-SOC Nexus

The synthesis of evidence from the included studies reveals a consistently strong negative relationship between desertification processes and SOC, with several studies quantifying substantial reductions in SOC stocks as land degradation intensifies. Empirical findings indicate that SOC losses vary significantly across land-use transitions and ecological zones. For example, conversion of natural vegetation to cropland has been shown to result in SOC reductions exceeding 30-50%, particularly in semi-arid and savannah environments (Villarino et al., 2017; Kassa et al., 2017; Tesfaye et al., 2016). Studies in West African drylands report marked declines in both carbon and nitrogen pools under degraded land conditions (Traore et al., 2015), while long-term land-use change analyses in

Asia demonstrate persistent SOC depletion associated with agricultural expansion and vegetation loss (Yang et al., 2018; Xiao et al., 2024).

Beyond absolute reductions, the literature highlights the nonlinear and threshold-dependent nature of SOC decline under desertification. Evidence suggests that once SOC levels fall below critical thresholds, soils experience reduced structural stability, diminished nutrient cycling capacity, and impaired biological functioning. For instance, Grilli et al. (2021) identified a critical SOC range below which soils in Mediterranean environments become increasingly vulnerable to degradation, indicating ecological tipping points. Similar patterns have been observed in dryland grasslands, where SOC depletion accelerates beyond certain degradation intensities, reinforcing the concept of threshold-driven system collapse (An et al., 2019; Tang et al., 2015). The relationship between desertification and SOC is further supported by strong statistical associations between SOC and key environmental variables, particularly vegetation cover and land-use type. Multiple studies report positive correlations between SOC and vegetation indices or biomass, and negative correlations with erosion intensity and bare soil exposure (Winowiecki et al., 2016; Zhang et al., 2019; Boubehziz et al., 2024). These findings emphasise the central role of vegetation in regulating SOC dynamics, whereby reductions in plant cover directly limit carbon inputs and increase susceptibility to erosion and carbon loss.

Erosion-driven processes emerge as a dominant mechanism of SOC depletion in degraded landscapes. Empirical studies demonstrate that both wind and water erosion significantly reduce SOC stocks by removing carbon-rich topsoil layers. Santra et al. (2013) reported substantial SOC and nitrogen losses due to wind erosion in arid environments, while Martinez-Mena et al. (2008) and Ruiz-Colmenero et al. (2013) highlighted the role of water erosion in reducing SOC stocks in semi-arid agricultural systems. In some cases, SOC redistribution occurs; however, this often results in net declines in productive soil carbon pools, particularly where depositional stability is limited (Fang et al., 2012; Wei et al., 2025). Overall, the findings demonstrate that the desertification-SOC relationship is multidimensional and strongly supported by empirical and statistical evidence, involving interactions between land-use change, climatic variability, vegetation dynamics, and erosion processes. The presence of quantifiable SOC losses, statistically significant correlations, and identifiable threshold effects highlights the urgency of early intervention. Preventing SOC decline before critical thresholds are reached is essential for maintaining soil functionality and advancing land degradation neutrality objectives.

5.2 Interacting Drivers and Feedback Mechanisms in SOC Decline

The decline in SOC under desertification is driven by a complex interaction of anthropogenic and climatic factors, rather than isolated processes. The reviewed studies consistently demonstrate that land-use change, overgrazing, deforestation, and unsustainable agricultural practices interact with climatic stressors to accelerate SOC depletion. The conversion of forest and natural vegetation to cropland significantly reduces SOC inputs due to the removal of biomass and the disruption of litter cycling (Villarino et al., 2017; Kassa et al., 2017; Xiao et al., 2024). Intensive cultivation and tillage practices enhance soil disturbance, exposing protected organic carbon to oxidation and increasing mineralisation rates (Kumari, 2016; Tesfaye et al., 2016). These processes collectively reduce the capacity of soils to maintain stable carbon pools. Overgrazing emerges as another critical driver, particularly in dryland ecosystems where vegetation recovery is limited. Empirical evidence indicates that excessive grazing pressure reduces plant biomass and ground cover, thereby limiting carbon inputs while simultaneously increasing soil exposure to erosion (Dlamini et al., 2016; Yu et al., 2019). This dual effect intensifies SOC depletion, especially under arid and semi-arid conditions where ecosystem resilience is already constrained. Deforestation further compounds these effects by altering microclimatic conditions, reducing soil moisture, and accelerating the decomposition of organic matter (Kassa et al., 2017; Grieco et al., 2024).

A key insight emerging from the literature is the presence of self-reinforcing feedback mechanisms linking SOC decline and desertification processes. As SOC levels decrease, soils lose their structural integrity, water-holding capacity, and nutrient availability, thereby reducing vegetation productivity (Dlamini et al., 2014; Traore et al., 2015). The resulting decline in vegetation cover further limits organic carbon inputs while increasing susceptibility to erosion, thereby accelerating SOC loss. This creates a positive feedback loop in which SOC depletion drives further land degradation, and degradation, in turn, exacerbates SOC decline. In extreme cases, this feedback can lead to irreversible transitions to degraded states, particularly in fragile dryland ecosystems. Several studies highlight the role of erosion-mediated carbon redistribution as a critical but often overlooked component of SOC dynamics. While erosion may lead to localised deposition of carbon in downslope or depositional areas, the net effect is typically a reduction in productive SOC pools, particularly in actively degraded landscapes (Fang et al., 2012; Martinez-Mena et al., 2008). This spatial redistribution complicates SOC assessments, as apparent gains in certain locations may mask broader system-wide losses.

5.3 SOC as a Central Regulator of Ecosystem Functioning

The reviewed literature consistently positions SOC not merely as an indicator of land degradation, but as a central regulator of soil functionality and ecosystem stability. Across diverse ecological settings, SOC is shown to influence key soil properties, including structure, nutrient availability, water retention, and biological activity. Declines in SOC under desertification, therefore, have cascading effects that extend beyond carbon loss, fundamentally altering ecosystem processes. Reductions in SOC have been associated with decreased soil aggregation and increased susceptibility to erosion, particularly in degraded dryland environments (Dlamini et al., 2014; Traore et al., 2015). These structural changes reduce the soil's capacity to support plant growth, thereby reinforcing vegetation decline and further limiting carbon inputs.

SOC further plays a critical role in regulating soil hydrological processes. Evidence indicates that soils with higher SOC content exhibit improved water infiltration and retention capacities, which are essential for sustaining vegetation in arid and semi-arid environments (Winowiecki et al., 2016; Nijbroek et al., 2018). Under desertification, the loss of SOC reduces the soil's ability to retain moisture, increasing vulnerability to drought and limiting plant establishment. This hydrological constraint contributes to a decline in vegetation cover, thereby reinforcing the feedback loop between SOC depletion and land degradation. In addition to its role in soil and ecosystem functioning, SOC is a key component of the global carbon cycle, influencing climate regulation. The reviewed studies highlight that SOC-rich soils act as significant carbon sinks, while degraded soils with reduced SOC become net sources of atmospheric carbon (Lal, 2003; Pravalie et al., 2021). This transition has important implications for climate change, as desertification-driven SOC losses increase greenhouse gas emissions. The capacity of soils to sequester carbon is therefore directly linked to their condition, with degraded lands representing missed opportunities for climate mitigation.

The literature also emphasises the role of SOC in enhancing ecosystem resilience. Soils with higher SOC levels are better able to withstand environmental stresses, including drought, erosion, and land-use pressures. This resilience is particularly critical in dryland regions, where ecosystems operate close to environmental thresholds. Studies on revegetation and restoration indicate that increasing SOC can improve soil stability, enhance vegetation recovery, and restore ecosystem functions (Zhang et al., 2024; Peng et al., 2020). However, once SOC levels fall below certain thresholds, the capacity for natural recovery diminishes, underscoring the importance of early intervention.

5.4 Effectiveness and Limitations of Land Management Interventions

The reviewed studies indicate that land management interventions can play a substantial role in slowing, halting, and in some cases reversing SOC decline under desertification conditions. However, their effectiveness is strongly dependent on ecological context, land-use history, and the degree of prior degradation. Across the literature, interventions that reduce soil disturbance, enhance vegetation cover, and improve organic matter inputs tend to show the most consistent positive effects on SOC retention and recovery.

Vegetation-based interventions, including afforestation, reforestation, agroforestry, and revegetation, were widely associated with improved SOC status and enhanced soil condition. Studies from dryland and semi-arid systems suggest that the restoration of plant cover increases litter inputs, improves the contribution of root biomass to soil carbon pools, and reduces direct soil exposure to erosive forces (Kassa et al., 2017; Zhang et al., 2024; Peng et al., 2020). Agroforestry appears particularly important because it combines productivity functions with ecological restoration, allowing soils to recover carbon while maintaining some degree of land-use value (Tesfaye et al., 2016; Huang et al., 2023). Vegetation cover management in cultivated systems has been shown to reduce erosion and enhance SOC accumulation, particularly where ground cover is maintained year-round (Ruiz-Colmenero et al., 2013; Repullo-Ruiberriz de Torres et al., 2024). Erosion control measures constitute another major class of intervention with direct implications for SOC retention. Studies on hedgerows, grass strips, exclosures, and runoff-control measures demonstrate that reducing soil loss substantially limits the removal of SOC-rich topsoil and promotes carbon sequestration over time (Lenka et al., 2012; Yaghobi et al., 2018; Meena et al., 2023). The benefits of erosion control extend beyond carbon storage to include improved infiltration, greater aggregate stability, and better long-term soil productivity. Nevertheless, the effectiveness of these measures varies with slope, rainfall intensity, and maintenance conditions, suggesting that intervention success depends heavily on site-specific design and implementation.

Despite the generally positive outcomes reported for many interventions, the reviewed studies also reveal important limitations. First, many management gains in SOC are context-dependent and not easily transferable across ecological zones. Practices that perform well in one dryland environment may yield weaker or delayed effects elsewhere due to differences in soil type, rainfall regime, vegetation composition, and the intensity of prior degradation (Boubehziz et al., 2024; Odebiri et al., 2024). Second, several interventions improve SOC only gradually, meaning that short-term monitoring may underestimate their eventual benefits. Third, some practices enhance

SOC in localised plots without necessarily addressing broader landscape-scale drivers of degradation, such as deforestation, climate variability, and unsustainable land-use expansion. A further limitation in the literature is that intervention effectiveness is often assessed using relatively narrow biophysical indicators, while socioeconomic feasibility, adoption barriers, and long-term maintenance receive less attention. This is particularly important in dryland regions, where the sustainability of any intervention depends not only on ecological performance but also on local land-use pressures, institutional support, and community acceptance. The most effective interventions appear to be those embedded within integrated land management systems rather than isolated technical fixes.

5.5 Measurement Challenges and the Need for Standardised SOC Assessment

The assessment of SOC across desertified landscapes presents significant methodological challenges, as evidenced by the diversity of measurement approaches and indicators reported in the reviewed studies. While a wide range of techniques, from field-based sampling and laboratory analysis to remote sensing and modelling, have been employed, the lack of standardisation in measurement protocols complicates cross-study comparisons. It limits the synthesis of SOC dynamics at broader spatial scales. One of the primary challenges relates to variation in SOC measurement depth and sampling strategies. Several studies assess SOC within shallow soil layers (e.g., 0-10 cm or 0-20 cm), while others extend measurements to deeper profiles, leading to inconsistencies in reported SOC stocks and trends (Tesfaye et al., 2016; Abebe et al., 2020). Given that SOC distribution varies significantly with depth, especially in degraded and erosion-prone landscapes, these differences can lead to underestimation or overestimation of total carbon stocks. This variability is further compounded by differences in sampling density and spatial coverage, with some studies relying on limited plot-level observations while others employ landscape-scale assessments.

In addition to depth-related inconsistencies, the use of different SOC indicators and metrics presents another layer of complexity. While some studies report SOC concentration (%), others quantify SOC stocks (e.g., Mg C ha-1), carbon density, or carbon pool indices, often without clear standardisation or conversion frameworks. This heterogeneity limits the comparability of results and complicates efforts to synthesise findings across regions and land-use systems (Stockmann et al., 2015; Nijbroek et al., 2018). Differences in analytical methods, such as dry combustion, Walkley-Black methods, and spectroscopic techniques, introduce additional variability in SOC estimation (Marques et al., 2020; Stockmann et al., 2015). The increasing use of remote sensing and spatial modelling approaches has improved the capacity to assess SOC at larger scales; however, these methods introduce their own uncertainties. While satellite-based and GIS-driven models enable spatially explicit mapping of SOC distribution, their accuracy depends heavily on calibration datasets, model selection, and environmental covariates (Lian et al., 2022; Odebiri et al., 2024; Wang et al., 2023). In many cases, model predictions are constrained by limited ground-truth data, particularly in remote or data-scarce dryland regions. While remote sensing enhances spatial coverage, it may propagate uncertainties if not adequately validated.

Another critical limitation identified in the literature is the inconsistent reporting of statistical relationships and uncertainty measures. Although many studies establish associations between SOC and environmental drivers, the reporting of statistical metrics, such as correlation coefficients, regression parameters, or confidence intervals, is often uneven. This lack of consistency reduces the ability to compare findings quantitatively and limits the robustness of meta-level synthesis. Few studies explicitly account for uncertainty arising from sampling error, model assumptions, or temporal variability, despite these factors being particularly relevant in heterogeneous and dynamic desertification contexts. Temporal inconsistency further complicates SOC assessment. Many studies rely on short-term observations or cross-sectional data, which may not adequately capture the long-term dynamics of SOC under desertification and restoration processes. Given that SOC changes often occur gradually, short monitoring periods may fail to detect meaningful trends or may misrepresent transient fluctuations as long-term patterns (Pravalie et al., 2021). This highlights the need for long-term monitoring frameworks that better capture SOC trajectories over time.

5.6 Toward Integrated Approaches for Land Degradation Neutrality (LDN)

The synthesis of findings across the reviewed studies underscores the central role of SOC in achieving Land Degradation Neutrality (LDN), particularly within dryland and desertification-prone environments. SOC emerges not only as a key indicator of land degradation status but also as a critical driver of soil functionality, ecosystem resilience, and climate regulation. Maintaining or enhancing SOC stocks is therefore fundamental to achieving LDN targets, which aim to balance ongoing land degradation with restoration and sustainable management efforts. The evidence indicates that a combination of land-use change, vegetation loss, soil erosion, and climatic variability drives SOC decline under desertification. These processes operate across scales and are reinforced by feedback mechanisms that accelerate degradation once critical thresholds are crossed. Achieving LDN, therefore, requires approaches that move beyond isolated interventions toward integrated land management strategies that simultaneously address multiple drivers of SOC loss. Studies examining restoration and management interventions suggest that combining vegetation-based approaches, soil conservation practices, and sustainable land-use systems offers the most effective pathway for stabilising and enhancing SOC stocks (Peng et al., 2020; Zhang et al., 2024; Repullo-Ruiberriz de Torres et al., 2024).

A key implication of the findings is that LDN strategies must be context-specific and spatially targeted. The variability in SOC responses across ecological zones, land-use systems, and degradation intensities highlights the limitations of uniform policy prescriptions. Interventions that are effective in semi-arid agroecosystems may not yield similar outcomes in more severely degraded or climatically constrained environments. Spatially explicit approaches, supported by geospatial technologies and SOC mapping, can help identify priority areas for intervention and guide resource allocation more efficiently (Lian et al., 2022; Odebiri et al., 2024; Darwish & Fadel, 2017). This aligns with the broader LDN framework, which emphasises the importance of baseline assessment, monitoring, and targeted action. The findings further highlight the importance of integrating biophysical and socio-economic dimensions within LDN implementation. While many studies demonstrate the technical effectiveness of land management interventions in improving SOC, their long-term sustainability depends on factors such as land tenure systems, institutional support, access to resources, and local capacity for adoption. Without addressing these enabling conditions, even technically sound interventions may fail to achieve sustained impact. This underscores the need for policy frameworks that support not only ecological restoration but also stakeholder engagement and capacity building (Feng et al., 2022; Ahmed et al., 2024).

The role of SOC in climate mitigation further reinforces its relevance within LDN strategies. By enhancing SOC stocks, degraded lands can transition from carbon sources to carbon sinks, contributing to broader climate change mitigation goals (Lal, 2003; Pravalie et al., 2021). This dual benefit, land restoration and climate regulation, positions SOC-focused interventions as critical components of integrated environmental policy. Realising this potential requires improved monitoring systems capable of capturing SOC dynamics accurately over time, as well as standardised methodologies that enable consistent reporting and evaluation. The findings also suggest that effective LDN implementation must account for threshold dynamics and feedback mechanisms associated with SOC decline. Interventions implemented after severe degradation may yield limited results due to reduced soil resilience and impaired capacity for recovery. Early intervention and preventive strategies are therefore essential for maintaining SOC above critical thresholds and avoiding irreversible degradation states. This highlights the importance of proactive land management policies that prioritise conservation alongside restoration.

6. Conclusion

This study provides a comprehensive synthesis of the relationship between desertification and soil organic carbon (SOC), highlighting SOC's critical role as both an indicator and a driver of land degradation. The evidence reviewed consistently demonstrates that desertification leads to significant declines in SOC stocks across diverse ecological settings, with reductions frequently linked to land-use change, vegetation loss, soil erosion, and climatic variability. These changes not only diminish soil fertility and productivity but also weaken soils' capacity to function as carbon sinks, thereby contributing to broader climate change feedbacks. The findings further reveal that complex interactions and feedback mechanisms govern SOC dynamics under desertification. Declines in SOC reduce soil structural stability, water retention, and nutrient availability, which in turn limit vegetation growth and accelerate further degradation. The presence of threshold effects suggests that once SOC levels fall below critical limits, recovery becomes increasingly difficult, emphasising the importance of early intervention in degradation-prone landscapes.

The review also highlights that while land management interventions, such as vegetation restoration, conservation tillage, erosion control, and improved grazing practices, can enhance SOC stocks, their effectiveness is highly context-dependent. Successful outcomes require integrated approaches that combine multiple interventions and are tailored to specific ecological and socio-economic conditions. The variability in SOC measurement methods and reporting across studies underscores the need for greater standardisation to improve comparability and support monitoring frameworks. Importantly, the study establishes SOC as a central component in achieving Land Degradation Neutrality (LDN). Enhancing SOC stocks offers a pathway to restoring soil function, improving ecosystem resilience, and contributing to climate mitigation efforts. Achieving these outcomes requires coordinated strategies that integrate scientific evidence, geospatial monitoring, and policy support, while also addressing local land-use dynamics and stakeholder engagement.

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8. Declaration of Competing Interest

The authors declare no conflict of interest.

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