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IMPACT OF LAND USE SYSTEMS AND MANAGEMENT PRACTICES ON DYNAMICS OF SOIL ORGANIC CARBON: A REVIEW

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ABSTRACT

Soil organic carbon (SOC) is an important component for the functioning of agro-ecosystems and its presence is central to the concept of sustainable maintenance of soil health. Soil is the largest terrestrial carbon sink which contains two and three times more carbon than the atmosphere and vegetation, respectively. Therefore, a meagre change in soil carbon sequestration will have a drastic impact on the global carbon cycle and climate change. Identification of location-specific, suitable land use and management practices is one of the options to mitigate the impact of the climate change. It can be done by re-balancing different carbon pools and emission fluxes. Labile organic carbon pools including microbial biomass carbon (MBC), particulate organic carbon (POC) and $KMnO_4$-C are the most sensitive indicators for assessing soil quality after the adoption of alternate land use and management practices.

Key words : Organic carbon, Ecosystem, Climate change, Carbon cycle.

Introduction

Carbon, vital to life, comprises 18% of the human body. CO_2, a key carbon compound, sustains Earth's warmth through the greenhouse effect. With human activities, like fossil fuel burning and deforestation, carbon accumulates in the atmosphere, likely raising temperatures by 1.4-5.8°C this century. The global carbon pools are interconnected, with flux influenced by human activities. Primary production averages 120 Pg C y^{-1}, balanced by plant respiration and soil decomposition. Anthropogenic emissions, mainly from fossil fuels and land use change, total 9.1 Pg C y^{-1}, affecting atmospheric, oceanic and terrestrial sinks. Land-based sink capacity may decline. Understanding terrestrial biosphere's net C sink requires assessing its budget and capacity across spatial scales. Agriculture has long contributed to atmospheric CO_2 and CH_4 emissions.

About 456 Pg of CO_2 was emitted by the terrestrial biosphere pre-1850, with 136 Pg between 1850-1998, primarily from land use changes. In 2008, 18% (1.6 Pg) of 9.1 Pg emitted annually came from deforestation and biomass burning. Fossil fuel combustion emitted 270 Pg between 1850-1998. This history helps estimate terrestrial biosphere's potential to absorb carbon, around 114 ppm. By restoring soils and vegetation, 45-55 ppm of CO_2 could be sequestered by 2050-2060. Evaluating this against other methods is crucial for stabilizing atmospheric CO_2. Terrestrial biosphere could play a vital role in mitigating climate change through carbon sequestration.

The Earth's climate, over its 4.5-billion-year history, has undergone natural cycles of change, impacting sea levels, rainfall and temperature. However, late 20th-century temperature increases suggest a unique greenhouse effect, surpassing natural variability. Industrialization, deforestation and land use changes have altered atmospheric gas concentrations, notably greenhouse gases (GHGs) like CO_2, CH_4 and N_2O. GHGs act like greenhouse panes, trapping heat and

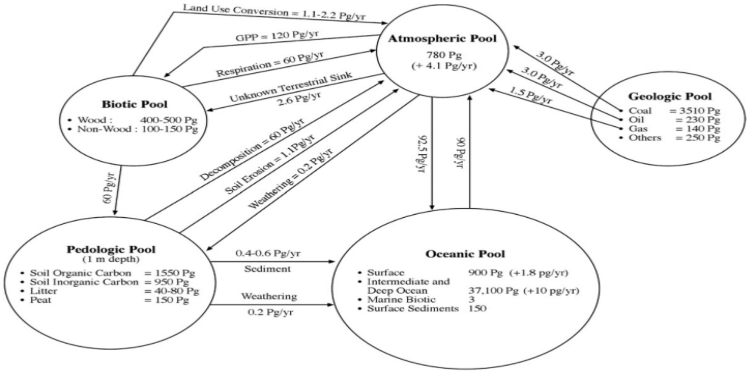

Fig. 1 : Global carbon cycle (Lal, 2008).

Table 1 : Concentration of GHGs in the atmosphere (Anonymous, 2018).

Gases	Conc. in 2008	Conc. in 2018	Annual increase (%)	Contribution (%)
Carbon dioxide (CO_2)	385 ppm	405.5 ppm	1.6	64
Methane (CH_4)	1797 ppb	1859 ppb	1.2	19
Nitrous oxide (N_2O)	320 ppb	330 ppb	0.9	6
CFC	0.18 ppb	0.24 ppb	3.0	11

causing atmospheric warming, influencing regional climate parameters such as rainfall and sea level. Climatic extremes like droughts and floods have become more frequent, likely due to global warming. GHGs originate from solar, volcanic and anthropogenic sources, with CO_2 primarily from fossil fuels and forests, N_2O from combustion, waste and methane from various sources including agriculture and mining. Addressing these emissions is crucial for mitigating climate change. The IPCC (2017) report has projected that by 2100 earth's mean temperature will rise by 1.4 to 5.8^{0}C, precipitation will decrease in the sub-tropical areas and frequency of extreme events will increase significantly. Agriculture sector in India contributes to greenhouse effect primarily through the emission of GHGs such as CH_4, N_2O and CO_2. The total GHG emissions at the country level are 1,523,777 Gg out of which the agriculture has contributed about 355.000 Gg, which constitutes about 23.3%.

Concern over CO_2 from human activity drives research on soil organic matter, carbon sequestration and emissions reduction through global policies and technologies. Storing carbon in soil and terrestrial biosphere via land management is crucial for climate action. Soil holds 1550 Pg of carbon, double that of the atmosphere and triple that of vegetation. Small shifts in terrestrial carbon could greatly affect climate change (Zhang *et al.*, 2016). Soil organic matter (SOM) is complex, comprising plant, microbial, and animal remains at various stages of decomposition. Vital for soil quality, SOM influences physical, chemical and biological properties, impacting soil fertility and productivity. Maintenance and enhancement of SOM are crucial for sustainable soil management, ensuring long-term fertility, structural stability, pH regulation, nutrient supply and microbial activity.

Various SOM pools, differing in decomposition and stability, aid in studying land use effects on SOC dynamics. Total organic carbon (TOC) includes labile and non-labile forms, sensitive to land use changes. Studies note labile fractions' significance, such as the light fraction organic carbon (LFOC) (Six *et al.*, 2002a), particulate organic carbon (POC) (Cambardella and Elliot, 1992), readily oxidized carbon (Blair *et al.*, 1995) and microbial biomass carbon (MBC) (Jenkinson and Powlson, 1976) are quickly changed and restored. Hence, compared to TOC, these labile SOM fractions can be used as sensitive indicators to study the effect of land use change and management practices on soil quality and SOM changes in the short-term. These indicators frequently react more quickly to management-induced changes in the SOC fractions than the bulk SOM and could serve as early sensitive indicators of the overall SOC stock change.

All the labile fractions of SOM appear to have a close linkage with one another and may have a noteworthy effect on soil quality.

Soil organic carbon (SOC) storage depends on input (vegetation, roots) minus output (CO_2). Influenced by topography, climate, soil type, depth, minerals, biota, land use and practices, their interactions determine SOC levels. Several studies have reported increased mineral-associated organic carbon with the increase in the fine fraction of soil particles under cropland, grassland, and forest (Six *et al.*, 2002). Climate change's impact on soil organic carbon (SOC) remains unclear but vital. Temperature affects carbon dynamics, altering build-up and SOC breakdown. Humid climates boost carbon fixation and SOC decomposition, while arid ones limit growth, slowing SOC breakdown. Land use is pivotal for food security, water, and soil quality. Changing land cover and practices significantly affect global carbon pools and fluxes, drawing scientific interest.

Land use shifts alter soil quality, affecting ecosystem function. Cultivating forests decreases soil organic carbon, while cropland conversion increases it. The conversion of fallow lands to cropland, horticultural land, or agroforestry land could increase the log-term build-up of

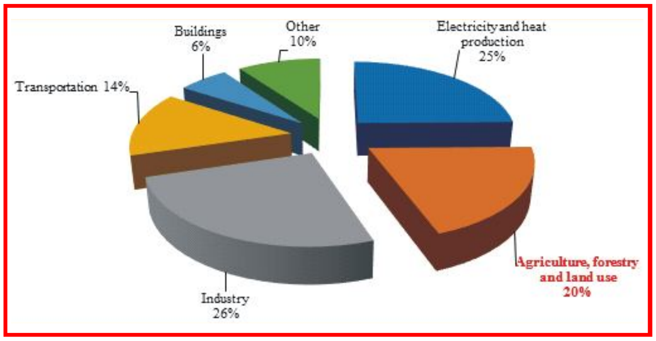

Fig. 2 : Global GHG emission by sector (Anonymous, 2018).

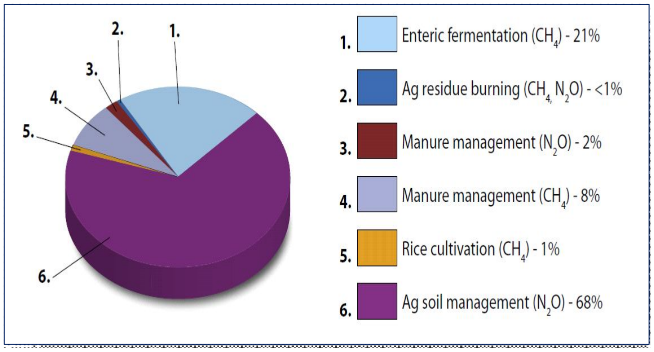

Fig. 3 : Agricultural greenhouse gas emissions by different source (Anonymous, 2018).

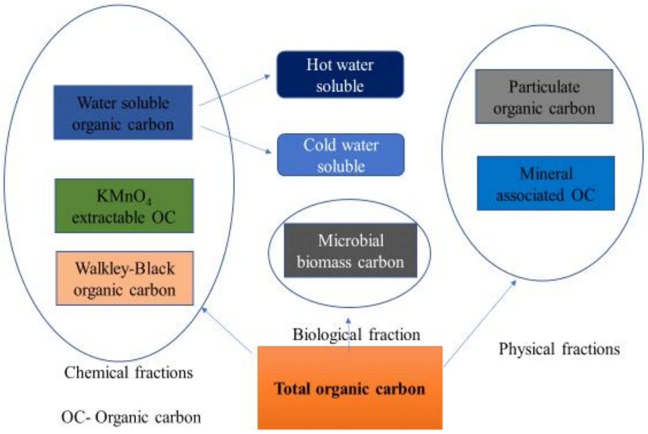

Fig. 4 :

SOC and fractions due to greater organic matter inputs through above ground and below ground biomass to the soil (Ramesh *et al.*, 2013). Studies show soil organic carbon (SOC) increases with residue, fertilization, mulching and integrated nutrient management, but decreases with tillage. Conservation practices improve soil quality, reduce degradation**.**

Factors affecting organic carbon dynamics

Soils store 4.5 times more carbon than terrestrial biomass, crucial in the carbon cycle. Soil Organic Carbon (SOC) balance depends on inputs, outputs, and factors like vegetation, soil properties, and disturbance. Variations in these factors can impact carbon feedback to the atmosphere and global warming. SOC also influences soil processes crucial for plant growth and ecosystem sustainability (Lal, 2004). Soil carbon stabilization unclear despite research. Models lack full decomposition integration, hindering accurate carbon response simulation to management and climate change.

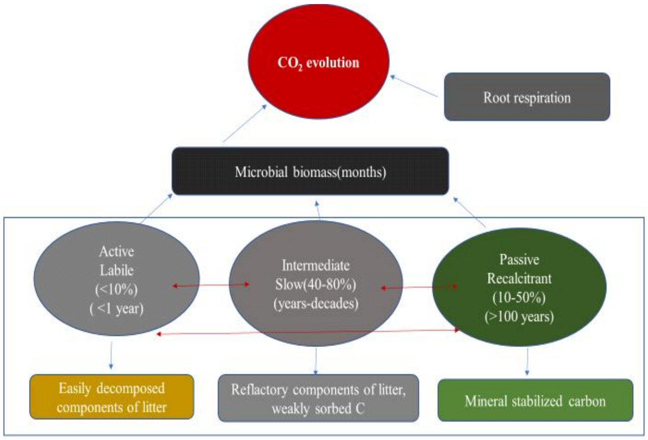

Fig. 5 : Characteristics of different soil organic carbon pools.

Climatic factors

Temperature

Temperature significantly impacts organic carbon decomposition, often modelled using the Arrhenius equation. While models suggest exponential rate increase with temperature, real-world processes exhibit optimal temperature thresholds. Above these, enzyme denaturation and complex cellular responses reduce activity rates. Studies propose reduced microbial populations and enzyme activities with warming, potentially decreasing carbon emissions. However, microbial acclimatization may enhance carbon use efficiency, intensifying decomposition despite reduced growth. Overall, the implications of temperature on soil organic carbon decomposition warrant discussion regarding its feedback on the global carbon cycle.

Rainfall

Rainfall significantly impacts soil organic carbon (SOC) dynamics across various land uses, including agriculture, horticulture, forests and grasslands. It directly influences plant growth, biomass production and SOC storage. Indirectly, it alters soil pH, redox potential, nutrient availability and mineralogy, affecting SOC sequestration. CO$_2$ release from SOC decomposition is influenced by root respiration and microbial activity, both tied to soil moisture levels. Changes in precipitation can lead to varied SOC outcomes. Soil moisture regulates carbon decomposition by facilitating substrate diffusion and enzymatic reactions. Extreme moisture levels affect oxygen diffusion and decomposition rates.

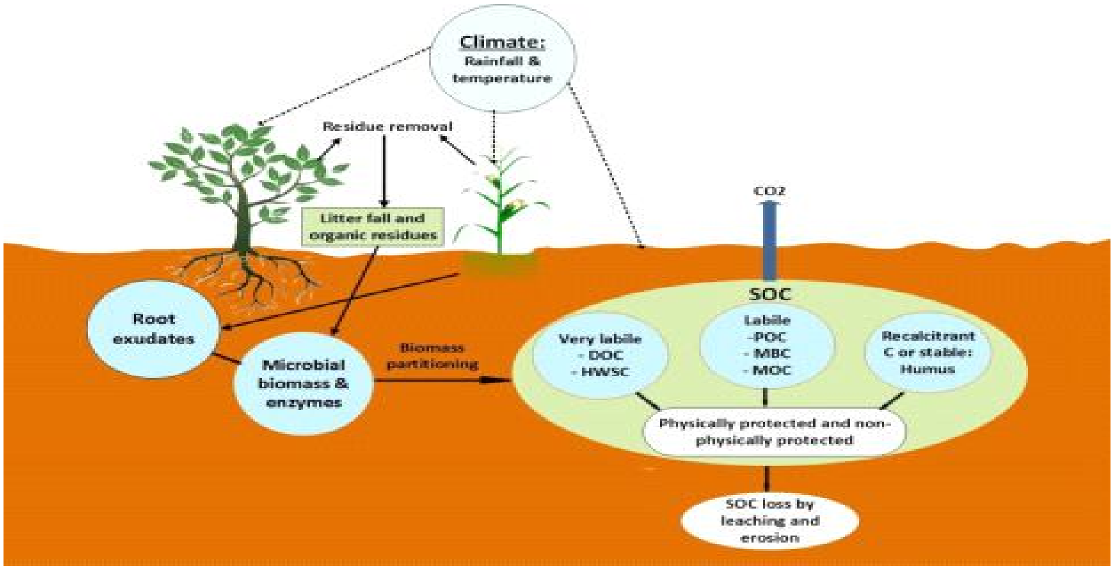

Fig. 6 : Schematic diagram of soil organic carbon dynamics. DOC, dissolved organic carbon; HWSC, hot water-soluble organic carbon; POC, particulate organic carbon; MBC, microbial biomass carbon; MOC, mineral associated organic carbon; SOC, soil organic carbon (Ramesh *et al*., 2019).

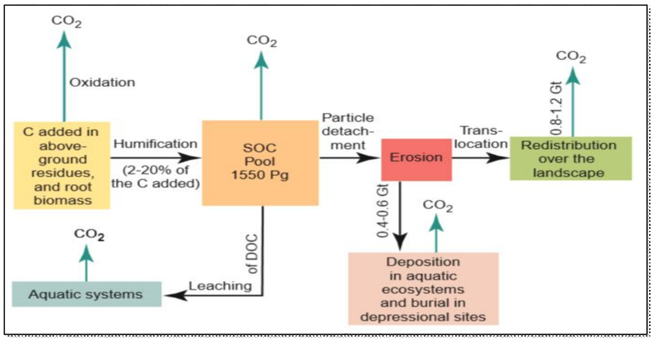

Fig. 7 : Processes influencing soil organic carbon dynamics (Lal, 2008).

Soil-related factors

Parent materials/soil type

Parent material and weathering status dictate soil geochemistry, mineral composition, and reactivity. Mineral resilience, vegetation, climate and hydrology impact weathering. Soil organic carbon (SOC) research focuses on small scales compared to pedological or edaphological studies, neglecting parent material and soil type interactions. SOC characteristics vary by soil type across ecosystems, from desert to forest. Clay-rich black and forest soils boast high carbon availability. Soil type affects SOC content, influenced by nutrients, mineralogy, and texture, determining biomass production and carbon sequestration potential. Clay mineral properties, like surface area and charge density, influence SOC bonding strength.

Soil texture

Soil texture refers to sand, silt and clay particles. Clay increases soil organic matter (SOM) via hindered decomposition and aggregate formation. Clay-rich soils shield organic matter from microbial degradation, resulting in higher SOM content compared to sandy soils. Soils with kaolinite clay are less effective in preserving SOM in tropical conditions due to rapid decay.

Soil pH

Soil pH greatly influences agricultural soil's ability to store carbon (SOC). Models like Century or Roth C often misrepresent SOC changes without considering pH. Understanding pH's impact on SOC dynamics is crucial. pH affects SOC decomposition through physical, chemical and biological processes, including rhizosphere effects and labile-C input-induced decomposition.

Soil moisture

The vadose zone, or unsaturated soil zone, is crucial for land-based water cycling. Soil moisture supports evapotranspiration, affecting plant growth and biogeochemical cycles. Moisture levels influence microbial decomposition of soil organic carbon (SOC) and carbon sequestration. SOC redistribution and CO_2 emissions during erosion depend on environmental factors like moisture, location and rainfall. Increased soil moisture enhances microbial activity until field capacity, beyond which water logging inhibits mineralization and promotes pathogenic growth, impacting plant health. Extended water saturation can enrich soil organic matter.

Soil structure

Soil structure arranges particles into groups like peds, affecting voids and solids. It influences Soil Organic Carbon (SOC) dynamics, acting as a binding agent for aggregates. SOC enhances aggregate stability, crucial for soil structure maintenance and carbon stabilization.

Porosity

Soil porosity, the volume of pore space in soil, facilitates air and water movement. It's categorized into macropores, between macro-aggregates, between micro-aggregates and within micro-aggregates. Pores support soil biodiversity, housing microorganisms like protozoa and bacteria. Microbial-derived SOC is vital for carbon sequestration, with hydrophobic SOC bound in 2–5µm pores and oxidized fractions at a nanoscale in heavy textured soils.

Soil microbial community

Soil microorganisms, including bacteria, fungi, and others, play crucial roles in decomposing organic matter. Soil organic matter (SOM) consists of living microorganisms and their remains, with a resilient humus fraction lasting millennia. Land use changes affect 29 microbe types involved in organic matter decomposition. Boosting soil fungi can slow SOC turnover, aiding carbon sequestration efforts.

Topography

Topography significantly influences soil carbon dynamics, impacting its distribution and sequestration across landscapes. No-till practices enhance soil organic carbon (SOC) content, particularly on mid- and upper-slopes with improved drainage. Erosion and water distribution further affect SOC dynamics. Quantitative data on SOC-topography interactions remain limited, despite efforts to explore their relationship. Understanding these dynamics is crucial for effective soil management.

Altitude

Soil organic carbon is governed by several factors that influence the build-up, as well removal of, carbon. In hilly regions, it is mainly governed by the nature and type of vegetation as well as altitude, because altitude influences to a great extent climatic factors, mainly temperature and moisture. Altitudinal variation has a strong influence on SOC content irrespective of the land uses. Generally, throughout the world, SOC content increases with elevation.

Land use and soil organic carbon dynamics

Soil is a significant carbon sink, storing about twice as much carbon as the atmosphere and three times more than vegetation. Land use and management determine whether soil emits or absorbs carbon. Practices with minimal soil disturbance increase organic carbon. Soil loses carbon when forests are converted to agriculture, but reforestation boosts carbon storage. Techniques like crop rotation, minimal tillage and organic farming enhance soil carbon.

Forests

Because of their high organic matter content, forest soils play a major role in the global carbon cycle and are major carbon sinks on earth. Sreekanth *et al*. (2013) examined organic carbon in four forest types in the South-western Ghats, India. Southern montane temperate forest (SF) had the highest SOC, POC and non-labile carbon. Tropical thorn forest (TF) had the lowest POC and labile carbon. Labile fractions constituted >61% of TOC, suggesting easily mineralizable carbon presence. Labile carbon fractions are sensitive indicators of soil quality changes compared to inert SOC fractions. Ramesh *et al*. (2013) found highest SOC in *Alnus nepalensis*, followed by *Moraxella oblonga,* and lowest in control (0.86-2.01 g/100g). *A. nepalensis* showed 32% higher SOC than control. SOC accumulation depends on tree species, root and litter chemistry, climate, and soil type. Soil N, P and K varied among species, decreasing with depth. Jamala and Oke (2013) found soil textures varying from sandy loam to clay loam in natural forests and fallow lands and loam to clay loam in crop lands. Land cultivation decreased total soil organic carbon, with fallow lands showing the lowest levels. Natural forests had 8-15% more organic carbon than crop and fallow lands. Mineral-associated carbon dominated, suggesting advanced humification favored by climate and soil stability. Forest soils have the highest soil organic carbon (SOC) stocks at 47.5 Mg ha^{-1}, followed by horticultural systems (42.4 Mg ha^{-1}), degraded (36.3 Mg ha^{-1}) and agricultural lands (35.1 Mg ha^{-1}). Agriculture and degraded lands had similar stocks, with lower SOC compared to forests. Losses of 12.4, 11.2 and 5.1 Mg ha^{-1} were observed from agriculture, degraded land and horticulture, respectively, compared to forests. The study found varying microbial biomass C (MBC) levels across land use types, with forests having the highest (107.9 mg kg^{-1} soil) and degraded soils the lowest (76.7 mg kg^{-1} soil). MBC decreased with depth, with agriculture exhibiting the sharpest decline. Water soluble organic carbon (WSOC) ranged widely among land uses but decreased with depth overall. Land use impacts carbon dynamics; forests contribute most, while agricultural practices lead to carbon loss through tillage and biomass removal. Agricultural soils showed the most significant decline in MBC and WSOC with depth, likely due to shallow root systems and surface-focused activities. In contrast, horticulture and forests with deeper root systems contribute organic matter to lower depths. Degraded lands showed lesser declines, attributed to lower surface values. Anthropogenic activities exacerbate carbon loss, particularly in agriculture, affecting soil health and erosion dynamics (Sharma *et al.*, 2014). The mean microbial biomass C values varied across land use systems, with the highest in forests (702.4 mg/kg), followed by pastures (436.4 mg/kg) and lower in converted agricultural areas. Forests and pastures showed higher values due to plant density and continuous organic matter deposition. Permanganate-oxidizable C, indicating labile soil C, followed a similar trend. Forest soils had the highest values (1101.9 mg/kg), followed by pastures, highlighting the impact of land use on soil carbon dynamics. Cold- and hot-water extractable organic C also mirrored these patterns, with forests exhibiting higher values. Hot water extracts more organic compounds due to its higher solubility and also disrupts microbial cells. Agricultural practices like crop residue removal and tillage contribute to carbon loss. Overall, forests retain more carbon, emphasizing the importance of land management in preserving soil carbon stocks (Geraei *et al.*, 2016). Seyum *et al.* (2019) found agriculture had highest carbon stock (8.99 Mg ha^{-1}) compared to forestlands. Land use change to open grazing had second highest SOC (8.69 Mg ha^{-1}), while agriculture-to-agriculture had lowest (5.78 Mg ha^{-1}). Low carbon in agriculture attributed to low TOC and soil structure loss from mono cropping and crop residue removal. Soil organic carbon (SOC) was significantly ($p < 0.05$) affected by land-use change and soil depth. In both soil depths (0-20cm and 20-40cm), SOC was lower in cultivated fields as compared to other land uses. The analysis of the effect of soil depth showed the highest SOC (3.79%) under forest soils at 0-20cm, While the lowest SOC (1.19%) was recorded in cultivated soils at the depth of 20-40cm. Extensive deforestation and the conversion of natural forests into agricultural lands in the Ethiopia ecosystem led to a significant decline in organic matter levels (Welemariam *et al.*, 2021).

Horticulture

Different land uses and management methods affect soil organic carbon (SOC) stocks, driven by biomass production, climate and soil type. Despite horticultural lands' potential to store carbon like forests, they're often overlooked for carbon dynamics and climate mitigation. Perennial horticulture crops enhance soil health and sequester more carbon than annuals, offering cost-effective emission reduction. Fruit trees, generating biomass from pruning, offer resources for fuel, soil improvement and feed, augmenting soil organic carbon. Prioritizing horticultural lands could amplify carbon storage and mitigate global warming. Singh *et al.* (2016) reported that, 25 representative surface soil samples (0–20 cm) were collected from orchards with five major fruit crops to estimate SOC stocks. The fruit crops included guava (*Psidium guajava*), pear (*Pyrus communis*), peach (*Prunus persica*), khasi mandarin (*Citrus reticulata*) and pineapple (*Ananas comosus*). Fruit crops showed a significant influence on changes in the SOC stocks. The maximum SOC stock was found in *P. communis* (68.7 Mg ha^{-1}) followed by *P. guajava* (64.8 Mg ha^{-1}), while *A. comosus* showed the lowest SOC stock (57.9 Mg ha^{-1}). Bhavya *et al.* (2017) noted that, surface soil (0-15 cm) exhibited higher organic carbon content across cropping systems, decreasing with depth. Mango orchards showed the highest levels (6500.00, 6316.00, 5846.00, 4611.00 mg kg^{-1}), followed by cashew orchards. Medicinal and aromatic blocks had the lowest content (4300.00, 3916.00, 3834.00, 3786.00 mg kg^{-1}). Continuous leaf fall in perennial crops contributes to organic matter accumulation, particularly in surface layers.

Agriculture

Soil's role as a carbon sink is crucial amidst rising emissions. Over a third of arable land is used for agriculture, making soil carbon storage vital. Agricultural practices can bolster soil organic carbon (SOC) through increased organic inputs and protective measures against decomposition. While uncertainties persist, prioritizing SOC in agriculture is imperative for mitigating carbon-induced climate change, especially as forest conversion and tillage accelerate SOC decline and CO_2 release. Srinivasarao *et al.* (2009) examined how crop production systems, across different climates and soils, affect soil organic carbon (SOC). They analyzed eight systems, finding highest SOC in soybean-based (62.3 Mg C ha^{-1}) and lowest in pearl millet- and finger millet-based systems. Cotton and sorghum-based systems had highest inorganic carbon stocks, while lowland rice had the lowest. Biomass production likely determines SOC distribution. Bhattacharya *et al.* (2017) found that, different land use systems significantly influenced total carbon (TC), total organic carbon (TOC) and inorganic carbon (IC) concentrations, ranging from 14.72–23.25 g kg^{-1}, 10.38–23.31 g kg^{-1} and 0.03–4.34 g kg^{-1}, respectively. Mango systems exhibited the highest TC and TOC levels, comparable to LTFE and Dalbergia. Organic systems had the highest IC content. LTFE showed notably higher TC and TOC compared to organic systems, while mango systems surpassed guava systems. Agroforestry systems showed no significant differences, except for Dalbergia in IC content.

Grasslands

Grasslands cover 26% of global land, crucial for agriculture, with 20% of soil carbon. Often mismanaged and overexploited, converted from native vegetation. Vital for milk and beef production. Temperate grasslands store 12% of global organic carbon, influenced by management. Intensive cultivation releases carbon, with 20% of CO_2 captured annually. Deforestation, land conversion and degradation cause significant soil carbon losses, equivalent to 30-40% of fossil fuel emissions. Rittl *et al*. (2017) analyzed SOC stock changes in Brazilian Amazon due to forest to pasture conversion. Pasture, maintained for varying periods (11–26 years), showed no significant SOC stock impact. However, transitioning pasture to soybean cultivation decreased SOC stocks by 14–32%. After 26 years, pasture had 8% higher SOC stocks than the natural forest.

Agronomic practices and soil organic carbon

Tillage and residue management

Tillage alters soil structure, affecting compaction and disrupting flora/fauna. Soil structure, defining solids and voids, regulates fluid flow and root growth. Intensive tillage impacts soil organic carbon (SOC), enhancing mineralization by exposing carbon to microbes, especially in optimal moisture conditions. Tillage also has a strong interaction with drainage and both these activities reduce soil moisture and increase soil temperature, thereby reducing SOC mineralization rates (Lal, 2004). Prasad *et al*. (2016) found that, at 0–20 cm depth, TC and TOC were significantly higher in MT than CT (27.6% and 19.2%, respectively). Similarly, 100% OS showed higher TC and TOC (20.1% and 12.2%) compared to 100% IOS and 50% OS +50% IOS. Fallow land had the highest TC and TOC, significantly surpassing all treatments, indicating reduced SOC due to continuous cultivation. RT had intermediate TC and TOC. Organic carbon, predominant (>95%) up to one-meter depth, was highest in MT, likely due to reduced soil disturbance. Continuous cultivation reduced TOC and TC stocks, notably compared to fallow land. Sapkota *et al*. (2017) analyzed soil organic carbon (SOC) influenced by tillage and establishment methods in RPCAU, Bihar. Treatments significantly impacted SOC concentrations across soil depths, with highest variation at 0.15 m. ZTDSR-ZTW+R and PBDSR-PBW+R showed 86%, 32% and 13% higher SOC concentrations than CTR-CTW at varying depths, but 5% lower at the deepest level. ZTDSR-ZTW had 50% and 26% higher SOC concentrations at shallower depths but lowers at deeper levels, attributed to residue retention, increased biomass and reduced decomposition. Kumar and Nath (2019) studied zero tillage (ZT) effects on soil aggregation and carbon sequestration. PTR–ZT+R increased carbon in macro-aggregate (28%) and meso-aggregate (39%) compared to PTR–CT due to added crop residue. RCMb and RC rotations increased active/ passive carbon pools and soil organic carbon over RW rotation. Legume rotations enhanced macroaggregate, indicating better carbon sequestration potential. Particularly, RCMb showed highest aggregated carbon, suggesting long-term legume inclusion boosts SOC storage. Malobane *et al*. (2020) noticed that the NT increased soil organic carbon (SOC), microbial biomass carbon (MBC) and various organic carbon fractions compared to conventional tillage (CT). SOC was 15.83% higher under NT. MBC, CWEOC, HWEOC, and POM, components of soil organic carbon (LOC), were 9.58%, 70.89%, 35.42% and 18.30% higher in NT. Residue retention at 30% showed significantly higher MBC compared to 15% and 0%, with increases of 35.85% and 51.50%, respectively.

Water management

Soil carbon models agree on optimal heterotrophic respiration in wet soil, decreasing with moisture until a minimum. Dryer soils limit microbial access to water, reducing respiration. Saturated soil sees reduced aerobic decomposition, shifting to anaerobic, with 30–40% efficacy. Models vary in optimal moisture values. Moisture regulates carbon dynamics; irrigation boosts biomass, enhancing SOC concentrations in drought-prone soils. Shufang *et al*. (2017) from China reported that the DOC, MBC and TOC concentrations decreased with increasing soil depths and the average concentrations under FI were larger than those under DI at all the measured soil depths. The concentrations of soil DOC and MBC under FI were larger than those under DI. This is due to the fact that high irrigation amounts under FI could result in temporary water saturation and could consequently inhibit the microbial activity, leading to higher DOC and MBC. Chatterjee *et al*. (2018) observed that the soil TOC content varied from 3.2 to 6.4 g/kg at 0–5 cm depth and 3.5 to 4.5 g/kg at 5–15 cm depth. Irrigation boosted TOC by 40.5% at 0–5 cm due to increased root biomass, but had no significant effect at 5–15 cm. Crop residue mulch increased TOC by 14.9% at 0–5 cm. 150 kg N/ha increased TOC by 22.2% at 0–5 cm. After two years, TOC increased by 6.4%. Overall, TOC stock ranged from 8.98 to 11.71 Mg/ha at 0–15 cm.

Nutrient management

Judicious nutrient management is vital for soil organic carbon (SOC) sequestration. Organic manures like farm yard manure (FYM) enhance SOC pools due to their stable complexes with plant proteins, resisting decomposition and enabling carbon accumulation.

Nutrient management improves crop productivity and SOC enrichment, enhancing soil aggregation and water content. However, mineral fertilizers can alter pH and adversely affect aggregation. Despite contrasting effects, nitrogenous fertilizers generally increase SOC stocks. Awale *et al.* (2013) reported that the both full early and full late nitrogen (N) treatments increased soil microbial biomass carbon (MBC) by 47% and 49% compared to half early/half late N fertilizer. Split-dose N application enhances plant N uptake synchrony, but may reduce soil available N, impacting microbial biomass. In this study, half early/half late N treatment showed lower soil available N than full N applied early or late, albeit not significantly different from each other. Srinivasarao *et al*. (2014) observed that the nutrient management significantly impacted carbon fractions. Applying 50% recommended fertilizers with 4 Mg groundnut straw ha^{-1} increased SOC and MBC content by 0.6 and 1.6 times, respectively, compared to control. Similarly, 50% RDF with 4 Mg farmyard manure ha^{-1} doubled POC content. Combining organic and inorganic nutrients notably increased all SOC fractions, likely due to higher crop yield and associated root residues/stubble. Srinivasarao *et al*. (2012) reported that the 13-year cumulative C inputs in soil from various sources: components (leaf, stubble, root, nodules, rhizo deposition and external inputs (FYM). Inputs ranged from 3.9 to 39.6 Mg C ha^{-1}, highest with FYM + 50% NPK. Balanced NPK, FYM, or both boosted biomass and C input (0.72–1.02 Mg C ha^{-1} year^{-1}) compared to control. FYM-treated plots gained extra 2.03 Mg C ha^{-1} year^{-1}. Soil organic carbon (SOC) stocks increased in fertilizer and manure treatments compared to control. In control plots, SOC stocks were 15.1 Mg ha^{-1} at 0–15 cm depth, rising to 19.5 Mg ha^{-1} with NPK + FYM. NPK + FYM showed significantly higher SOC stocks compared to control, N, NPK and FYM treatments, on par with N + FYM. Manure application with N or NPK notably boosted SOC stocks over other treatments, with FYM contributing to organic matter build up and SOC enhancement (Shahid *et al*., 2017).

Mulching

Soil water levels significantly impacted soil organic carbon (TOC) and dissolved organic carbon (DOC) concentrations. Higher water levels, especially with GM and WS residue, notably increased TOC (up to 13.2-fold) and DOC (up to 24.1-fold). Controls at different water levels showed varying TOC and DOC levels, with GM and WS incorporation enhancing mean concentrations. Overall, water level W_2 demonstrated higher TOC and DOC than W_1 (Hassan *et al*., 2016). Venkateswarlu *et al*. (2007) reported that, incorporating Horse gram and fertilizer treatments boosted soil organic carbon (SOC) levels in plots with sorghum-sunflower rotation, ranging from 0.37% to 0.53%. Fallow plots showed SOC variation from 0.28% to 0.46%. Long-term Horse gram incorporation significantly increased microbial biomass carbon (MBC) over fallow, with MBC ranging from 120 to 290 lg g^{-1} soil in incorporated plots and 115 to 217 lg g^{-1} in fallow. Fertilizer treatments had a greater impact than incorporation.

Conclusion

1. Bringing degraded soils under different land uses into forests or perennial vegetative uses can improve the SOC pool.
2. Forest land upon conversion to grasslands can sequester more carbon than when converted to croplands. On average, temperate grasslands store about 331 Mg ha^{-1} SOC.
3. No-tillage practice increases the SOC and MBC content in soil by 15.83 per cent and 9.58 per cent, respectively compared to conventional tillage.
4. Application of crop residue mulch and irrigation will increase the total organic carbon (TOC) concentration by 14.9 per cent and 40.5 per cent, respectively at 0 to 5 cm soil depth.
5. The balanced use of NPK fertilizer along with a lower amount of FYM or other crop residues to provide a C-input of 1.62 Mg ha^{-1} year^{-1} is a feasible option for a sustainable crop production.

Future line of work

1. Quantifying soil C sequestration potential for diverse land use and management scenarios at regional and national levels.
2. Developing the methods of measuring the rate of soil C sequestration that can be used for trading C credits.

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