Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 22 | No. 4 | pp. 1809-1819 | 2023

Original Research Paper

https://doi.org/10.46488/NEPT.2023.v22i04.009

Open Access Journal

Carbon Storage Potential of Soil in Diverse Terrestrial Ecosystems

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 12-10-2022
Revised: 23-01-2023
Accepted: 08-02-2023

Key Words:
Carbon storage
Carbon sequestration
Carbon pools
Soil organic carbon
SOC stocks

ABSTRACT

Soil is one of the largest carbon reservoirs sequestering more carbon than vegetation and atmosphere. Due to the enormous potential of soil to sequester atmospheric CO_2, it becomes a feasible option to alleviate the current and impending effects of changing climate. Soil is a vulnerable resource globally because it is highly susceptible to global environmental problems such as land degradation, biodiversity loss, and climate change. Therefore, protecting and monitoring worldwide soil carbon pools is a complicated challenge. Soil organic carbon (SOC) is a vital factor affecting soil health since it is a major component of SOM and contributes to food production. This review attempts to summarize the information on carbon sequestration, storage, and carbon pools in the major terrestrial ecosystems and underpin soil carbon responses under climate change and mitigation strategies. Topography, pedogenic, and climatic factors mainly affect carbon input and stabilization. Humid conditions and low temperature favor high soil organic carbon content. Whereas warmer and drier regions have low SOC stocks. Tropical peatlands and mangrove ecosystems have the highest SOC stock. The soil of drylands stores 95% of the global Soil Inorganic Carbon (SIC) stock. Grasslands include rangelands, shrublands, pasturelands, and croplands. They hold about 1/5th of the world's total soil carbon stocks.

INTRODUCTION

Soil is a major carbon reservoir with great potential to store carbon twice the potential of the atmosphere or vegetation (Schlesinger 1997, Yang et al. 2010). The stocks of soil organic carbon (SOC) act as major carbon inventories in the environment that help in sequestering atmospheric CO_2, acting as its prominent sink (Gomes et al. 2019) and contributing significantly to plummeting the effects of existing and impending climate change (Batjes 1998, IPCC 2014). The atmospheric CO_2 plays a pivotal part in sustaining the temperature of the Earth's surface globally (Dinakaran et al. 2014). Scientists have averaged the surface temperature over land and ocean in 2021 and observed an increase of 1.87°F (or 1.04°C) in comparison to the pre-industrial period (1880-1900) and at the same time, an increase of 1.51°F was observed as compared to the average of 21st century. It is also predicted to rise in mean global surface temperature by 5°C until the end of the 21st century, mostly due to increasing carbon discharges from the expanding use of fossil fuels in automobiles, industries, and alterations in land use patterns (USGCRP 2017). There was a rise in atmospheric CO_2 level from 280 ppm prevailing at the pre-industrial time to 397 ppm by 2014 (Ramachandran et al. 2007, Arias et al. 2021). According to a technical report by IPCC (2021), about 2390 Gt CO_2 was emitted between 1850 to 2019 through anthropogenic sources only (Arias et al. 2021).

In 2020, global CO_2 emissions fell by 5.8%~ 2 Gt CO_2, which is reported to be the largest decline ever, but there was again a hike in global CO_2 release by 4.9% in 2021. India and China surpassed their emission rates by 13% and 4% in 2020-2021 due to the worldwide pandemic hitting the demand for coal and oil more than other energy resources (IEA 2021). With the growing intense focus on escalating climate change impacts and sustaining CO_2 dynamics, in the year 1992, the United Nations Framework Convention on Climatic Change (UNFCCC) was adopted, which aims to maintain the concentration of atmospheric greenhouse gases to a level that is capable of averting harmful anthropogenic intrusion with the climate. The Kyoto Protocol, an international treaty to implement the objectives of the 1992 UNFCCC, was adopted in 1997. It aims to facilitate the advancement and distribution of such mechanisms that help in developing resilience to the effects of changing climate. In its first commitment period (2008-2012), industrialized countries, economies in transition, and the European Union were bound to accomplish the target of an average 5% emission reduction compared to 1990 levels by limiting their fossil fuel usage or by growing net sequestration of carbon in terrestrial carbon sinks (Morisada et al. 2004). An amendment to the Kyoto Protocol, named The Doha Amendment, adopted in 2012 for the second commitment period (2012-2020), aimed to reduce GHG emissions from 5% to 9%. In Article 3, the Kyoto Protocol demands serious measurement of net GHG emissions, carbon sequestration rates, changes occurring in carbon stocks, and a need to establish baseline data of carbon stock worldwide.

Consequently, it is necessary to calculate the magnitude of fluctuations in carbon pools in above- and below-ground environments (Johnson & Kern 2003, Morisada et al. 2004). It is a complicated challenge to protect and monitor carbon stocks at national and global levels (FAO 2017). Land use land-use change and forestry (LULUCF) plays a crucial part in maintaining carbon source and sink and are directly related to land cover changes and, ultimately, in the carbon stocks. LULUCF also alters the quantity of biomass and, ultimately, carbon sequestered in foliage (IPCC 2006). Soil has become one of the most susceptible resources in the world due to land degradation, biodiversity loss, and climate change. The global terrestrial carbon cycle may be affected by slight fluctuations in carbon storage in different horizons of the soil (Johnson et al. 2007, Yang et al. 2010). Anthropogenic activities can also affect and change the soil's potential to carry out sequestration of greenhouse gases.

The soil carbon pools can be augmented by carbon sequestration from the atmosphere to the soil via plant or animal biomass and microbial interface. SOC sequestration takes place in three stages:

1. Photo-autotrophic and chemo-autotrophic fixation of atmospheric CO_2.
2. Dead organic matter incorporated in the soil as SOM (Soil Organic Matter).
3. Microbial decomposition of SOM leads to the addition of carbon in the soil carbon pool (FAO 2017).

Microorganisms produce some extracellular enzymes, either freely present in soil or attached to the inert soil component. These enzymes decompose and break litter into simple nutrients, facilitating nutrient cycling and carbon dynamics (Hofmann 1963). SOC is a significant parameter as it indicates the health of the soil and is a chief constituent of SOM. SOC is not only a significant contributor to food production, but it also helps in moderation and adaptation to changing climatic patterns, thus favoring the attainment of sustainable development goals.

On a global level, estimated average soil organic carbon stocks are reported to be around 1500PgC in the initial 1 meter of soil with some spatial and temporal variability. SOC hot spots such as peat lands or black soil can be very helpful in mitigation and adaptation to impacts of the changing climate as they are highly efficient in sequestering large amounts of carbon in them. Therefore, the soil is a phenomenal and dynamic reservoir of carbon. The soil carbon pool depends on the equilibrium between carbon deposits and the quantity of carbon departing from the soil as CO_2 and CH_4 after decomposition (Kane 2015, FAO 2017). SOC sequestration by means of appropriate and environmentally suitable agricultural methods must be promoted to counterbalance the mounting level of CO_2 in the atmosphere caused due to disturbance in the terrestrial environment (Stockmann et al. 2013, Smith et al. 2016).

The current review focuses on the major aspects influencing SOC, carbon sequestration, and dynamics. The paper also outlines the importance and need to quantify carbon inventories to combat climate change by reviewing the SOC content in different ecosystems worldwide. Finally, the conclusions are summarized with recommendations for land use and effective management techniques to alleviate the climate change impacts.

FACTORS AFFECTING SOIL ORGANIC CARBON STOCK

Significant environmental factors affect the SOC stocks in carbon dynamics involving influx and efflux of carbon. Major environmental features known as the SCORPAN factors, including- soil, climate, organisms, parent material, topography, soil information, time, and space, have a major impact on the SOC (Minasny et al. 2013, McBratney et al. 2003). These conditions strongly influence the processes that control the spatial occurrence of SOC stock, directly or indirectly, and provide an outlook to estimate actual and potential carbon inventories (Wiesmeier et al. 2019). Generally, regional climate regulates the primary productivity, and decomposition processes, influencing the sources, transfer, buildup, and breakdown of organic matter (Sutfin et al. 2016).

Climatic Factors

Carbon reservoirs are primarily correlated with climatic features, particularly solar influx, moisture content, and temperature (Chen et al. 2013, Carvalhais et al. 2014, Ramesh et al. 2019, Wiesmeier et al. 2019). Ahirwal et al. (2021) estimated the fluctuations in biomass, C stock, and SOC stock of the Indian Himalayan region. They grouped the entire region with different ecosystem levels in three prime climatic areas, i.e., tropical, subtropical, and temperate regions. Their study highlighted that SOC stock in temperate regions (167.77 Mg.C.ha^{-1}) is less than in tropical areas (178.6 Mg.C.ha^{-1}).

(a) Precipitation

In many terrestrial environments, precipitation governs the net primary productivity (NPP) and hence accumulation of C in soil. Humid conditions or moisture content in soil favors the formation of SOC by increasing the activity of soil microbes, litter disintegration, and formation of SOM and also favors stabilizing of minerals as a result of the amplified breakdown of parent material (Chaplot et al. 2010, Doetterl et al. 2015). For example, the Amazon biome within Brazil region has a humid tropical climate with mean annual precipitation (MAP) higher than 3100 mm and mean annual temperature (MAT) ranging between 25.9 to 27.7°C stores 36.1 PgC carbon stock (Gomes et al. 2019). Whereas the semi-arid eastern region of Rajasthan in India has a dry climate with average 500-1000 mm annual rainfall and an estimated carbon stock of 2129.9 Tg or 2.13 Pg (Singh et al. 2007). In arid or semi-arid conditions, shortage of water negatively affects NPP, and proportionally, SOC input is also reduced (Hobley et al. 2016, Wiesmeier et al. 2019). Low precipitation often causes soil acidification, resulting in low soil disintegration rates of organic matter (Meier & Leuschner 2010).

(b) Temperature

It is a significant determining aspect for storage of carbon in soil since it affects the biological disintegration of SOM in two ways: firstly, temperature affects or alters soil enzyme activities, microbial metabolism, and labile SOC content in areas with extended fertilization processes (Qi et al. 2016) and secondly it influences solubility and diffusion of carbon substrate which extrinsically depends upon temperature (Von Lützow & Kögel-Knabner 2009, Conant et al. 2011, Ramesh et al. 2019). Many studies suggest that an increase in temperature directly correlates with CO_2 efflux (Ramesh et al. 2019), and there is a relative importance of temperature and moisture. Both these are also two major limiting factors for SOC storage. As a result of these collective determining factors, higher stocks of SOC are found in cold-humid regions due to low evaporation/precipitation ratio and optimum temperature for microbial activity to carry out SOM degradation. In contrast, warmer and drier climatic regions have low SOC stocks globally (Post et al. 1982, Jobbagy & Jackson 2000).

Soil Type and Texture

Organic carbon storage is directly associated with soil type and properties in various ecosystems with varying climatic conditions (Lukina et al. 2020). Soil type is strongly influenced by parent material, which undergoes weathering to form secondary minerals such as Fe-oxides (e.g., ferrihydrite and goethite), hydroxides, and other clay minerals. These minerals determine soil reactivity, composition, and biomass production and protect SOC from biodegradation by actively forming soil aggregates. Soils with high nutrient content produce high biomass and sequester more organic carbon proportionally. Soil systems consist of different-sized particles ranging from gravels and boulders to fine fractions such as sand (0.05-2 mm), silt (0.002-0.05 mm), and clay (0.002 mm) (Dinakaran et al.

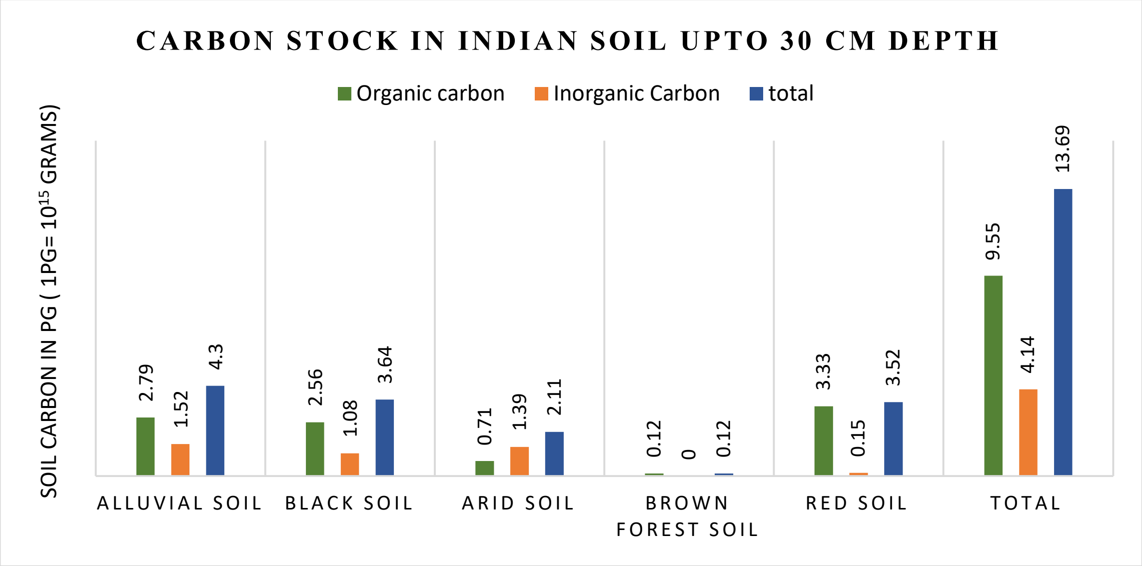

Fig. 1: Organic and Inorganic carbon stock in different soil types of the Indian subcontinent (Bhattacharya et al. 2011).

2014). Soil texture refers to the relative percentage of sand, silt, and clay particles (Kettler et al. 2001). The texture is an important soil characteristic influencing carbon sequestration and stabilization rate. Black and forest soils store high carbon as they have large fractions of clay (34.5%). In general, desert soils stock the least quantity of SOC, while tropical forest soil accumulates the maximum quantity of SOC (Batjes 2016). Drylands exhibit poor soil fertility and less organic matter content (Ramesh et al. 2019). Srinivasarao et al. (2009) examined organic carbon stocks in dominant soil types of tropical India and showed that vertisols have greater SOC stocks followed by inceptisols, alfisols, and aridisols. Bhattacharyya et al. (2009) classified Indian soil mainly into five groups, among which red soils (Alfisols and Ultisols) store the highest amount of organic carbon, followed by alluvial soils (Entisols and Inceptisols) and black soils (Vertisols). Aridisols and alluvial soils have maximum inorganic carbon content (Fig. 1).

Vegetation Cover

Vegetation types on different landforms worldwide influence the SOC dynamics and soil carbon pool though it's a major determinant of SOC distribution. The dominant plant species have varied net primary production, litter chemistry, and rooting depth, influencing carbon input, stabilization, and losses (Gill & Burke 1999). A few studies have also suggested that in tropical forests of India, a variation in SOC storage among different vegetation systems can be seen upto 150 cm in depth. Some studies similarly show that teak plantations with deep roots can stockpile higher carbon than shallow-rooted bamboo cover deeper (Dinakaran & Krishnayya 2008). Consequently, the type of plant species profoundly impacts the deposition of SOC in forest ecosystems at global and regional scales. According to Martin et al. (2010), the type of forest and cultivation influences carbon storage as it was seen that soil of hilltop forest with the cover of *Rhododendron*, *Cedrus,* and *Quercus* plant species stored more carbon upto 30 cm soil layer as compared to carbon stored in similar soil but under agricultural land up to a depth of 150 cm. Thus, the type of cultivation done on agricultural land and varied agroecosystems also influence the SOC. Lal (2018) reported that efficient SOC sequestration is possible in about 4,900 Mha of agricultural land with about 332 Mha area and irrigation facilities. Even soils under Pinus Forest at low slope gradient were found to store less carbon (30.8 $kg.m^{-2}$) than the soils beneath *Rhododendron* and *Quercus* forests (34.7 $kg.m^{-2}$) due to high humification rate (Srivastava et al. 1994). This indicates that the forest type highly influences carbon accumulation in the soil. If we consider the cultivation system, it also follows a similar pattern in terms of carbon storage. In a study throughout tropical India, it was found that crop type has an impact on carbon storage as the soybean cultivation system (62.31 Mg C ha^{-1}) hoarded more carbon stock than groundnut (41.71 $Mg.ha^{-1}$) and maize (47.57 $Mg.ha^{-1}$) agriculture (Srinivasarao et al. 2009). Thus, this indicates that the nature of foliage impacts carbon accumulation in soil.

Altitude and Topography

Altitudinal variation significantly influences SOC content through climatic variables and vegetation. In general, the global quantity of organic carbon in soil increases along with elevation (Ramesh et al. 2019, Choudhury et al. 2016), as climatic factors like mean annual rainfall (MAR) increase with height which subsequently control soil aggregation and further soil processes whereas MAT consistently decreases with elevation. Choudhury et al. (2016) conducted a study in the northern Himalayas which shows, mean rainfall, silt, and clay content increased, while MAT, sand content, and bulk density showed a decline with higher elevation. Similarly, SOC stock increased from 27.1-31.1 Mg ha^{-1} at the 0-500 masl baseline to 55.8 ± 6.7 Mg ha^{-1} at 2500-3500 masl altitude. Soil carbon sequestration potential of landscapes also depends upon the topography, parent materials, and regional climatic conditions. Topographical features are also important in response to SOC storage because they regulate precipitation, water flow pathways, accumulation and discharge of water significantly, and soil erosion. Sloppy areas or convex curvatures result in high water discharge, whereas low-inclined concave curvatures accumulate water. However, Soil moisture is important in controlling NPP, microbial activity, SOC input, and output (Wiesmeier et al. 2019). Bhattacharyya et al. (2009) attempted to estimate SOC stock in different physiographic regions of the Indian subcontinent. Their findings showed that the Northern mountains covering 55.3 Mha of hilly area accumulated 7.89 PgC organic carbon, which is 39% of the total SOC stock of the entire country. This is twice the SOC stock of the Great Plains (3.281 PgC) that spread over 72.4 Mha area and Peninsular Plateau (3.62 PgC) covering 105.7 Mha area.

SOC STOCKS IN DIFFERENT ECOSYSTEMS

Forests

Forests cover nearly 30% of Earth's land area, i.e., 4.03 billion hectares. They account for one-third of gross primary production (GPP) among terrestrial ecosystems and contribute 80% of Earth's total plant biomass (Kindermann et al. 2008). Forests approximately hoard 400 to 700 Pg of Carbon in the soil up to 1m depth (Jobbagy & Jackson 2000, Pan et al. 2011). The elevated organic material in forest soils significantly facilitates the global carbon cycle and becomes important sinks of atmospheric carbon on Earth. The world's forests are broadly grouped into the following major biomes, i.e., tropical forests, temperate forests, and boreal forests. About 30% of the global forest area comprises boreal or taiga forest that lies at circumpolar belt/circumboreal belt across high altitude regions of Russia, Canada, and the United States. Temperate forests cover approximately 25% of the world's forest area and occur approximately between 25°-50° latitudes in both hemispheres, sharing borders with tropical forests and boreal forests in the south and north regions, respectively, and have evergreen and deciduous plant types. The carbon sink potential of this biome is currently estimated as 0.2-0.4 Pg $C.year^{-1}$ (Tyrrell et al. 2012). Tropical forests are generally found between 25° north and south of the Equator and involve predominantly rainforests, montane forests, and mangroves. The tropical domain comprises evergreen and deciduous plant species (FAO 2015, Lal 2005). Ecosystems such as tropical peatlands and mangroves act as storehouses of the highest biomass density, below-ground biomass (roots), and ultimately high soil SOC stock. There was a loss in the forested area between 1990 and 2010, which consequently led to a fall in the total carbon stock contribution of the global forest from 668 gigatonnes (Gt) in 1990 to 662 Gt in 2010, however in 2020 it remained at 662 Gt as there had been a rise in forested areas in, North and Central America, Europe and Asia (UN-DESA 2021). According to Malhi (2010), the destruction and alteration of the Tropical biome resulted in a carbon source of 1.3- 0.2 Pg $C.year^{-1}$ to the atmosphere, while undisturbed tropical biomes were predicted to act as a net carbon sink of 1.1- 0.3 Pg $C.year^{-1}$. The study also illustrates that from 2000 to 2005, the carbon absorption by tropical forests was around 12±3% of total emissions, accounting for 47% of terrestrial carbon sinks. The Boreal forests' soil carbon may constitute around 85% of the terrestrial C stock, while temperate forests have 60% and tropical rainforests have 50% C stock. The soils of the tundra, pre-tundra, and taiga regions constitute much of the total SOC stocks (Table 1).

Table 1: Carbon stock estimation in major forest biomes of the world (Prentice et al. 2001; Lal 2005).

Forest	Area [Mha]	Soil Carbon Stock [Pg]	Soil Carbon density $[Mg.C.ha^{-1}]$
Boreal Forest	1.37	338	296
Temperate Forest	1.04	153	122
Tropical forest	1.76	213	122
Total	4.17	704	-

Morisada et al. (2004) quantified stock of organic carbon in the forest soil in Japan covering a total area of 2,42,940 km^2 and found that brown forest soil (70% with Cambisols and Andisols as major components) and black soil were the second largest types (13%). The rest comprised immature, red-yellow, gleysol, and peaty soil. The estimations illustrated that the total organic carbon (TOC) in the top 30cm soil depth was 2180±50 Tg ($1Tg=10^{12}g$) which is approximately half of TOC up to 100cm depth in mineral soil, i.e., 4570±500 Tg (total ±95% confidence limit). The average value of area-weighted carbon density for the 30cm soil profile was reported to be 9.0 kg/m^2. In contrast, the organic carbon density for the upper 100cm depth was 18.8 $kg/m^{2,}$ which was more than the mean global carbon density ($11.3\ kg.m^{-2}$) (Sombroek et al. 1993) but larger than the carbon density of the cool temperate wet forest, i.e., 13.9 $kg.m^{-2}$ (Post et al. 1982). It is assumed that volcanic ash is responsible for such high carbon density of Japanese forest soil because it has higher efficiency in absorbing, retaining, and stabilizing organic matter. Another study done by Kyuma (1990) and Gomes et al. (2019) to estimate SOC stock in Brazilian soil revealed that Brazil is majorly covered by the Amazon biome (49.29%), having a humid tropical climate, with MAP $\geq$ 3100 mm and MAT of 25.9-27.7°C, Cerrado biome (22% of terrain) and Atlantic Forests. The Atlantic Forest has MAT ranging between 11-26°C and MAP between 700-1500 mm and stores 11.49 Pg of carbon in the upper 100 cm soil layer. Even though the Amazon biome has accumulated a maximum quantity of SOC (36.1 PgC), still the Atlantic Forests possesses the highest average carbon density, valued at 12.08 $kg.m^{-2}$. The stock of SOC in the protected areas was calculated in Brazil up to 100cm depth. It was found to be double the overall collective stock of SOC (11.8 PgC) estimated for the countries of Poland (1.75 PgC), Italy (0.99 PgC), Denmark (0.37 PgC), Bulgaria (0.31 PgC), Netherlands (0.30 PgC), Belgium (0.303 PgC) Slovakia (0.12 PgC), French territory (3.1 PgC) (Arrouays et al. 2001) and Great Britain (4.6 PgC) (Bradley et al. 2005, Panagos et al. 2013). Ahmad Dar (2014) assessed the SOC stock at different depths in the temperate forests of *Pinus wallichiana* and *Abies pindrow* in the Himalayan region of west Kashmir at Pahalgam (India). He reported that the mean range of SOC stock ranged between 50.37 - 55.38 Mg C ha^{-1} in 30cm soil depth. Ramachandran et al. (2007) guided a study in the forested regions of Kolli Hills, a part of the Eastern Ghats, Tamil Nadu (India), to estimate carbon stock using geospatial techniques. Kolli hills are hilly terrain, situated at an altitude range of 200-1415 m above msl, and occupy an area of nearly 27,103 ha. This Reserved Forest is divided into five sub-forest types, categorized as (i) Tropical broadleaved hill forest or semi-evergreen, (ii) dry mixed deciduous forest, (iii) secondary deciduous forest, (iv) thorn forests, and (v) *Euphorbia* scrub forests.

The TOC stock in the soil of Kolli Hills was found to be 3.48 Tg. Further, the SOC stock distribution was higher in the deciduous forest as it occupied a maximum geographical area of ~ 47.7% of forest holding a SOC stock of 1.62 Tg, followed by semi-evergreen forest, which covers 14.9% of RF (Reserved Forest) having a SOC stock of 1.005 Tg. Other forests, such as the southern thorn forest, secondary deciduous, and *Euphorbia* Forest, contained 0.46, 0.35, and 0.03Tg of SOC, respectively.

Drylands

Nearly 40% of the Earth's surface accounts for drylands, and they spread approximately 430 million ha of land in segregated form with unclear boundaries (FAO & ITPS 2015, Schlesinger 2017). Drylands are areas where the ratio of precipitation to potential evapotranspiration (PET), also known as aridity index (AI), is less than 0.65mm/mms. In other words, these areas receive lesser average rainfall than the loss of moisture via transpiration and evaporation. They are mainly categorized as hyper-arid, arid, semi-arid, and dry sub-humid regions. Scanty organic matter, nutrient content, and recurrent water-stressed conditions are major characteristics of soils of drylands (FAO & ITPS 2015). The soils of drylands store 95% of the global soil inorganic carbon (SIC) stock (Table 2), which is projected to be around 1237±15 Pg (Wang et al. 2016). This is 2 to 3 times more than organic carbon in soil (SOC) up to 100cm depth due to excessive formation of lithogenic or pedogenic carbonates (silicatic pedogenic carbonates and calcitic pedogenic carbonates) as a consequence of physical and chemical weathering of parental rock material and leaching of carbonates in soil and groundwater. The SOC stock in drylands ranges from 470 ± 7 Pg in 1m soil depth to 646 ± 9 Pg in 2 m depth. Humid regions store twice the SOC of drylands in the upper 1m soil profile (Plaza et al. 2018). Global drylands are expanding due to anthropogenic activities, conversion of natural ecosystems into agricultural lands, global warming, and rainfall patterns fluctuations. Some studies also indicate that drylands might expand up to 56% of the Earth's surface area by 2100 (Plaza et al. 2018, Lal 2019). It is reported that drylands have higher efficiency in sequestering carbon, very similar to the pine forests of Europe. 38% of the total global population lives in drylands. Hence 250 million people residing in the area can be affected by a slight increase in land degradation (Shekhawat et al. 2012).

Singh et al. (2007) estimated soil carbon stock (CS) in the arid and semi-arid areas of Rajasthan at two different depths, i.e., 0-25 and 0-100 cm. According to their estimations total carbon sock was 2129.9 Tg or 2.13 Pg. The surface layer (0–25 cm) accumulated about 31% of 0.64 Pg of total carbon. Out of the total carbon stock of the state, SOC stock comprised 58.9%, equivalent to 1230.7 Tg, while the SIC was found to be 899.2 Tg making 41.1% of the total carbon stock. Consequently, Entisols covered 43.6% of the land area and confined the highest CS of 0.72 Pg or 33.6% CS,

Table 2: Classification of drylands Soil Organic Carbon (SOC) and Soil Inorganic Carbon stocks (SIC) (mean ± standard deviation) (Plaza et al. 2018)

Dryland	Aridity index [AI] mm/mm	Area Mkm^2 [Million-kilometre square]	Soil Organic Carbon [Pg]			Soil Inorganic Carbon [Pg]		
			0-30 cm	0-100 cm	0-200 cm	0-30 cm	0-100 cm	0-200 cm
Hyper-arid	<0.05	8.6	11±1	22±1	31±1	20±2	65±3	127±5
Arid	0.05-0.2	20.8	45±3	91±3	127±3	63±2	241±5	487±9
Semi-Arid	0.2-0.5	24.1	100±2	190±3	259±3	48±2	207±4	456±7
Dry sub-humid	0.5-6.5	13.2	91±3	167±4	228±6	15±1	66±2	168±4
Dry	>6.5	-	248±6	470±7	646±9	145±4	578±8	1237±15

Table 3: Soils carbon stock (in Tg) in different soil types of Rajasthan in 1992 (1000 Tg = 1 Pg) (Singh et al. 2007).

Soil type	Area [km^2]	Soil Organic Carbon		Soil Inorganic Carbon		Total Carbon Stock	
		0-25cm	0-100cm	0-25 cm	0-100cm	0-25cm	0-100 cm
Aridisols	93082.6	42.3	225.2	43.9	472.1	86.2	697.3
Inceptisols	77141.8	81.6	368.2	22.4	250.6	104.0	610.8
Alfisols	2460.4	4.1	15.7	0.0	0.0	4.1	15.7
Vertisols	10212.2	17.3	56.7	9.9	49.2	27.2	105.9
Entisols	138278.4	205.7	578.4	56.2	137.7	261.9	716.1
Total	321175.0	337.7	1230.7	302.6	899.2	640.3	2129.9

followed by Aridisols (28.9% of total area) with 0.70 Pg or 32.7% of CS. Inceptisols covering 24.01% area had 0.61 Pg or 28.6% of CS, and the rest of the soils, like Alfisols and Verisols, were deficient in CS with 0.015 and 0.105 Pg C, respectively (Table 3).

Grasslands

Grasslands covered approximately 3.5 billion ha in 2000, 26% of Earth's surface and 3/4th of the agricultural area globally (Bol 2010). Grasslands commonly include shrublands, rangelands, croplands, and pasturelands used to cultivate fodder crops or as pastures. They have treasured around 20% of the entire terrestrial carbon stock (Ramankutty et al. 2008, FAOSTAT 2009, Eze et al. 2018). Integrating data from FAOSTAT (2009) and Sombroek et al. (1993), globally, SOC stock of grasslands is about 343 billion tonnes, which is 50% more as compared to forests worldwide (FAO, 2017). According to Schlesinger (1997), grasslands have high intensity to inherit soil organic matter (SOM) content, around 333 Mg.C.ha^{-1}. Practices supporting carbon sequestration in grasslands also enhance resilience to combat climate variability and ultimately aid in long-term adaptation towards impending climatic change. Till now, 7.5% of the total grasslands of the world have already been degraded, and in continuation, most grasslands are still vulnerable to degradation because of intensive grazing for higher livestock production. Africa's rangelands are greatly affected and face pressure to fulfill the increasing supply of milk and beef in the subcontinent (Reid et al. 2004). It has been reported that about 49% of the world's grassland and approximately 50% of natural grassland has undergone degradation to various extent due to land mismanagement, and several countries have brought a large area of grazing and grasslands under cultivation (Gibbs & Salmon 2015). Recently, it has been indicated that 16% of rangelands, comprising 20-25% of the total area worldwide, are under threat of degradation due to cultivation which substantially credits approximately 0.8 Mg carbon from soil to the atmosphere every year (Schlesinger 1990). Thus, it is important to sustainably manage grassland ecosystems and maintain high levels of soil organic matter. In Australia, 81% of land area is rangelands and are estimated to store 34 - 48 Gt of carbon, representing a high ability of carbon sequestration, i.e., 78 Mt C/year with little upsurge of about 0.25% annually (Eady et al. 2009, Wang et al. 2018). The southern part of Brazil has a Pampas biome occupied by temperate grasslands with MAP of 1300mm – 2500mm and MAT of 14 to 20°C, which can store 1.49Pg C stock. The average carbon storage increases with depth as 1m depth soil hoards approximately 10 kg.m^{-2} of organic carbon, as shown in Fig. 2.

Determination of SOC was done by Yang et al. (2008) in the Qinghai-Tibetan Plateau, situated at an average altitude of ~4000 m, covering an area of approximately 200 million hectares, which is the highest on the Earth and larger than Alaska (Li et al. 1998) having MAT of 1.61°C and MAP of 413.6 mm. The dominant ecosystems covering over 60% area are the alpine steppe and alpine meadows. The quantity of SOC accumulated in the upper 100 cm of soil in the entire alpine grasslands was calculated as 7.4 PgC, and the mean carbon density was 6.5 kg.m^{-2}. The SOC stock and organic

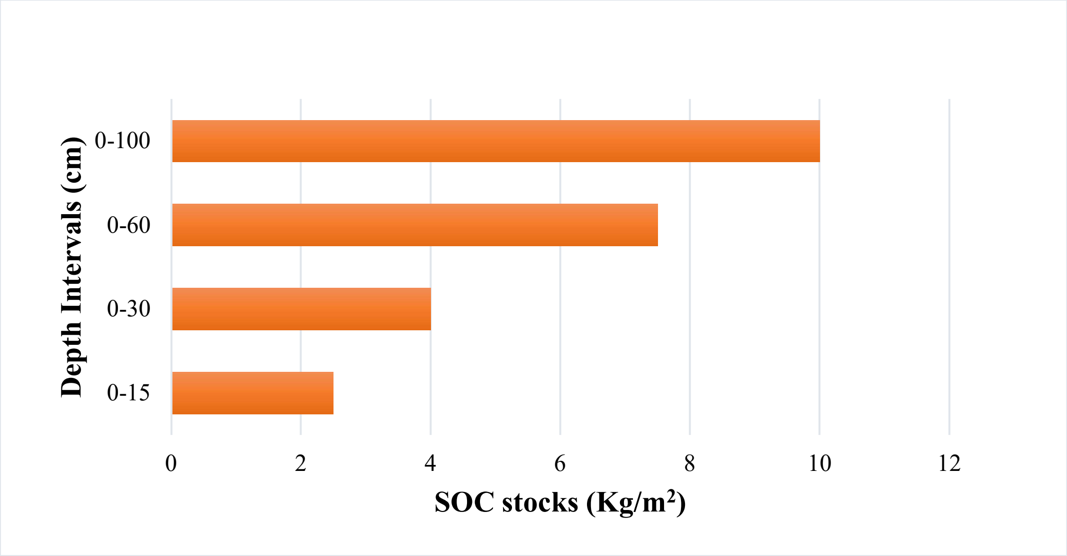

Fig. 2: Cumulative SOC stocks (kg/m^2) for the Pampas grasslands at different depth intervals (Gomes et al. 2019).

carbon density up to 1m soil layer in the alpine meadow were 4.68 PgC and 9.05 kg.m$^{-2,}$ respectively, twice that of the alpine steppe with 2.68 PgC SOC stock and 4.38 kg.m^{-2} carbon density. Upland grassland soils of Yorkshire Dales of northern England (UK) showed accumulation of a substantial amount of organic carbon that ranged between 58.93±3.50 to 100.69±8.64 Mg.ha^{-1} and similarly, an average C stock of 69 Mg.ha^{-1} was found to be present in grasslands of Britain up to 15cm soil depth (Carey et al. 2008). Bradley et al. (2005) also stated that England's pastures store 80 Mg ha^{-1} SOC stock in 30 cm, and Ward et al. (2016) reported similar statistics of SOC stocks for grasslands of England which were intensively and extensively managed and reported about 82.6 Mg.C.ha^{-1} and 84.7 Mg.C.ha^{-1} respectively.

Wetlands

Wetlands or peatlands are distinct ecosystems that contain high amounts of peat or organic matter from dead plant materials and are saturated with water seasonally or permanently. These ecosystems are characterized by hydrological soils, vegetation, and biological features different from land and water ecosystems. They have the highest productivity and a prominent role in the global carbon cycle because of organic matter's slow decomposition, resulting in a huge carbon pool. Wetlands cover 3% of the total land area, storing almost 20-30% of global carbon stock, approximately 447 PgC of SOC up to a depth of 30cm. Wetlands are one of the most important sinks of atmospheric carbon as the anoxic conditions favor the accumulation of large amounts of carbon due to slower decomposition. The carbon seized in saline ecosystems of tidal areas is generally denoted as "blue carbon" and terrestrial carbon as "green carbon." Nahlik and Fennessy (2016) conducted a study. They revealed that the total stored carbon in the wetlands situated in the adjacent United States is 11.52 PgC, mostly in deeper layers below 30 cm (Fig. 3). According to their data, the wetlands found in Eastern mountains and upper Midwest regions of the US store about 50% of the total carbon in US and plains in the interior region had minimum carbon pools. An extensive area of freshwater inland wetland holds almost 10 times additional C compared to the tidal saline regions. However, the author refers to carbon accumulated in freshwater wetlands of inland regions as teal carbon.

Extensive anthropogenic activities, hydrological modifications, and land degradation result in a high degree of variability in carbon densities in different regions, which ranges between 195±25 tC.ha^{-1} in interior plains to 539±47 tC.ha^{-1} in the Upper Midwest region and Eastern Mountains up to 100 cm depth. The low precipitation area of coastal plains and west faces recurrent dry downs and slow rates of carbon sequestration, holding 198±21 and 216±30 tC.ha^{-1} carbon in the soil.

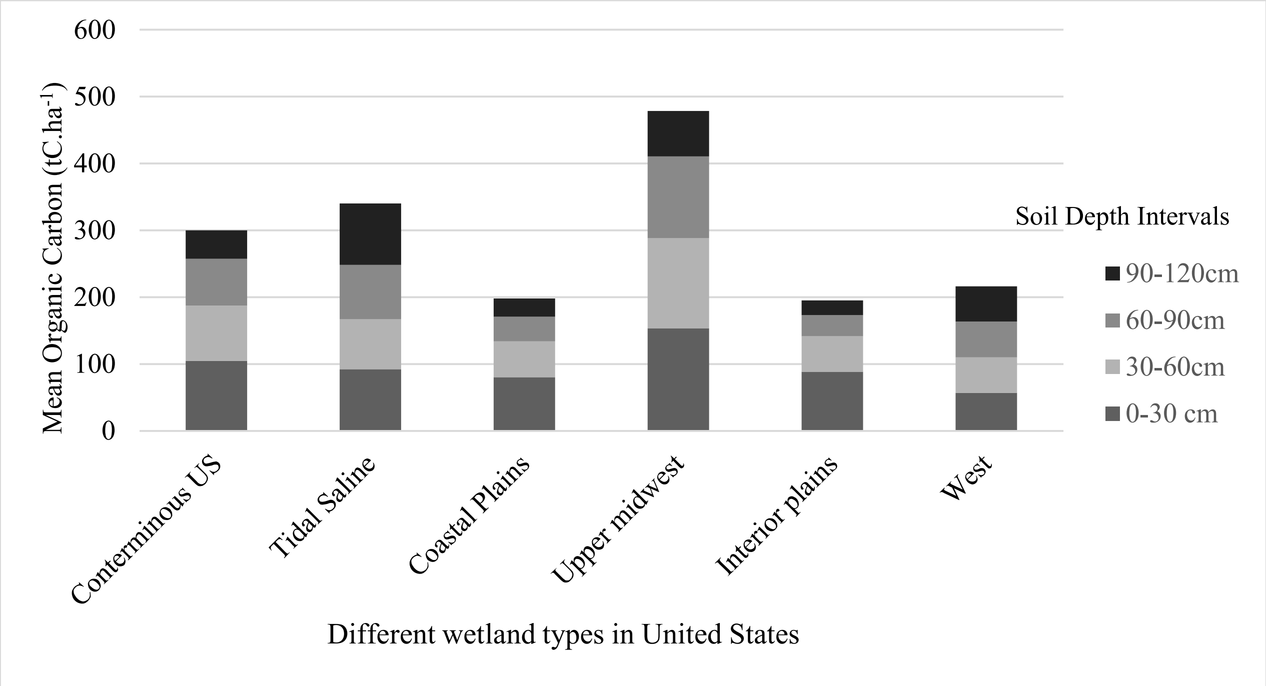

Fig. 3: Soil organic carbon (tC.ha^{-1}) up to 120 cm depth in diverse wetlands sites across the United States (Nahlik & Fennessy 2016).

CONCLUSION

Global warming and climate change scenarios develop a crucial prerequisite for quantifying carbon pools and their monitoring. SOC dynamics involve the influx and efflux of carbon in the form of CO_2 and CH_4. Different phenomena like soil erosion, land use changes, and disturbances lead to the release of carbon back into the atmosphere. SOC hotspots are sensitive to temperature increase as drylands expand and SOC stocks reduce. Therefore, fortification and monitoring of SOC stocks at the global level is a challenging task. Climatic and pedogenic factors control carbon sequestration and its stabilization in deeper layers. Mainly temperature and precipitation govern carbon input in soil along with the proportion and type of vegetation in an area. As the review suggests, cold and humid areas have higher SOC stock than warm and dry regions. SOC is heterogeneously distributed due to variable soil types and climatic conditions. Forests are the major sink of $CO_{2,}$ accumulating about 400-700 PgC in soil. Whereas grasslands cover 40 % of the area and store 343 billion tonnes of C – almost half of the carbon stock of forests (Bol 2010). Converting grasslands into cropland, deforestation, and degradation leads to loss of soil carbon, which is equal to 450–800 Gt CO_2, which accounts for 30-40% of collective emissions of fossil fuel (Marland et al. 2000, Olofsson & Hickler 2008, Bol 2010). Drylands store 95% of the global SIC stock, estimated as 1237±15 Pg. They have the potential to sequester more carbon. Therefore, land use management and conservation practices can foster SOC sequestration and retain carbon for longer periods in the soil. SOC is equally significant in ensuring food security because it maintains good water and nutrient-holding capacity in the soil, ultimately enhancing soil productivity and high yields. Therefore, it is crucial to study and determine the prevailing SOC stock and carbon saturation points of different ecosystems to determine the carbon sequestration potential of various soil types and ultimately manage them to combat climate change sustainably and efficiently.

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