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Improving Forest Soil Health and Ecosystem Services to Minimize the Impact of Climate Change

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Abstract

The presence of increasing quantities of greenhouse gases is fostering climate change. This review chronicles the emerging research addressing the role of soil to sequester carbon across biomes, understand the soil mechanisms responsible for soil carbon preservation and indicate the need to estimate the intensity for site-specific carbon sequestration. To negate the continuing increase of atmospheric greenhouse gases requires using well-documented soil pathways to sequester carbon. For deciduous forests, emerging concepts center around two approaches: 1) increasing the ecosystem's net primary productivity coupled with increasing the carbon supply into soil using appropriate land management practices, and 2) supporting soil processes that increase soil carbon retention. New perspectives suggest that soil carbon may be preferentially preserved because organic materials are adsorbed onto phyllosilicates and oxyhydroxides and subsequently protected from microbial degradation because of soil structure improvement. Thus, augmenting soil structure may promote soil organic matter persistence. Each soil has a soil carbon carrying capacity; however, soil survey databases infer that soil organic matter concentrations have a significant variance at the soil series level. The need exists for more precise estimates of the soil's carbon carrying capacity at the pedon level to support land management practices that encourage land management options designed to preserve soil carbon. However, the complexity of the soil system may limit its usefulness for routine soil management decisions. Our modern understanding of soil carbon preservation processes and emerging soil carbon saturation deficit concepts may potentially improve decision support tools for managing soils for carbon sequestration.

Keywords

Soil Carbon, Afforestation, Land Management, Climate Change,

Nature-Based Solutions

1. Introduction

Considerable controversy exists about whether soil-plant continuum may transform sufficient atmospheric carbon dioxide (CO_2) to soil organic matter and limit atmospheric CO_2 accumulation. Forests generally have significant soil and vegetation carbon stocks (**Table 1**). Jandl *et al.* [1] reported that forest ecosystems contain 80% of all terrestrial aboveground carbon and 70% of the soil organic carbon. Deng *et al.* [2] reported research showing that the global soil organic carbon abundance was three-fold greater than that of the atmosphere and each soil has a specific soil carbon carrying capacity. Bossio *et al.* [3] noted that soil carbon stocks, if managed properly, may account for 25% of the carbon reduction required for mitigating climate change, of which 40% is associated with maintaining existing soil carbon stocks and 60% is repairing depleted soil carbon stocks. Smith *et al.* [4] reviewed long-term CO_2 emission studies and showed that policies supporting forest development would likely sequester CO_2 as soil organic carbon. Lal [5] noted that the ratio of soil carbon abundance to vegetation carbon abundance typically increases in the higher latitudes.

Considering that forest ecosystems have a high carbon density, afforestation and appropriate forest management have potential to increase soil carbon sequestration. Shi *et al.* [6] performed a meta-analysis and assessed that agroforestry could store 5.3×10^9 Mg additional carbon, with most of the storage in the tropics and subtropics. In China, Wang *et al.* [7] investigated forest productivity

Table 1. Total soil organic carbon stocks and average weighted soil organic carbon.

Forest	Total SOC (Tg C)	SOC (Mg C ha^{-1})
Spruce	1700	260
Aspen birch	3000	270
Slash pine	1100	140
Oak/Pine	1600	80
Loblolly Pine	2100	90
Oak/Hickory	4200	85
Spruce/Fir	1000	170
Douglass Fir	1400	100
Elm/Ash/Cottonwood	200	120
White/Red Pine	1300	190
Maple/Beech/Birch	2800	140

SOC is soil organic carbon. Source: data from D'Amore and Kane [14].

from 1999-2008 and used various databases to infer that nine soil provinces released 25.5 Tg C yr^{-1}, while 22 provinces sequestered 103 Tg C yr^{-1}.

The objectives of this manuscript are: 1) to compare the soil and vegetation carbon stocks across different biomes, 2) to elucidate the soil processes that provide ecosystem services and indicate their fragility, and 3) to evaluate forest soils for their carbon carrying capacity and potential land management protocols to sequester carbon.

2. Optimizing Forest Soil Processes to Encourage Environmental Stewardship

The overriding concept is that maintaining soil processes and providing environmental ecosystem services typically support increased net primary production and offsets soil carbon losses. Baveye *et al.* [8] proposed that research should focus on soil functions and environmental services because they are potentially more productive than focusing solely on soil carbon sequestration. Soil functions and services include: 1) carbon sequestration, 2) provision of food and fiber, 3) cultural heritage, 4) soil formation, 5) support infrastructure, 6) source of pharmaceuticals and genetic resources, 7) habitat and habitat connectivity, 8) nutrient cycling, 9) climate regulation, 10) water purification, 11) flood risk reduction, and 12) sediment trapping [9] [10] [11] [12] [13].

Particulate soil organic matter, frequently called "plant-derived carbon", is a significant terrestrial carbon stock [14] [15] [16] [17] [18]. Fungal growth and microbial activity assist in the transformation of particulate material to soil organic carbon (humus), with a portion of the newly synthesized soil organic material supporting soil structure development and maintenance [11]. Humus is a somewhat stabilized soil organic matter component derived from the microbial decomposition of more labile litter, residue, and other cell materials. Noting that humus is derived from plant and animal material, its chemical composition varies with soil type, vegetation, climate, and disturbance events [19] [20] [21]. Because of the biotic and abiotic decomposition processes, humus is somewhat stabilized from further decomposition because of the preferential accumulation of more difficult to decompose plant materials. However, recently many soil scientists have supported the idea that many factors influence soil carbon persistence [22]-[27]. Lehmann *et al.* [22] proposed that soil carbon persistence is more related to the ability of the microbial community to continue soil organic matter decomposition than the creation of recalcitrant soil organic carbon species. Thus, there is increasing evidence that multiple factors influence the persistence of soil organic matter [23] [24] [25] [26] [27].

Forest soil carbon storage is a function of: 1) forest species, leaf litter, coarse woody debris, roots, root exudates, and dissolved organics, 2) carbon losses attributed to decomposition and biodegradation, and 3) climate induced changes in precipitation and temperature [14]. Lal [28] reviewed soil carbon sequestration and its actual and potential impacts on global climate change. Soil carbon stocks were partitioned as: 1) above ground residues and root biomass, 2) soil organic carbon, 3) carbon redistributed across the landscape because of erosion, and 4) sediment deposition in aquatic systems. Carbon transfer resulting in CO_2 emissions include: 1) microbial decomposition of forest litter and root biomass, and 2) mineralization of soil organic carbon. Lal [28] supported the premise that soil organic carbon sequestration is a function of soil texture, soil structure, rainfall, temperature, farming systems, and soil management. Soil carbon strategies to increase carbon stocks include: 1) soil restoration, woodland regeneration, and afforestation, 2) no-till farming, 3) cover crops, 4) nutrient management including manure and sludge application, 5) improved grazing, 6) water conservation and harvesting, 7) efficient irrigation, and 8) growing energy crops on less productive lands.

Fahey *et al.* [29] evaluated the biogeochemical behavior of carbon in forested watersheds of the Hubbard Brook Experimental Forest. The largest pools of C in the reference watershed were soil organic matter (43% of total ecosystem C), living biomass (40.5%), and surface detritus (14.5%). After a disturbance the ecosystem becomes a large net source of carbon to the atmosphere (500 - 1200 g C $m^{-2}\cdot yr^{-1}$) and eventually becomes a net sink about 15 - 20 years after the disturbance. The forest remains a net sink of about 200 - 300 g C $m^{-2}\cdot yr^{-1}$ for about 40 years before approaching steady state. Developed in the United States in a Federal-State partnership, ecosystem site descriptions are one mechanism for land management assessment and to optimize the continuance of soil pathways essential to maintain desired ecosystem services [13]. The fate of forest soil carbon and the optimization of ecosystem services are entirely intertwined. Assessing the influence of potential warming temperatures, Groffman *et al.* [30] in the northern hardwood forest at the Hubbard Brook Experimental Forest predicted that nitrogen mineralization and nitrification will be inhibited because of anticipated reduced soil moisture contents. Nitrogen cycling processes appear to be more sensitive soil moisture variations, whereas carbon cycling appears to be more influenced by temperature variations.

3. Forest Soil Carbon Reserves

In selected forest ecosystems, D'Amore and Kane [14] reviewed soil organic carbon concentrations and reported that soil organic carbon stocks are frequently greater than the corresponding vegetation biomass and forest litter, especially in cooler climates. Large above ground carbon stocks do not necessarily correlate with high soil carbon stocks, given that warm temperatures, oxic soil conditions, and land management practices support increased nutrient and carbon cycling from the soil to the vegetation and atmosphere [1] [14] [15]. Anoxic soil conditions attributed to water saturation coupled with reduced temperatures collectively act to maintain higher soil carbon stocks [31]. Similarly, greater abundances of clay provide more surface area for organic material adsorption, thus limiting the potential for soil organic matter decomposition [22]-[27].

D'Amore and Kane [14] documented total soil organic carbon contents and the soil organic carbon contents per land area for 11 forest types (**Table 1**). The soil organic carbon concentration per land area was greatest for spruce, aspen-birch forests and the least for oak pine and oak hickory forests.

Investigating Histosols and Gelisols, Aide *et al.* [31] determined that soil organic matter abundance is a function of climate, topography, hydrology, and vegetation. For 13 ecosystems, McGuire *et al.* [32] estimated the 1) net primary productivity (NPP), 2) carbon concentration in vegetation (CV) per land area, 3) and the carbon to nitrogen ratio (C:N) and 4) the soil carbon concentrations per land area. Net primary productivity was greatest in tropical deciduous and evergreen forests and the smallest in polar deserts. The carbon concentrations in vegetation per land area were the greatest in the tropical deciduous and evergreen forests and least in grasslands. Soil carbon per land area was greatest in the moist tundra and boreal forest and least in the desert and arid shrublands. In general, forests that support greater net primary productivities and greater vegetation carbon stocks, especially in the lower latitudes, may not exhibit the largest soil carbon stocks. Significant soil carbon stocks in cooler climates typically have a comparatively smaller net primary productivity; however, reduced microbial activities and slower decomposition rates act to preserve the soil carbon stocks.

More recently Vlek *et al.* [33] listed carbon stocks associated with biomes for vegetation and soil; as well as their areal extent. Tropical forests exhibited the greatest proportion of carbon in vegetation (49.5%), followed by temperate forests (37.1%). Temperate grasslands exhibited the smallest carbon stocks in their vegetation (3%), whereas croplands only presented 2.3% of their carbon residing in the vegetation. Boreal forests have the greatest soil carbon stocks at 471 Gt. When considering their areal extent, total carbon stocks followed the order boreal forests (559 Gt), tropical forests (428 Gt), and tropical savannas (330 Gt).

4. Forest Soil Carbon Dynamics

Historically our understanding of soil carbon turnover was regulated by the soil biology. Microbial populations transform particulate organic materials into humus and control the equilibrium of mineralization and immobilization of carbon materials. One supposition was that the persistence of humus rests largely with an ever-increasing abundance of recalcitrant soil organic materials; that is, soil organic matter that is increasingly composed of heterogenic compounds that become increasingly less susceptible to microbial decomposition. New discoveries reveal that particulate organic matter may be preserved by inclusion in soil structures and by phyllosilicate adsorption. Thus, the complex nature of soil carbon pathways is promoting research into these pathways to gain a more lucid concept of carbon flux through forested ecosystems. **Table 2** lists some of the more recent research initiatives and results, where all content is from the indicated authors.

Table 2. Forest soil carbon pathways and the factors that influence pathway intensities.

Reference Citation	Factors influencing soil carbon dynamics
Jandl *et al.* [1]	Improved Forest productivity enhances the stable carbon pool.
Deng *et al.* [2]	Conversion of farmland to either grasslands or forests increased soil carbon stocks.
Van Cleve and Powers [15]	Rhizosphere activities influence amino acids, phenolic and aliphatic acids, which is regulated by the diversity of the microbial community across soil conditions.
Elliott *et al.* [9]	Net primary production improved with increased litter mass and plant tissue nitrogen.
Witzgall *et al.* [16]	Soil oxygen levels influence soil organic matter turnover. Articulated the emerging hypothesis that the availability of reactive mineral surfaces explained soil organic matter persistence.
Herbert and Bertsch [19]	In forest soils the dissolved soil organic matter concentrations follow the sequence A > B > C horizons across many soil orders.
Schweizer *et al.* [23]	Increasing clay content correlated with particulate soil organic matter preservation.
Singh *et al.* [24]	Soil moisture and texture influence microbial respiration.
Kleber *et al.* [25] [26]	Mineral-organic associations support soil organic matter retention, a feature partially attributed to reduced microbial activity because of reduced organic matter accessibility.
Grandy *et al.* [27]	Conversion of cultivated land to forests improves soil enzyme, fungal to bacteria ratios and soil texture influence soil carbon pathways.
Lal [28]	Microbial decomposition of forest litter and root biomass and soil mineralization control carbon emissions.
Bouwman-Leeman [34]	Provided information on the quantity of the soil carbon pools for vegetation and soil across various forest ecosystems.
Liu *et al.* [35]	With vegetation restoration, organic carbon storage improved.
Cook and Patton [36]	Georeferenced soil carbon accumulation rates and inferred that soil carbon accumulation has significant potential. Carbon arising from coarse woody debris and litter were more abundant for boreal, temperate conifers, temperate broadleaf biomes.
Fox [37]	Fungi and bacteria differ in the types of low-molecular-weight organic acids released because of decomposition.
Harris *et al.* [38]	Integrating ground and Earth observation data concluded global forests were a carbon sink.

Continued

Zhao *et al.* [39]	Increased soil temperatures encourage soil organic matter decomposition and improved net primary productivity would not offset the carbon loss.
Williams *et al.* [40]	Soil mineralization is influenced by the soil organic nitrogen, bulk density, and soil water content.
Lu *et al.* [41]	Long-term soil nitrogen additions decreased soil mineralization rates, attributed to acidification, and induced phosphorus.
Felete *et al.* [42]	Dryer forested sites had smaller biological activities that resulted in larger soil organic carbon contents.

Grier *et al.* [43] provides a compelling listing of North American forest regions and their estimated biomass ($t \cdot ha^{-1}$) and net primary productivity ($t \cdot ha^{-1} \cdot yr^{-1}$). Grier *et al.* further contended that the net primary productivity is a complex function involving biomass and detritus production, which are features that alter substantially with climate, forest type, stand age, succession, topographic position, and soil features. Important soil features include water availability, fertility and nutrient status, and aeration. Soil carbon loss rates are influenced by an array of soil features that influence soil biology and microbial activity.

5. Soil Carbon Preservation

Our understanding of soil organic matter preservation is rapidly evolving. Schrumpf *et al.* [44] noted that soil organic matter stability was a complex function of plant residue, carbon occlusion in soil aggregates (soil structures), organo-mineral complexes (especially Fe-oxyhydroxides), and location in the soil profile. Soil organic matter that was occluded in soil structures supports soil organic matter persistence. In China, Liu *et al.* [45] investigated soil organic matter accumulation in mixed and Larch forests. Soil organic carbon in the organic (O) and A horizons was preferentially preserved in macroaggregates, whereas soil organic matter in deeper soil horizons was preferentially preserved in microaggregates.

Schmidt *et al.* [46] reiterated that soil organic matter persistence was primarily a function of physio-chemical and biological influences, rather that the resulting molecular structure. These authors noted that multiple influences determine soil organic matter accumulation and persistence, including: 1) root type and root biomass, 2) physical separation from microbial activity, 3) deep soil carbon is associated with very long turnover rates, 4) permafrost thawing and the emission of greenhouse gases, and 5) microbial metabolic activities and community structures. In Kenya, Verchot *et al.* [47] investigated long-term soil organic matter storage an intensive agroforestry system. Carbon was partitioned among macro-aggregates, meso-aggregates, and micro-aggregates. The organic carbon distribution among the aggregates is varied by soil type and tillage. The meso-aggregates and macro-aggregates were enriched in carboxylic-C and aromatic-C, inferring that the decomposition of plant-derived C stabilized larger aggregates. Microbially derived polysaccharides were more important in micro-aggregate stabilization. The authors proposed that the independent formation of micro-aggregates is critically important to long-term carbon storage.

Kumar *et al.* [48] discussed the capability of plant roots and residues to develop micro- and macroaggregates, which subsequently sequester soil organic carbon. These authors defined three binding agents that provide stability to soil aggregates: 1) temporary (plant roots, fungal hyphae, and bacterial cells), 2) transient (polysaccharides and organic mucilage's), and 3) persistent (humic compounds and polymers, polyvalent cations). Initially clay particles are sorbed by these substances and begin the aggregation soil process. Transient agents are also sorbed and facilitate the formation of macroaggregates. Persistent agents are more affiliated with microaggregates. Witzgall *et al.* [18] performed an incubation study involving litter amendments to coarse-textured and fine-textured soils. Microbial activity and fungal growth were more evident in the coarse-textured soils. The authors proposed that soil organic matter persistence is attributed to decaying plant litter regulating microbial activity, which promotes particulate soil organic matter occlusion and organic matter sorption on mineral surfaces.

In Quebec, Canada, Fortier *et al.* [49] compared soil carbon contents of poplar and herbaceous riparian buffers. Measuring large and fine root diameters and determining soil carbon contents these authors noted that tree and herbaceous species varied greatly in their soil carbon sequestration. The soil resource also influences carbo sequestration. Thus, tree species selection for afforestation projects is critical to improve carbon sequestration. Spodisols maintain a substantial amount of carbon the surface horizons (epipedons) which may be easily disturbed, whereas Alfisols may have considerable soil carbon in the argillic horizon where the soil carbon is protected in microaggregates and soil adsorption. Afforestation supports the buildup of soil carbon, especially oak-hickory forests where soil carbon is concentrated in the deeper soil horizons.

6. Selected Missouri Soil Organic Matter Contents near the Mississippi River

Twenty-two Mississippi River floodplain soil series in Missouri with established or ancestral forests were selected. The A horizon soil organic matter ranges (**Table 3**) were obtained from soil surveys [50] [51].

The selected soils have textures ranging from loamy-skeletal and coarse-silty to very fine. Soil organic matter contents in the surface horizons range generally from 0.5% to 4%, with the Beaucoup series (Fluvaquentic Endoaquolls), with a fine-silty control section, and the Darwin series (Vertic Endoaquolls), with a fine-texture control section, having soil organic matter contents ranging from

Table 3. Classification and surface SOM of selected Mississippi river floodplain soils.

Soil Name	Subgroup	Control Section	A Horizon SOM (%)
Alligator	Chromic Dystraquerts	very-fine	1 - 3
Beaucoup	Fluvaquentic Endoaquolls	fine-silty	5 - 6
Bowdre	Fluvaquentic Hapludolls	clayey over loamy	1 - 3
Commerce	Fluvaquentic Endoaquepts	fine-silty	0.5 - 2
Caruthersville	Typic Udifluvents	coarse-silty	1 - 2
Darwin	Vertic Endoaquolls	fine	4 - 5
Dupo	Aquic Udifluvents	coarse silty over clay	1 - 2
Elsah	Typic Udifluvents	loamy-skeletal	1 - 3
Falaya	Aeric Fluvaquents	coarse-silty	0.5 - 3
Haynie	Mollic Udifluvents	coarse-silty	1 - 3
Jackport	Chromic Epiaquerts	fine	1 - 3
Haymond	Fluventic Eutrudepts	coarse-silty	1 - 3
Leta	Fluvaquentic Hapludolls	clayey over loamy	2 - 4
Mhoon	Fluvaquentic Endoaquepts	fine-silty	0.5 - 2
Nameoki	Aquertic Hapludolls	fine	2 - 4
Parkville	Fluvaquentic Hapludolls	clayey over loamy	1 - 3
Sharkey	Chromic Epiaquerts	very-fine	0.5 - 2
Steele	Aquic Udifluvents	sandy over clayey	0.5 - 1
Wakeland	Aeric Fluvaquents	coarse-silty	1 - 3
Walbash	Vertic Endoaquolls	fine	2 - 4
Waldron	Aeric Fluvaquents	fine	2 - 4
Wilbur	Fluvaquentic Eutrudepts	coarse-silty	1 - 3

4% to 6%. Of the 22 soils, 11 of the soils have an aquic moisture regime, suggesting these soils preserve humus contents by restricting sufficient oxygen to inhibit sustained respiration rates. However, the soil organic matter concentration variance indicates that many environmental constraints influence soil organic matter accumulation and persistence.

7. The Menfro Soil Series and Estimating the Soil Carbon Saturation Deficit

The authors of this manuscript evaluated two sites of the Menfro series (Fine-silty, mixed, superactive, mesic Typic Hapludalfs). The Menfro soil series consists of very deep, well-drained soils formed in thick loess deposits on uplands adjacent to the Mississippi River. The ochric epipedons (A, E and BE horizons) have soil organic matter contents ranging from 1.6% to greater than 8% and the argillic horizons have soil organic matter contents between one and 2% (**Figure 1**). The total soil organic matter contents for each horizon were determined on an aerial basis (kg·m^{-2}) using soil organic matter contents determined by loss on ignition, horizon thickness, and horizon bulk density. The two sampled pedons have total soil profile organic matter contents on an aerial basis of 36 and 47 kg·m^{-2}, respectively. These well-drained pedons have soil textures that support a high available water capacity, thus the rooting depth and root density support soil organic matter accumulation in the argillic horizons.

Soil Survey, where sufficiently detailed, may support developing a of soil carbon saturation deficit estimate for soils at the series level. Considering the Menfro soil series the National Cooperative Soil Survey Soil Characterization Database (Lab Data Mart) [52] provides physical and chemical characterization data for 134 pedons of the Menfro series. Considering only the A horizon, the mean, low and high soil organic matter contents are 1.4%, 0.8%, and greater than 4%. The range in the A horizon soil organic matter content is attributed principally to land management of the individual pedons, with some pedons in pristine forests and other pedons in cultivated fields. However, there is sufficient data to estimate the soil carbon saturation deficit when allowances are made for the pedon's history of land management. That is, Menfro pedons having long-term forest residence are likely candidates for soils having an elevated carbon content.

8. Evaluating Soils to Advance Soil Carbon Sequestration

Every individual soil has a specific soil carbon carrying capacity; however, variance exists at the soil series level. Soil science does not currently have a rigorous capability to quantitatively estimate an individual soil's carbon carrying capacity. Required soil criteria to predict the soil's carbon carrying capacity would necessarily need to estimate the soil's carbon accumulation rate and the soil's carbon loss rate. The soil's carbon accumulation rate is linked to the ecosystem's

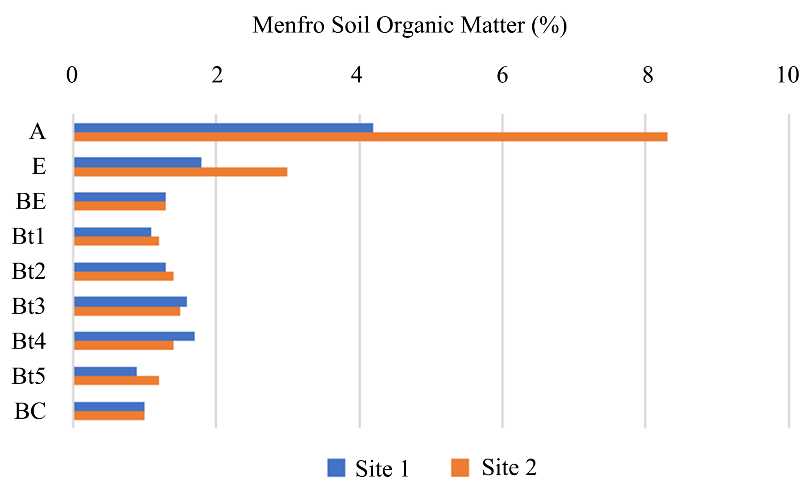

Figure 1. Soil organic matter contents for two Pedons of the Menfro series.

net primary productivity. The net primary productivity is a function of the gross primary productivity minus ecosystem respiration, which are difficult to precisely measure. Net primary productivity strategies to increase soil carbon stocks include: 1) forest regrowth activities, 2) no-till farming, 3) cover crops, 4) nutrient management including manure and sludge application, 5) improved grazing, 6) water conservation and harvesting, 7) efficient irrigation.

Soil properties influence the soil's carbon carrying capacity. Key soil pathways important to establishing carbon's soil abundance include: 1) comparative rates of immobilization and mineralization, 2) the root rhizosphere and release of dissolved organic metabolites, 3) carbon adsorption on phyllosilicates, and 4) soil structure formation and its maintenance [18] [47] [48]. The intensity of these pathways is influenced by land management, soil hydrology and available water capacity, pH, oxidation-reduction status, soil biology and microbial activity, soil oxygenation, and other environmental factors. Soil scientists qualitatively understand how each of these factors influence the soil's capacity to accumulate and then protect soil carbon. However, complications arise when several of these factors are simultaneously operating as their interaction is difficult to model.

The soil carbon saturation deficit is equal to the maximum soil organic carbon content (also termed the saturated soil organic matter capacity) minus the actual soil organic matter content. Zhang *et al.* [53] inferred that the main drivers of the soil organic carbon saturation deficit for various karst forested regions across China were variable; however, the main drivers for many regions were: 1) litter carbon input, 2) total nitrogen, 3) total phosphorus, 4) total soil organic carbon, and 5) neutral phosphatase. Bastin *et al.* [54] investigated the restoration potential of forests and documented that up to an extra 0.9 million hectares of new canopy cover could store 205 Gt of carbon. It was noted that restoration initiatives should only be considered where other naturally existing ecosystems are not impacted.

9. Future Research Needs

Climate change is occurring at an alarming rate. Knowledge gaps include the interaction between soil organic carbon and soil structure, especially when focusing on carbon sequestration, stability, residence time, and pathway mechanisms. The soil organic carbon distribution in aggregates is not yet elucidated. Additionally, conception models that describe the relationships between micro-aggregate and macro-aggregate genesis is needed. Thus, the preservation of soil carbon is integral to offsetting climate change.

Soil, especially forest soils, is increasingly perceived as being important reservoirs for: 1) maintaining their carbon stocks, or 2) capturing additional carbon. Protecting forest ecosystem services remains a critical land management component with addressing human responses to mitigating climate change. Understanding that different soils have different carbon carrying capacities focus attention on individualized land management guidance, the development of more refined ecosystem site descriptions that support the maintenance of ecosystem services, including carbon sequestration, are also required.

10. Conclusions

This review focuses attention on comparing soil and vegetation carbon stocks in biomes with tropical forests having substantial existing carbon in vegetation, followed by temperate forests. Temperate grasslands and croplands have the smallest vegetation carbon stocks. Boreal forests have the greatest soil carbon stocks at 471 Gt.

The maintenance of well-functioning soil processes that provide ecosystem services is critical to mitigate detrimental changes attributed to climate change. The maintenance of important soil characteristics integral to well-functioning ecosystems includes soil-water relationships, soil fertility and nutrient status, soil aeration, sustainable net primary productivity, and soil carbon sequestration. To support forest soils in accelerating their carbon accumulation estimates of a soil's carbon carrying capacity and its responses to land management needs refinement.

Conflicts of Interest

The authors have no conflict of interest.

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