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Carbon Cycling in Global Drylands

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Abstract

Purpose of Review The aim of this paper is to describe the carbon cycle in drylands in relation to the processes, factors, and causes affecting it. A specific focus is placed on both biotic and abiotic mechanisms of carbon sequestration in drylands in relation to mitigation of the anthropogenic climate change.

Recent Findings Global dryland area is increasing along with an increase in risks of desertification, salinization, and eolian/hydrologic processes of accelerated soil erosion with strong impacts on the carbon cycle. Nonetheless, drylands contribute strongly towards the land-based sink of the atmospheric carbon dioxide through sequestration of carbon in the soil, ground water, and biomass. Thus, dryland ecosystems affect inter-annual variability in the global carbon cycle and create a negative feedback through carbon sequestration.

Summary Global drylands, covering 66.7 M km^2 or 45.36% of the Earth's land area, strongly impact the ecosystem carbon stock, contribute to the land-based carbon sink, and provide a negative feedback to the global carbon cycle. Whereas the net primary productivity is limited by the water scarcity, especially in hyper-arid and arid ecoregions, sequestration of inorganic carbon in soil and ground water is an important control of the carbon cycle. Desertification, caused by eolian and hydrologic erosion along with salinization, must be controlled and reversed to enhance carbon sequestration, achieve land degradation neutrality, and create a negative feedback. Carbon sequestration strategy recognizes "soil" as a rights holder to be protected, restored and naturally evolve.

Keywords Carbon sequestration · Secondary carbonates · Desertification · Global carbon cycle · Drylands

Introduction

Drylands are characterized by the aridity index (AI), the ratio of precipitation (P) to potential evapotranspiration (PET), of less than 0.65 mm/mm [1]. Using this criterion, global drylands cover about 41% of Earth's land area or approximately 60 million (M) km^2 [2, 3] and are home to about 2.8 billion people [4]. However, global drylands are increasing because of climate change and other anthropogenic activities (i.e., land use change). Some recent estimates indicate that the global dryland area has increased to 45.36% of Earth's land area or 66.7 M km^2 [5] of the total surface area of 147 M km^2. Land area, based on the revised estimates of drylands, comprises (i) hyper-arid (AI < 0.05 mm/mm) at 8.6 M km^2 (5.9%), (ii) arid (AI 0.05–0.2 mm/mm) at 20.8 M km^2 (14.2%), (iii) semi-arid (AI 0.2–0.5 mm/mm) at 24.1 M km^2 (16.4%), and (iv) dry sub-humid (AI 0.5–0.65 mm/mm) at 13.2 M km^2 (9.0%) [4, 5]. The increase in global land area under drylands, attributed to climate change between 1950 and 2000, may be intensified between 2000 and 2100. Consequently, the dryland area may change to 12.6% under hyper-arid, 14.9% under arid, 20.3% under semi-arid, and 8.3% under sub-humid ecoregions [6], covering 56% of the total land area of Earth [4].

Drylands provide numerous ecosystem functions and services, including sequestration of atmospheric CO$_2$ [7], but these services are constrained by low fresh water availability. Of the 66.7 M km^2, 11% is used as cropland and 30% as pastures [4]. However, the low water availability is a major limiter of net primary productivity (NPP), and also a serious constraint to sequestration of soil organic carbon (SOC) in drylands [8]. The projected climate change may reduce the surface area covered by patchy vegetation and expand that of bare soil exposed to harsh climate. The vegetation cover

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in these fragile ecosystems is highly sensitive to anthropogenic and natural perturbations. Yet, the projected decline in fresh water availability and the likely expansion of global drylands may strongly impact the carbon (C) cycle, weaken essential ecosystem functions and services, and jeopardize human wellbeing and nature conservation. Thus, the objectives of this article are to (i) describe the carbon cycle in drylands (CCD), (ii) deliberate the impact of climate change and the feedback to CCD, (iii) explain the effect of land use and soil management on CCD, and (iv) outline practices and systems which may enhance soil C sequestration in drylands and reverse the degradation/desertification trends.

Carbon Cycle in Drylands

Primary components of the CCD, similar to those of the global carbon cycle (GCC), comprise the gaseous exchange among the atmosphere, vegetation, soil, and the ocean (Fig. 1). The magnitudes of the C stock in different reservoirs of the CCD and of the annual flux among them, as influenced by natural and anthropogenic factors, are even more uncertain than those of the GCC. Yet, dryland ecosystems may significantly impact the inter-annual variability of the GCC [11]. The soil C source and sink may play an important role in the CCD as that in GCC. Available estimates of the global soil C stock are variable, and the uncertainty is exacerbated by the non-flatness of the terrain and topsoil because the surface area increases with increase in uneven nature of the terrain [12]. Total soil C stock in drylands comprises more soil inorganic carbon (SIC) than SOC (Table 1), and that in the vegetation (both above and below ground) is much smaller than those in humid and sub-humid ecoregions (Table 1, Fig. 1). The SOC stock in drylands represents about 50% of that in humid regions to 1-m depth (Table 1), and range from 470 ± 7 Pg (petagram = 10^{15} g = 1 billion metric ton = Gt) to 1-m to 646 ± 9 Pg to 2-m depth (Fig. 2). However, drylands may store as much as 95% of the global SIC stock through the formation of caliche or concrete [13]. SIC stock to 2-m depth is estimated at 1237 ± 15 Pg ([4], Table 1).

The SOC density in drylands is low and ranges from 1 to 3 kg C/m^2 in Africa and North and Central America compared with 2 to 7 kg C/m^2 in Asia [14, 15]. Cultivated drylands, about 11% under cropland and 30% under pastures [4], are located in dry sub-humid and semi-arid ecoregions (AI of 0.2–0.65 mm/mm) and have SOC density of about 3.5 kg C/m^2 with a total SOC stock of about 40-Pg C. These cultivated ecosystems have a potential to sequester both SOC and SIC through improved management [7, 14]. Thus, C sequestration (both SOC and SIC) provides a negative feedback to CCD.

Whereas a considerable progress has been made in estimating SIC and its dynamics [9, 16–19], available estimates of the total and SIC stocks and annual fluxes are highly uncertain and need to be improved and validated under site-specific conditions, and upscaled. Several studies have documented that drylands have a large negative C flux (~ 1 Mg/ha year) due primarily to inorganic/abiotic processes [9, 20]. The SIC stock in drylands, much greater than that of the SOC in 0–1.0 and 0–2.0-m depths (Table 1), comprises three components: (i) primary or lithogenic carbonates derived from the weathering of calciferous rocks and other parent materials,

Fig. 1 Carbon cycle in drylands depicting feedbacks among atmosphere, soil, ocean (data from [4, 9, 10])

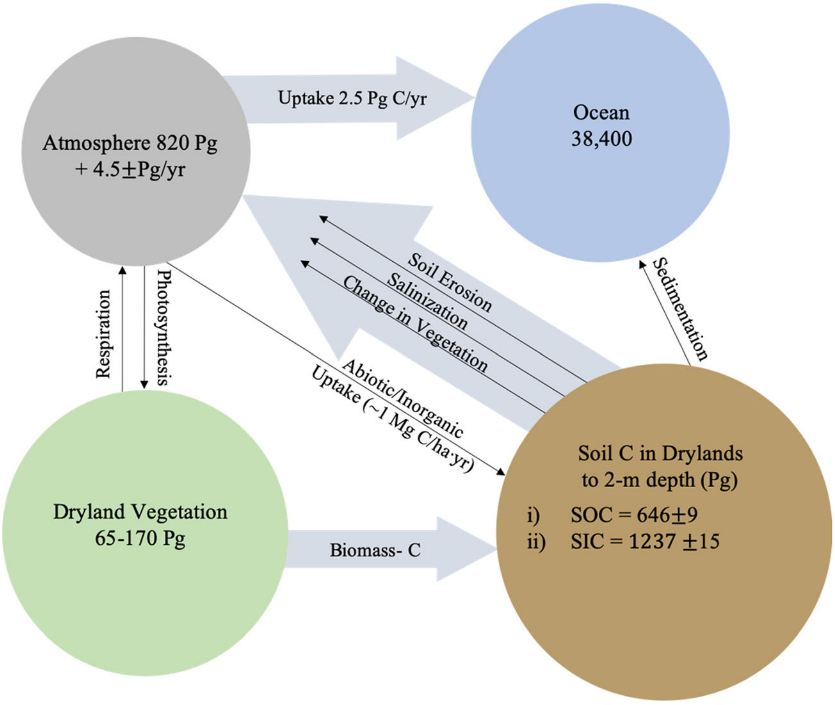


Table 1 Global soil C and N stocks (Pg) to different depths [4]

Depth (cm)	Soil organic carbon			Soil inorganic carbon			Total nitrogen			C:N	
	D	H	D:H	D	H	D:H	D	H	D:H	D	H
0–0.3	248 ±6	502 ±12	0.49	154 ±4	28±3	5.2	22.6±0.4	36.1±0.7	0.63	11.0	13.9
0–1.0	470 ±7	955 ±19	0.49	578 ±8	107 ±5	5.4	47.7±0.5	72.6±1.1	0.66	9.9	13.1
0–2.0	646 ±9	1401 ±36	0.46	1237 ±15	321 ±9	3.9	73.2 ±0.6	111.1 ±1.6	0.66	8.8	12.6

D, dryland; *H*, humid climate; C:N ratio

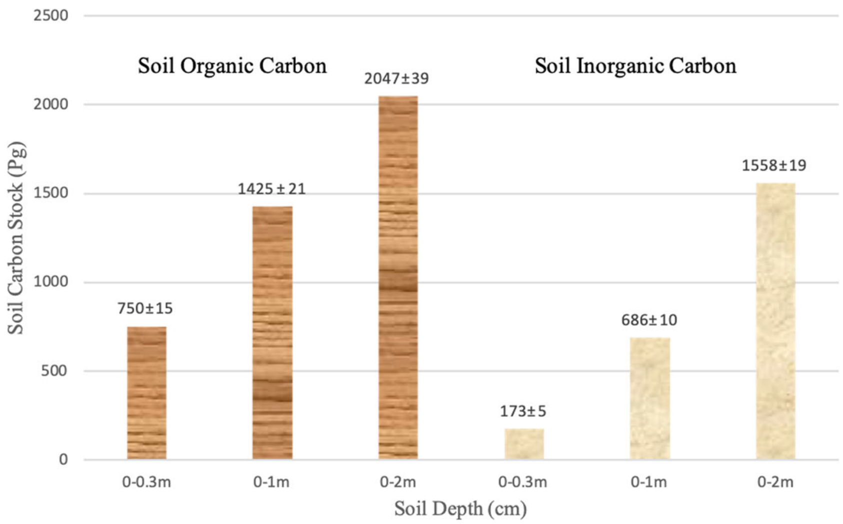
(ii) secondary or pedogenic carbonates (also called caliche or concrete) formed from pedologic processes and also influenced by land use and soil management [21], and (iii) bicarbonates leached into and contained in the ground water. The global SIC (primary and secondary carbonates) stock is estimated at 1237 Pg to 2-m depth [4] and an additional 1404 Pg as bicarbonates stored in ground water [19]. Classification of pedogenic (secondary) carbonates has been updated to "silicatic pedogenic carbonate" and "calcitic pedogenic carbonates" [19], and only "silicatic pedogenic carbonates" give rise to net sequestration of atmospheric CO_2. In some site-specific conditions, the SIC stock may be 10–17 times the SOC stock [14, 22, 23], especially under hyper-arid and arid ecoregions with AI < 0.2 mm/mm, scanty and patchy vegetation cover, and extremely low NPP. The SIC stock in hyper-arid and arid ecoregions may be as much as 732-Pg C [2]. The close link between SOC and SIC on the one hand and SOC and soil biodiversity on the other indicates the urgent necessity of restoring soil C stocks, keeping drylands alive [24] and creating a negative feedback to CCD.

The C stock in vegetation of drylands may be one-fourth of that in the SOC [10], with a low density of 0.4–4.0 Mg C/ha in hyper-arid lands [25], 0.8–4.0 Mg C/ha in arid regions [26], 10 Mg C/ha in grasslands [27], and 40–50 Mg C/ha in dry sub-humid forested drylands [28]. Another estimate of biomass (Mg/ha) of dryland vegetation (~40% C) indicated 14 for savanna, 4–6 for dry savanna, 5 for steppe grassland, 0.8–0.9 for semi-shrub desert, and 0.2–0.3 for sub-tropical desert [29]. The global average C stock in dryland vegetation is estimated at 65-Pg C by Serrano-Ortiz et al. [14] and 81-Pg C by Safriel et al. [2]. In some regions (e.g., savanna, dry savanna, and steppe grasslands), increase in the biomass-C stock can also increase SOC and SIC stocks and strengthen the negative feedback to CCD.

Factors Affecting the Dryland Carbon Cycle

The C stock in dryland ecosystems is strongly impacted by a range of processes, factors, causes, and interaction among them (Fig. 3), which are also the primary control (determinants) of the fluxes between the atmosphere and other C reservoirs (i.e., vegetation, soil, ocean, Fig. 1). Soil C stock in drylands is also affected by erosional processes, both eolian and hydrologic, which influence transport, redistribution, and deposition over the landscape (Fig. 4). However, the fate of C transported and deposited by erosional processes is a researchable priority.

Fig. 2 Global dryland stocks of soil organic carbon and soil inorganic carbon (drawn from [4])



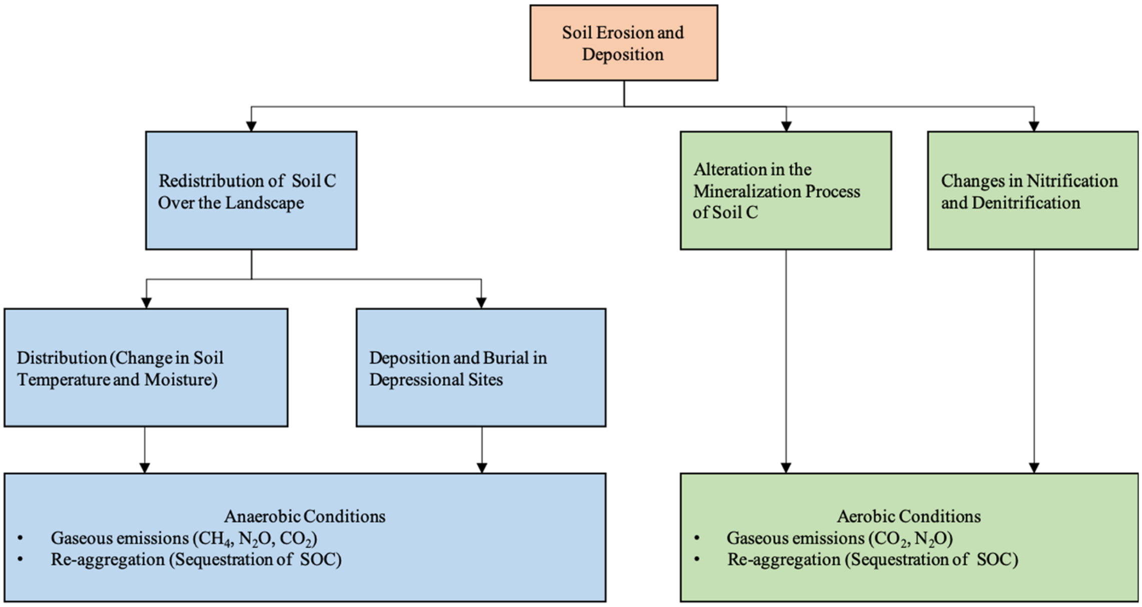


Fig. 3 Fate of carbon and nitrogen transported by erosional process

Predominant biotic processes of C sequestration in drylands are those related to NPP (photosynthesis, respiration) and abiotic due to the formation of secondary carbonates, leaching of bicarbonates, and weathering of silicate minerals. Drought, heat, and wildfires, in conjunction with the intensity and frequency of extreme events, have a strong impact on NPP. Abiotic processes of soil C sequestration are affected by decomposition of biomass-C added through NPP, leading to a high concentration of CO_2 in soil air, formation of weak carbonic acid through its dissolution in soil water, and its precipitation as carbonates by interaction with cations (Ca^{+2}, Mg^{+2}) added into the system through external sources [19]. Formation of secondary carbonates is also accentuated by soil biotic activity (i.e., earthworms, termites) and microbes (i.e., fungi) [30, 31]. Although phytolith-occluded C, formed within plants, is relatively recalcitrant, it is sensitive to land use change and soil/crop management [14, 32]. Despite a considerable progress in scientific understanding, research data on the impact of projected climate change on highly complex and non-linear processes of soil C dynamics [33–35] are scanty.

Global Estimates of SOC/SIC and Total Nitrogen and Factors Affecting Their Dynamics

Depth distribution of SOC, SIC, and total nitrogen (TN) stocks shown in Table 1 indicates strong differences among

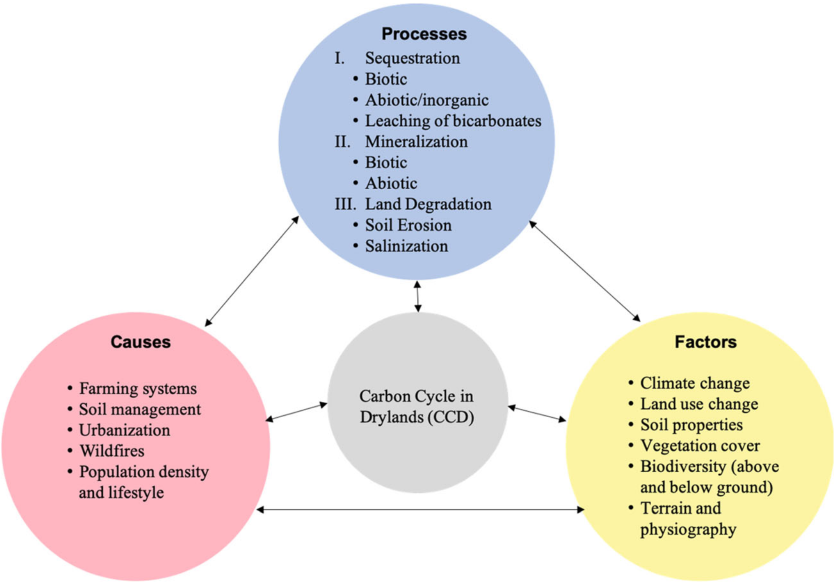


Fig. 4 Processes, factors, and causes affecting the carbon stocks in the terrestrial ecosystems (soil, vegetation) and the carbon cycle in drylands (CCD)

dry and humid climates. The ratio of SOC stock in dry:humid climate for all three depths indicates that SOC stock in drylands is about 50% of that in the humid climate. In contrast, SIC stock in dry climates is > 5 times that in humid climates for 0–0.3 m and 0–1.0 m depth and ~ 4 times that in 0–2.0 m depth (Table 1). Total N stock in dry climates is about two-thirds of that in the humid climates at all three depths.

The ratio of SOC to TN stock, presented in the last column of Table 1, indicates similarities and differences in the C:N ratio. With regard to the similarity, the C:N ratio decreases with an increase in depth in both dry and humid climates. For example, the C:N ratio decreases from 11.0 for 0–0.3-m depth to 8.8 for 0–2-m depth in dry climate, and from 13.9 for 0–0.3-m depth to 12.6 for 0–2-m depth for the humid climate. However, the C:N ratio for each of the three depths is more for humid compared with that for the dry climates indicating relative abundance of undecomposed (labile) fractions in humid climates. Conversion efficiency of biomass-C into stable SOC is more for narrow than wide C:N ratio.

i) Climate change and soil C stock in drylands: Temperate drylands are likely to shrink with the climate change, and thus the total soil C stock may decrease. This shrinkage is attributed to the anthropogenic climate change and the attendant increase of temperature in the temperate region [36]. Further, shift in vegetation structure and composition due to climate change is exacerbating risks of land degradation in drylands [36]. Two large regions of temperate drylands include the following: the Southwestern United States and central Asia. Li et al. [37] reported that the C stock in central Asia with a land area of 5.6 M km^2 was 31.3–34.2 Pg in top 1 m of soil and an additional 10.4–11.1 Pg stored in 1–3-m deep sub-soil. This stock represented 90% of the total C stock in central Asia and had comparatively higher soil C density than that in the other desert regions. However, the soil C density declined during the decadal drought of 1998–2008 resulting in loss of soil C stock by 0.46 Pg from 1979 to 2011. The loss of C stock was especially high in Kazakhstan, which experienced a decline in annual precipitation of 90 mm/decade [37].

ii) Desertification and soil erosion by water: The widespread problem of desertification is compromising the soil C stock of the drylands with the attendant impacts on soil/ecosystem functionality and adverse impacts on human wellbeing [38]. Sub-Saharan Africa (SSA) is strongly prone to desertification [39] because of a rapid land use conversion of natural to agroecosystems to meet the demands of a growing population. Soil degradation in SSA is indicated by a linear decline in SOC [40], and as much as 65% of agricultural land in SSA is degraded [41]. Accelerated soil erosion by water and wind are the major forms of land degradation in SSA with serious impacts on agricultural productivity through a decline in SOC stocks, and vice versa. Furthermore, the fate of soil carbon transported by erosional processes is an important researchable issue and a part of the displaced C may be emitted into the atmosphere [42], making soil erosion a source of greenhouse gases (Fig. 4). Estimating the magnitude of soil erosion by using RUSLE, Tamene and Le [43] reported the mean average soil erosion of 35 Mg/ha year. in the White Volta Basin of the Nile Basin. The overall mean erosion was 75 Mg/ha per year with a range of 0–650 Mg/ha year [43]. Similar to SSA, desertification is also observed in Arab countries. Darwish and Fadel [44] observed that SOC stocks are low in more than 69% of the cultivated soils characterized by Xerosols, Arenosols, and Lithosols. The average SOC stock in Arab countries is 37± 36 MgC/ha in the topsoil and 78 ±69 Mg/ha in the sub-soil. The total SOC stock in Arab countries estimated at 50.5 Pg is prone to decline by accelerated soil erosion. Accelerated water erosion and indiscriminate urban expansion have already depleted SOC stocks by 25 Pg and 53.6 Pg, respectively, in Arab countries [44].

Soil erosion risks are exacerbated by the change in vegetation cover, both due to natural and anthropogenic perturbations. In the Southwestern United States, change from grass-dominated to shrub-dominated landscape has reduced the SOC stock through an increase in soil erosion by water especially in the high-magnitude runoff events characterized by flash floods. Shrub-dominated drylands may lose more than 3 times as much SOC as the grass-dominated landscapes [45]. Thus, understanding of the erosion-induced SOC loss at the landscape level is critical to minimizing the risks of desertification and loss of SOC stocks. Knowledge of the changes, anthropogenic, and others, in ecosystem structure and functions (e.g., runoff and erosion), is critical to the adoption of sustainable land management options [46, 47].

iii) Soil erosion by the wind: Degradation of drylands by wind erosion is aggravated on drylands which are also prone to water erosion. The hydrologic-eolian erosion and vegetation dynamics in dryland strongly impact the CCD because of the erosion-induced loss of SOC. Projected climate change may lead to abiotic control of land degradation in drylands and shift to eolian rather than hydrologic soil erosion processes [36].

Therefore,the adoption of a holistic approach is critical to addressing the vegetation-hydrologic-eolian land degradation nexus. Reducing risks of SOC erosion by wind is an important strategy for advancing the concept of land degradation neutrality or LDN [48, 49]. Land use, including agriculture, forestry, and others, along with management practices must be specifically targeted to minimize risks of SOC erosion by eolian processes.

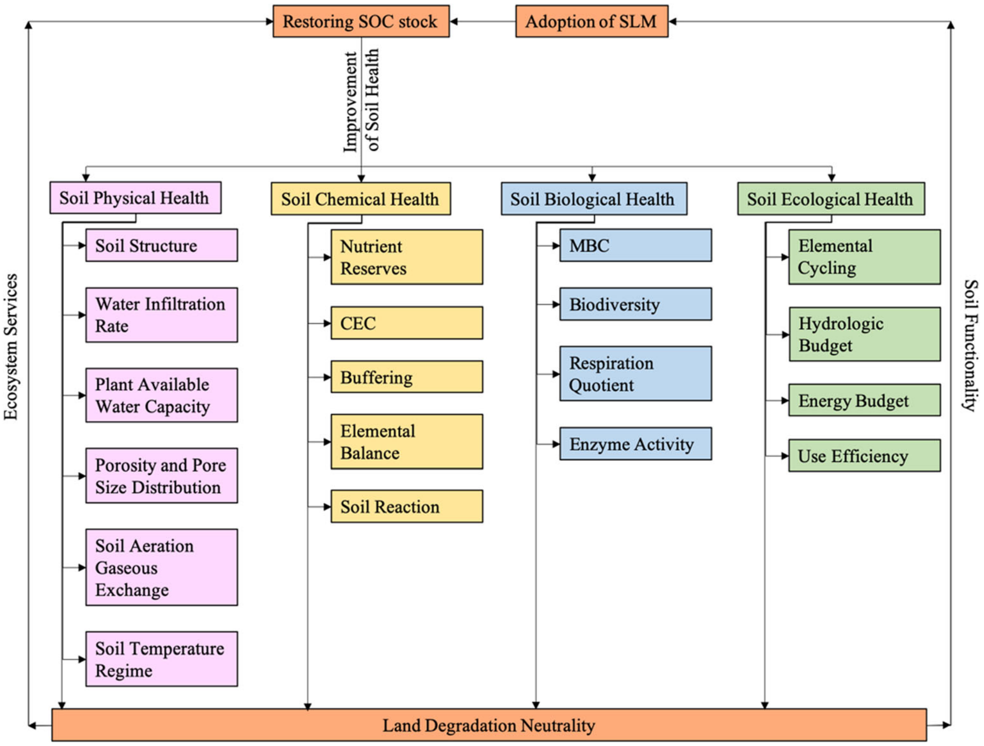
iv) SOC loss by salinization: Climate change and aridization are aggravating risks of soil salinization, especially those of the secondary salinization of irrigated lands. Salinization aggravates SOC depletion because of loss in NPP and less input of biomass-C into the soil. Decline in NPP due to salinization is attributed to complex factors including an increase in risks of drought, elemental imbalance, and a deficit of essential plant nutrients. Saline soils, covering about 397 Mha [50, 51], have reportedly lost an average of 3.47 Mg SOC/ha [52]. Thus, global SOC loss by salinization may be more than 1.4-Pg C because of the large areas affected by primary salinization in drylands and humid ecosystems. The historic loss of 1.4 Pg is also an indication of the C sink capacity through the restoration of salt-affected soils. Prominent among sustainable land management(SLM) to restore SOC by enhancing NPP are the following: saline culture, halomorphic plants, water conservation, drip sub-irrigation/fertigation, erosion control, agroforestry, etc.

v) Other processes affecting carbon cycle in drylands: SOC stocks in drylands can also be depleted by other degradation processes related to nutrient depletion, soil structural decline and reduction in activity, and species diversity of soil biota [7, 53]. In addition, phytodegradation involves the direct breakdown of SOC by ultraviolet light and emission of CO$_2$ [14, 54]. The problem of phytodegradation may be aggravated by a future decrease in the cloud cover and increase in the O$_3$ concentration in the stratosphere [55], which may be an abiotic process [56] leading to SOC loss of as much as 160 kg/ha for the dry season [54] in the Southwestern United States.

Impact of Land Restoration on Carbon Cycle in Drylands

Enhancing soil C (both SOC and SIC) in drylands is a pertinent strategy to reduce the rate of increase in atmospheric CO$_2$ concentration by anthropogenic activities. Restoring soil C

Fig. 5 Relationship between SLM and SOC to advance LDN (CEC, cation exchange capacity; MBC, microbial biomass carbon; SLM, sustainable land management; SOC, soil organic carbon; LDN, land degradation neutrality). The respiratory quotient is a ratio of the volume of CO$_2$ released by the soil microorganisms to that of the O$_2$ consumed



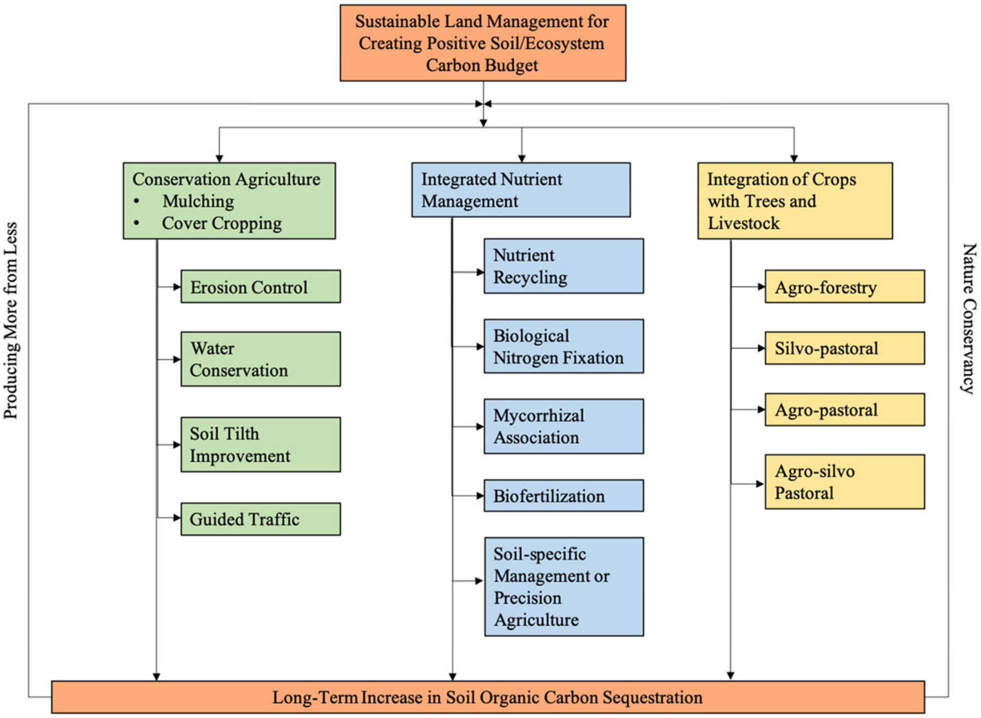


Fig. 6 Technological options for achieving soil carbon sequestration. The term "guided traffic" refers to limiting the passage of tractor tyres in farmland to a specific region to minimize the risks of soil compaction over the entire landscape

stock has a strong impact on soil physical, chemical, biological, and ecological properties and processes and on the overall soil health (Fig. 5). Therefore, adopting options for SLM of the dryland is critical to increasing SOC/SIC stocks (Fig. 6). For example, drylands store 646 Pg of SOC and 1237 Pg of SIC to 2-m depth, and 248 Pg of SOC and 145 Pg of SIC to 30-cm depth. Increasing SOC of 248 Pg by 0.4%/year, according to the "4 per thousand" initiative [57], would imply offsetting anthropogenic CO_2 emissions by as much as 1 Pg C/year. However, estimates of SOC storage through the restoration of drylands vary widely. The rate of soil C sequestration depends on a range of site-specific factors including soil, vegetation, climate, and land use. In western Australia, Hoyle et al. [58] evaluated SOC capacity for a rainfall gradient of 421–747 mm/year, and observed that the average SOC stock to 0.3-m depth ranged from 33 to 128 Mg C/ha, and that the SOC stock of 59 to 140 Mg C/ha could be achieved within 100 years. The additional SOC sink capacity of 7 to 27 Mg C/ha was mostly in the surface layer and with a limited capacity of storage in the sub-soil. Farage et al. [59] assessed the potential for soil C sequestration in three tropical dryland farming systems of Africa and Latin America by using CENTURY and RothC models. With case studies in Nigeria, Sudan, and Argentina, annual rates of soil C sequestration ranged from 0.08 to 0.17 Mg/ha per year and these rates could be maintained for 50 years. The rates were 0.09 Mg/ha per year for the application of manure, 0.15 Mg/ha per year through maintenance of tree cover, and 0.04 Mg/ha year by the adoption of no-till farming [59]. The SOC sequestration through the input of biomass-C (i.e., manuring, cover cropping, afforestation, conservation tillage) must also consider the potential losses by the so-called priming effect [60]. In addition, there is also a potential of fixation of SIC in the groundwater [19], especially in irrigated lands that cover about 350 M ha globally.

Managing Carbon Cycle of Drylands

The global potential rate of soil C sequestration in drylands is estimated to range from 0.5 to 1.4 Pg C/year (Table 2). Managing SOC has strong positive effects on soil health, (Table 3) and the attendant strengthening of ecosystem services that it creates. With the present land area of 66.7 M km^2 and expanding by the end of the twenty-first century, sustainable management of CCD is a prudent strategy to mitigate anthropogenic climate change and create climate-resilient landscapes. With the soil C stock to a 2-m depth of 646 Pg of SOC and 1237 Pg of SIC (1883 Pg), the priority lies in protecting the existing soil C stocks and restoring the depleted stocks in degraded lands. The observed land-based C sink of 3.2 Pg out of 10.8 Pg C/year emissions (~ 30%) for the decade of 2008–2017 [64] indicates that the capacity of land-based sink can be increased through targeted management. Several observations, pointing towards the uptake of 1 MgC/ha year through abiotic processes, indicate the gross potential soil C sink capacity can be as much as 6.7 Pg C/year for the total land area of 66.7 M km^2.

$$\left[1\,Mg\frac{C}{\cancel{ha}\cdot yr}\times 66.7\times 10^{6}\cancel{km^{2}}\times\frac{10^{2}\cancel{ha}}{\cancel{km^{2}}}=6.7\times 10^{9}Mg\frac{C}{yr}=\frac{6.7\,PgC}{yr}\right]$$

Therefore, managing CCD can be a high priority for mitigating the anthropogenic climate change. Apparently, the linear extrapolation as shown in the equation above leading to a large number of 6.7 PgC/year may be a gross over-estimate and is merely an indication of a large potential sink capacity even if only 25% of it can be realized. Thus, targeted management of dryland ecosystems for C sequestration may increase the magnitude of sink capacity from 0.5–1.4 Pg C/year (Table 2) [61–63, 65] to even a higher level towards the maximum possible of 6.7 Pg C/year. However, the credibility of the data from Eddy-Covariance instruments, proven useful for forest ecosystems, has been questioned for arid lands [66].

Processes During the Carbon Cycle in Drylands

The C stock in the atmosphere was ~ 360 Pg during the last global maximum, was 560 Pg during the pre-industrial era [67], and is 820 Pg at present and increasing at the rate of about 4.7 Pg C/year [64, 68]. A rapid increase in the atmospheric stock, especially since the 1960s, has created a strong interest in the identification of sources and sinks that can moderate the rate of increase of the atmospheric C stock. Whereas melting of the permafrost is a major threat to accelerating the anthropogenic climate change [67, 69], dryland ecosystems may be a major driver of CCD and potentially a large sink [11, 70]. Despite warnings about the uncertainties and limitations of the strategies of mining carbon dioxide from the atmosphere by ecosystems (i.e., [71]), carbon sequestration in terrestrial ecosystems is a viable option to partly off-set anthropogenic emissions. In addition to SOC, sequestration of SIC in soil and ground water [19], primarily driven by abiotic processes in drylands [70], must also be understood and harnessed. Further, the concept of net ecosystem carbon balance or (NECB) [72] is also pertinent to the drylands because SIC plays an important role in CCD. The NECB of drylands can be enhanced to create a negative feedback to CCD as follows:

i) Greening of the Sahel: The large tract of the arid and semi-arid region towards the south of Sahara can be managed to create a "Green Wall" [73] to reverse the desertification trend and increase NECB. The "Green Wall" initiative is also being aided by a recovery from the great Sahelian droughts [74]. The recent trend of greenness of the semi-arid areas observed across the globe must be promoted through policy interventions. Irrigation can increase SOC by 90 to 500% in cultivated desert soils and 11 to 35% in semi-arid regions [75], while also enhancing leaching of bicarbonates.

ii) Fire management: Wild fires, aggravated by climate change and droughts, create a positive feedback to CCD and GCC. Any gains in NECB can be offset by the increase in intensity and frequency of fires [76]. Fires can aggravate uncertainty in any reliable estimate of NEBP and in the quantitative assessment of the components of CCD. Therefore, identification and implementation of strategies to minimize the frequency and intensity of fires in drylands would enhance ecosystem C budget in global drylands and also decrease the magnitude of uncertainty in estimates of soil C stock.

iii) Improving knowledge of the ecosystem carbon dynamics: Despite the realization that dryland ecosystems are driver of the CCD and moderator of the land-based residual C sink, the scientific understanding of the CCD of these fragile regions is weak and the credible database is scanty. Factors affecting soil moisture dynamics in the sub-soil, that can strongly impact the photosynthesis of acacia and other woodlands in these regions [77], must be studied and managed on the basis of credible scientific knowledge. Equally important is improving the understanding of SOC dynamics in drylands regarding the persistence of SOC [78–81], and of the total SOC stocks based on measurements and modeling [82]. Being a major component of the soil C sock, sequestration of SIC following afforestation [83, 84] and other processes [19] is a high research priority. It is also pertinent to understand the dynamics of SOC and SIC in deep sub-soil and the entire profile when cropland is abandoned [85], and when other land use and land cover changes occur [86]. With an important impact on CCD, judicious management of the landscape is also critical to enhancing the biodiversity [87], and thus, restoring SOC/SIC stocks in drylands.

Table 2 Estimates of soil C sequestration through the restoration of degraded/desertified drylands

Soil carbon sequestration potential Pg C/yr	Reference
0.5	[61]
0.6–1.4	[62]
1.0	[63]

Table 3 Effects of soil organic matter on soil properties and processes

Physical		Chemical		Biological	
Properties	Processes	Properties	Processes	Properties	Processes
1. Structure	Soil erosion	Cation exchange capacity	Nutrient retention leaching	Microbial biomass	Respiration, decomposition
2. Water	Runoff, plant available water capacity, infiltration rate	Soil reaction	Nutrient availability	Biodiversity	Ecological processes (nutrient cycling)
3. Tilth	Crusting, compaction	Electrical conductivity	Osmosis	Respiratory quotient	Gaseous exchange, greenhouse effect
4. Heat capacity	Temperature regime	Zeta potential	Fluctuation and aggregation	SOC dynamics	Greenhouse effect, radiative forcing
5. Porosity	Aeration, gaseous exchange			Methanogens	Methanogenesis
6. Surface area	Absorption/adsorption, buffering			Nitrifiers	Nitrification/denitrification
7. Mineralogy	Plasticity, trafficability				

Zeta potential is the potential difference across phase boundaries between soil solids and solutions because of electric charge and nature of cations on the surface of colloidal particles. Also known as electrokinetic potential, and measured in units of millivolts (mV), it is used to explain the double layer characteristics of a dispersed colloidal system. It directly affects swell-shrink properties, flocculation, aggregation, and other rheological properties

iv) Addressing challenges and limitations of carbon sequestration: Whereas this article has attempted to synthesize the existing knowledge about the technical potential of C sequestration (both SIC and SOC) through enhanced understanding of C cycling on global level but with specific focus on drylands, it is also pertinent to objectively consider the counterarguments against C sequestration [66, 88]. Constraints, limitations, and challenges of C sequestration must be addressed through development of site-specific land use and management (i.e., SLM) technologies such that the technical potential of C sequestration (both SOC and SIC) can be realized to harness co-benefits (i.e., food security, water quality and renewability, biodiversity) of this promising and natural option to adaptation and mitigation of climate change. The soil-centric approach of addressing anthropogenic climate change is also in accord with the concept of the "legal rights-of-soil" [89], to reverse the tide of global environmental crisis. It is just the right time to recognize that soil, as an integral part of nature, has the right to regenerate, restore, thrive and naturally evolve so that human can live in harmony with nature.

Conclusions

The synthesis presented supports the conclusion that CCD creates a negative feedback to anthropogenic climate change by sequestering atmospheric CO_2 through both biotic and abiotic processes. Further, the soil C sink capacity can be enhanced through conversion to restorative land uses and adoption of site-specific recommended management practices for effective soil and water conservation and erosion management, reclamation of salt-affected soils, and improvement of water productivity. Management of extreme events (i.e., drought, heat wave, wild fire) is another option to enhance soil C stock and the sink capacity in drylands. Negative feedbacks can be accentuated by increasing soil moisture storage and relative humidity and decreasing the degree-days of supra-optimal soil temperatures through provisioning of a continuous ground cover (inorganic as gravel or organic as crop residues and vegetative cover). Benefits of the CO_2 fertilization on NPP can be realized through the choice of appropriate plant species (halophytes) and improvement in soil fertility (i.e., N) through options of integrated nutrient management and biological N fixation.

Some researchable priorities, based on the knowledge gaps, and review of some urgent issues of global significance include the following:

- Assessing temperature-sensitivity of SOC, SIC, TC, and TN stocks at different depths in dry vis-à-vis humid climates,
- Evaluating soil C sink capacity for SOC and SIC stocks in dry climates, with regard to different processes and site-specific management options,
- Understanding the dynamics of soil degradation with regard to alterations in runoff and erosion, and relative predominance of eolian processes of soil erosion,
- Identifying land use and management systems for the buildup of SOC and SIC, and
- Determining the fate of carbon (SOC and SIC) transported by water and wind erosion.

Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest. The research is sponsored by the Carbon Management and Sequestration Center of The Ohio State University, Columbus, Ohio, 43210, USA.

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