

CARBON DYNAMICS IN FOREST SOILS UNDER DIFFERENT MANAGEMENT PRACTICES

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ABSTRACT

Forest soils represent one of the largest terrestrial carbon reservoirs and play an important role in regulating atmospheric carbon dioxide (CO₂), nutrient cycling, ecosystem productivity, and climate change mitigation. Soil carbon dynamics are governed by the balance between carbon inputs from litterfall, root biomass, rhizodeposition and woody residues, and carbon losses through microbial decomposition, respiration, leaching and disturbance. This review examines carbon dynamics in forest soils under different management practices, with particular emphasis on harvesting, thinning, prescribed burning, wildfire, afforestation, reforestation, restoration, species composition and sustainable forest management. Forest soil carbon occurs in pools with different stability and turnover rates, particularly particulate organic matter and mineral-associated organic matter, which respond differently to environmental and management changes. Microbial activity, litter quality, root-derived carbon, soil properties, temperature, moisture and nutrient availability further regulate carbon transformation and stabilization. Forest harvesting, especially intensive biomass removal, can reduce soil carbon by decreasing litter and root inputs and disturbing soil organic matter, while repeated or severe fires can cause substantial carbon losses. In contrast, appropriate thinning, residue retention, restoration and mixed-species management can promote carbon accumulation and improve ecosystem resilience. Afforestation and reforestation can gradually enhance soil carbon through increasing litter inputs, root turnover and microbial activity, although outcomes depend on species, site conditions and previous land use. Sustainable forest management therefore requires integrated strategies that balance carbon sequestration, biodiversity conservation, soil health and forest productivity.

KEYWORDS: Forest soil carbon, Carbon dynamics, Carbon sequestration, Soil organic carbon, Forest management, Carbon cycling, Climate change, Sustainable- forest management.

1. INTRODUCTION

Forest soils constitute one of the largest terrestrial reservoirs of organic carbon and play a vital role in regulating atmospheric carbon dioxide (CO₂), nutrient cycling, and ecosystem productivity. Soil carbon originates mainly from plant litter, root biomass, rhizodeposition, woody residues, and other organic inputs. The amount and persistence of carbon stored in forest soils depend on the balance between carbon inputs, microbial decomposition, transformation, stabilization, respiration, and leaching. Forest soil carbon is not a single uniform pool but consists of different fractions with varying turnover rates and stability, including particulate organic matter (POM) and mineral-associated organic matter (MAOM). Understanding these carbon pools and their dynamics is essential for evaluating the capacity of forest ecosystems to store carbon and contribute to climate-change mitigation. Carbon dynamics in forest soils are strongly influenced by vegetation characteristics, microbial activity, environmental conditions, and forest management practices. Litter decomposition, root turnover, rhizodeposition, and microbial transformation continuously regulate the movement of carbon between different soil pools, while temperature, soil moisture, nutrient availability, soil properties, and tree species influence decomposition and carbon stabilization.

Forest management practices such as harvesting, thinning, prescribed burning, afforestation, reforestation, restoration, and changes in species composition can either enhance or reduce soil carbon storage depending on their intensity, duration, and site conditions. For example, intensive harvesting and repeated fire may reduce soil carbon, whereas appropriate thinning, residue retention, restoration, and mixed-species management can support long-term carbon accumulation. Therefore, understanding how different forest management practices alter soil carbon pools and cycling processes is essential for developing sustainable strategies for carbon sequestration and climate-change mitigation. Sustainable forest management integrates carbon conservation with biodiversity protection, soil and water conservation, forest productivity, and ecosystem resilience.

2. Forest Soil Carbon Pools and Carbon Dynamics

Forest soils represent one of the largest terrestrial reservoirs of organic carbon and play a critical role in regulating atmospheric CO₂ and ecosystem productivity. Soil carbon is derived mainly from plant residues, litterfall, root biomass, rhizodeposition, and dissolved organic carbon inputs. The size and persistence of the soil carbon pool depend on the balance between carbon inputs, microbial decomposition, transformation, stabilization, and losses through respiration and leaching. Because even relatively small changes in the large soil carbon reservoir can

influence atmospheric CO₂ concentrations, understanding forest-soil carbon dynamics is important for climate-change mitigation and sustainable forest management.

Forest soil carbon can be considered as a collection of pools with different turnover rates and degrees of stability rather than as a single homogeneous reservoir. A useful contemporary framework separates soil organic matter into **particulate organic matter (POM)** and **mineral-associated organic matter (MAOM)**. POM consists largely of relatively undecomposed plant fragments and is comparatively accessible to decomposition, whereas MAOM comprises organic compounds associated with soil minerals and is generally more protected and persistent. These pools differ in their formation pathways, residence times and responses to environmental change, making their distinction particularly useful for understanding and predicting soil carbon storage.

Carbon accumulation in forest soils is strongly influenced by the source and pathway of organic inputs. Although aboveground litter has traditionally been considered the major source of soil carbon, increasing evidence highlights the importance of belowground inputs, including root turnover and rhizodeposition. Root-derived dissolved organic carbon enters the rhizosphere directly, where microbial activity is high, and can be efficiently transformed into microbial products and subsequently stabilized as mineral-associated carbon. Sokol and Bradford reported that belowground inputs can form mineral-stabilized soil carbon more efficiently than aboveground inputs through microbial pathways, although the relative contribution of each pathway depends on the proportion of rhizosphere and bulk soil and on environmental conditions.

Microorganisms are therefore central to the formation and stabilization of forest soil carbon. They have a dual role: decomposition releases carbon as CO₂, while microbial growth, turnover and necro-mass production can contribute to persistent soil organic matter. Microbial residues, particularly fungal and bacterial necro-mass, can become important constituents of the stable soil carbon pool through association with minerals and physical protection. Thus, forest soil carbon dynamics are controlled not only by the quantity of litter and root inputs but also by microbial community composition, soil mineralogy, nutrient availability, tree species, soil depth and environmental conditions.

3. Carbon Cycling Processes in Forest Soils

Carbon cycling in forest soils is a continuous process involving **carbon inputs, decomposition, microbial transformation, stabilization, and carbon losses**. Forest soil receives carbon primarily through leaf and needle litter, fine-root turnover, woody debris, root exudates, and other forms of rhizodeposition. Once organic residues enter the soil, they are decomposed by microorganisms and transformed into dissolved organic compounds, microbial biomass, microbial residues, and more stable soil organic matter. Soil CO₂ efflux, which includes root and rhizosphere respiration as well as decomposition of soil organic matter, represents one of the major pathways through which terrestrial carbon returns to the atmosphere. Temperature and soil moisture are important environmental controls, but plant-derived carbon supplied to the rhizosphere can also strongly regulate decomposition.

Litter decomposition is a major pathway connecting forest vegetation with belowground carbon cycling. The rate at which litter decomposes depends on its chemical quality, particularly its C:N ratio and concentrations of relatively resistant compounds such as lignin, phenolics and tannins. High-quality, easily decomposable substrates can stimulate microbial activity, whereas more recalcitrant litter generally decomposes more slowly and can contribute to longer-term carbon accumulation. During decomposition, microorganisms use organic carbon as an energy source, releasing part of it as CO₂ while incorporating another fraction into microbial biomass and microbial residues. Consequently, carbon cycling is closely connected with nutrient cycling because microbial decomposition requires nutrients, particularly nitrogen.

Root-derived carbon and rhizosphere processes are particularly important in forest soils. Living roots release soluble organic compounds through exudation and other forms of rhizodeposition, providing readily available carbon to microorganisms and mycorrhizal fungi. This additional carbon can increase microbial activity and stimulate the production of extracellular enzymes involved in organic matter decomposition. Such stimulation is known as the **rhizosphere priming effect**, whereby root activity can either accelerate or suppress the decomposition of existing soil organic matter. Experimental work with birch trees demonstrated that belowground carbon supply was closely linked with soil organic matter turnover and that the magnitude of priming depended on the biochemical quality of organic substrates entering the soil.

Microbial and mycorrhizal processes ultimately determine the transformation and fate of much of the carbon entering forest soils. Ectomycorrhizal fungi receive carbon from host trees and use it to develop extensive mycelial networks, while helping plants acquire nutrients from soil. These fungi can produce enzymes that contribute to the breakdown and mineralization of soil organic matter, thereby linking carbon and nutrient cycling. At the same time, microbial transformation can transfer carbon into more persistent soil organic matter pools, including mineral-associated organic matter. Thus, forest soil carbon cycling represents a balance between carbon stabilization and carbon loss through respiration, and this balance is influenced by litter quality, root carbon allocation, microbial communities, nutrient availability, temperature, moisture, tree species and forest management.

4. Effects of Forest Harvesting on Soil Carbon Dynamics

Forest harvesting significantly influences soil carbon dynamics by altering the balance between carbon inputs and losses. Forest soils contain a major proportion of ecosystem carbon, and harvesting reduces carbon inputs through the removal of trees, litter and roots. Clear-cutting generally causes greater disturbance than partial harvesting

because it removes most of the overstory and reduces litterfall and root-derived carbon inputs. Opening of the canopy also changes soil microclimate, particularly increasing soil temperature, while physical disturbance can expose previously protected organic matter and accelerate its mineralization.

The **forest floor or organic layer is particularly sensitive to harvesting**. A global meta-analysis reported an average reduction of about **11.2% in soil carbon after harvesting**, with the largest loss occurring in the O horizon (about **30.2%**). Topsoil carbon losses were smaller, whereas responses in deeper soil varied considerably. Soil carbon recovery can take several decades, and in some soil types such as Spodosols and Ultisols, recovery required at least 75 years. Similarly, conventional harvesting was associated with approximately **22% loss of SOC in the forest floor**, with the loss remaining evident for more than a decade. However, carbon accumulation in deeper mineral layers can partly compensate for losses from the forest floor and upper soil.

Harvesting intensity and residue removal are important determinants of soil carbon loss. Conventional stem-only harvesting may have relatively limited effects on total soil carbon because some carbon lost from the forest floor can be redistributed or accumulated in deeper mineral soil. In contrast, intensive biomass harvesting, involving removal of stems together with branches, foliage, stumps and other residues, can reduce carbon in both organic and mineral soil layers. Recent evidence also indicates that SOC decline becomes more pronounced when harvesting is combined with **residue removal or site-preparation burning**, which can extend carbon depletion into deeper soil layers.

The response of soil carbon also differs between **clear-cutting and thinning/partial cutting** and depends strongly on site conditions and recovery time. A recent meta-analysis of eastern North American forests found that total ecosystem carbon declined after harvesting, mainly because of changes in aboveground biomass, while carbon in mineral soil horizons showed little overall variation between harvesting treatments. Forest-floor carbon, however, showed a negative response to clear-cutting, particularly in temperate forests. Overall, forest harvesting can therefore cause short- to long-term changes in soil carbon through reduced litter and root inputs, altered decomposition and respiration, physical soil disturbance, and removal of harvest residues; the magnitude and duration of these effects depend on harvesting intensity, soil type, climate, site preparation and time since harvesting.

5. Thinning and Silvicultural Practices

Thinning is an important **silvicultural practice** in which selected trees, particularly deformed, suppressed, overcrowded or otherwise undesirable trees, are removed to regulate stand density and improve the growth and health of the remaining trees. Different thinning approaches include **selective, progressive, uniform and strip thinning**, while tree selection may involve removal of small-diameter trees (thinning from below), large-diameter trees (thinning from above), or both. The intensity of thinning is also important; studies commonly distinguish light, moderate and heavy thinning according to the proportion of trees, basal area or volume removed.

Thinning modifies forest microclimate, soil properties, litter inputs, root activity and microbial processes, thereby influencing soil carbon dynamics. By opening the canopy, thinning can increase light penetration and soil temperature and alter soil moisture and microbial activity. A global meta-analysis found that thinning increased soil carbon accumulation, with average soil C stocks increasing from **70.5 to 76.5 Mg ha⁻¹ in the 0–30 cm layer** and from **115.6 to 125.8 Mg ha⁻¹ in the 0–60 cm layer** compared with un-thinned forests. Thinning also increased soil C, N and P pools and improved soil structure through reduced bulk density and increased porosity.

However, the response depends strongly on **thinning intensity and recovery period**. Light and moderate thinning can favour residual tree growth, understory vegetation and microbial activity, whereas excessive thinning can reduce plant biomass and litter inputs, increase drought stress and restrict microbial activity. One meta-analysis found that thinning increased soil respiration by **29.4% overall**, particularly during the early recovery period, although it did not detect a significant overall change in soil carbon stocks. Another recent synthesis reported a **3.53% increase in soil organic carbon stocks**, but the positive effect disappeared after more than 10 years of recovery. These differences indicate that soil carbon responses are dependent on forest type, thinning intensity, stand density and time since treatment.

Other silvicultural practices associated with thinning can further modify carbon storage. **Stem-only harvesting**, which retains branches, foliage and bark on site, leaves organic residues that gradually return nutrients such as N, P and K to the soil, whereas whole-tree harvesting removes substantially more biomass and nutrients. Pruning and understory vegetation removal have also been associated with increased SOC in some studies, while removal of large trees can reduce SOC. Overall, the articles indicate that **moderate and carefully planned thinning, appropriate stand density, retention of residues and suitable supplementary practices** can support tree growth and soil carbon accumulation while avoiding the negative effects associated with intensive thinning.

6. Prescribed Burning and Wildfire Effects

Fire is an important disturbance regulating forest soil carbon dynamics. **Prescribed burning** is generally applied under controlled conditions to reduce fuel loads and maintain ecosystem structure, whereas **wildfires** can vary considerably in intensity and severity and may cause greater losses of vegetation and soil organic matter. Fire directly alters soil carbon through the combustion of litter, dead organic matter and surface organic horizons. However, the magnitude and direction of these changes depend on fire frequency, intensity, duration, vegetation type, soil characteristics and post-fire recovery. Frequent burning can produce long-term changes in soil carbon and nitrogen and consequently influence forest productivity and carbon sequestration.

Repeated or high-frequency fires can reduce soil carbon stocks by consuming organic matter and reducing subsequent carbon inputs from litterfall and root turnover. Long-term evidence indicates that frequently burned ecosystems can experience substantial reductions in surface-soil carbon and nitrogen, particularly where repeated fire reduces vegetation productivity. Thus, fire-induced carbon loss is not restricted to direct combustion; changes in nutrient availability and plant productivity can subsequently reduce the amount of carbon returned to the soil. However, fire does not necessarily cause a uniform decline in soil carbon. Fire can modify **soil aggregation, pH, microbial biomass, microbial community composition and the accessibility of organic matter**, while incomplete combustion can produce relatively persistent **pyrogenic carbon**. Consequently, post-fire soil carbon storage is determined by the balance among combustion losses, new plant-derived carbon inputs, microbial decomposition, stabilization, erosion and leaching. Some changes in the stability of soil organic matter may partly compensate for reductions in carbon inputs following fire.

Overall, the effects of prescribed burning and wildfire depend strongly on the **fire regime and ecosystem characteristics**. Low-intensity prescribed fire may primarily affect surface litter and organic horizons, whereas severe wildfire can cause greater organic-matter losses and modify soil structure and post-fire erosion. Repeated fires may have longer-term effects on soil carbon and nutrient cycling. Therefore, sustainable fire management should balance fuel-reduction and ecological objectives with conservation of soil carbon and fertility. Understanding these processes is increasingly important as climate change alters wildfire frequency and severity and potentially affects the long-term carbon sequestration capacity of forest soils.

7. Afforestation, Reforestation and Restoration Forestry

Afforestation, reforestation and restoration forestry are important **nature-based approaches for increasing forest carbon storage, recovering degraded ecosystems and improving ecosystem resilience**. Afforestation establishes forests on land that has not recently been forested, while reforestation restores forest cover after disturbance or degradation. Restoration forestry goes beyond simply increasing tree cover by aiming to recover ecological functions, biodiversity, soil quality and long-term ecosystem stability. These approaches can increase carbon storage through the accumulation of tree biomass and, over longer periods, through greater inputs of litter, roots and rhizo-deposits to the soil. Natural climate solutions that include reforestation, improved forest management and restoration can provide substantial climate-mitigation benefits while also supporting soil productivity, biodiversity and other ecosystem services.

The effectiveness of afforestation and reforestation depends strongly on **tree species, species mixtures, planting density and site conditions**. Recent modelling of boreal forests showed that medium-density mixed stands containing approximately 25–40% deciduous trees stored 15–30% more net ecosystem carbon than conifer monocultures. Replanting under-stocked forests with such mixtures increased long-term carbon storage by 18–30% compared with business-as-usual management. The combination of rapidly growing deciduous species with longer-lived conifers can therefore provide both rapid early carbon uptake and longer-term carbon retention. These findings indicate that restoration programmes should emphasize appropriate species composition and stand structure rather than focusing only on the number of trees planted.

Restoration also influences **soil carbon and nutrient dynamics** as vegetation becomes re-established. Increasing litter inputs, root turnover and microbial activity can gradually replenish soil organic matter and improve soil carbon and nitrogen pools. However, soil-carbon responses are not uniform because they depend on the previous land use, initial soil carbon and nitrogen status, climate, soil properties, tree species and time since restoration. Consequently, successful restoration should protect existing soil carbon while promoting continuous belowground carbon inputs. Meta-analytical evidence on afforestation and related land-use transitions indicates that changes in soil carbon can vary substantially among ecosystems, highlighting the importance of site-specific restoration strategies.

From a climate-mitigation perspective, restoration forestry can provide substantial benefits, but **carbon sequestration should be evaluated together with disturbance risks and other climate feedbacks**. Fire, drought, pests and climate warming can reduce the permanence of forest carbon stocks, while changes in surface albedo may partly offset the climatic benefits of afforestation, particularly in high-latitude regions. The recent boreal modelling study showed that mixed-species strategies could maintain high carbon sequestration while improving disturbance resilience, and that partial harvesting followed by replanting could preserve or sometimes increase long-term ecosystem carbon stocks. Therefore, future restoration programmes should integrate **soil-carbon conservation, species diversity, disturbance resilience, planting density and long-term monitoring** to maximize persistent carbon sequestration rather than simply maximizing short-term tree biomass.

8. Species Composition and Forest Management

Tree species composition plays an important role in determining **forest soil carbon storage, carbon stability and nutrient cycling** because different species vary in litter quality, root production, nutrient requirements and mycorrhizal associations. Evidence synthesized by Mayer et al. (2020) indicates that coniferous species generally store a greater proportion of carbon in the forest floor, whereas broadleaved species can promote greater and more stabilized carbon storage in mineral soil horizons. These differences are associated with variations in litter decomposition, root-derived carbon inputs and interactions between vegetation and soil properties. Therefore, the most suitable tree species for maximizing soil carbon sequestration depends on site-specific conditions such as soil fertility, climate, soil texture and biological characteristics.

Tree species diversity and mixed-species forestry can further influence carbon accumulation through complementary use of aboveground and belowground resources. Mixed stands may increase canopy productivity and litter inputs while allowing roots to exploit different portions of the soil profile more efficiently. Some studies have reported greater soil carbon stocks with increasing tree diversity, although the relationship is not always consistent. Importantly, tree species identity—particularly the presence of nitrogen-fixing species—may sometimes have a stronger influence on soil carbon than species richness alone. Mixed forests can nevertheless provide greater resilience to natural disturbances and climatic changes, potentially helping to maintain soil carbon stocks over the long term.

Forest management practices, including **species selection, stand density, thinning, harvesting and management of species diversity**, can modify carbon inputs and soil carbon dynamics. Changes in stand density influence canopy development, litter production, root biomass, soil temperature and moisture, thereby affecting decomposition and carbon turnover. The review by Mayer et al. indicates that management of tree species diversity is generally associated with positive or neutral effects on soil carbon, whereas the long-term effects of stand density and thinning remain comparatively uncertain because of limited experimental evidence. Consequently, management decisions should consider both aboveground biomass production and their effects on belowground carbon inputs and soil organic matter.

Recent modelling further demonstrates the importance of **species mixtures and stand density** for long-term forest carbon storage. Ofofu et al. (2025) found that medium-density mixed stands containing different coniferous and deciduous species maintained high net ecosystem carbon stocks over long time periods, while very high-density conifer stands showed reduced gains later in stand development because of self-thinning. These findings suggest that forest management should not simply maximize planting density or favour a single commercially valuable species. Instead, combining suitable species, maintaining appropriate stand density and promoting structural and functional diversity may improve carbon sequestration while increasing forest resilience. Thus, species selection and silvicultural management should be integrated with soil characteristics and local climate to achieve **persistent soil carbon storage and sustainable forest productivity**.

9. Sustainable Forest Management for Carbon Sequestration

Sustainable Forest Management (SFM) is a key strategy for enhancing carbon sequestration while maintaining the ecological, economic, and social functions of forest ecosystems. It integrates practices such as sustainable harvesting, conservation, afforestation, reforestation, restoration of degraded forests, and protection against deforestation to maximize long-term carbon storage. Well-managed forests continuously absorb atmospheric carbon dioxide through photosynthesis and store it in living biomass, dead organic matter, soils, and harvested wood products. At the same time, sustainable management ensures biodiversity conservation, soil and water protection, and the provision of forest-based livelihoods, making forests an essential component of climate change mitigation and sustainable development.

Forest management practices such as selective harvesting, longer rotation periods, reduced-impact logging, afforestation, reforestation, agroforestry, and the conservation of existing forests significantly increase carbon sequestration potential. These approaches not only enhance carbon storage in forest biomass but also promote long-term carbon retention in wood products while reducing greenhouse gas emissions associated with land degradation and deforestation. Studies emphasize that combining conservation, restoration, improved forest management, and efficient wood utilization provides greater climate mitigation benefits than relying on any single practice. Furthermore, integrating forests with agricultural systems through agroforestry improves soil fertility, water conservation, biodiversity, and rural livelihoods while increasing carbon stocks across landscapes.

Effective sustainable forest management also depends on strong governance, adaptive policies, and continuous monitoring. Recent studies highlight that ecological sustainability alone is insufficient; social, cultural, institutional, and political factors strongly influence successful forest management. The use of sustainability indicators, adaptive management frameworks, and community participation enables regular assessment of forest condition, management effectiveness, and carbon sequestration performance. Integrating local knowledge with international sustainability goals helps balance conservation objectives with socioeconomic needs while improving the resilience of forest ecosystems to climate change.

Globally, sustainable forest management forms a major component of natural climate solutions and is recognized as an essential pathway for achieving the Paris Climate Agreement and Sustainable Development Goals. Improved stewardship of forests through conservation, restoration, and sustainable management can contribute substantially to global carbon mitigation while delivering co-benefits such as biodiversity conservation, improved soil and water quality, enhanced ecosystem resilience, and livelihood security. However, the full mitigation potential can only be achieved when forest management is combined with rapid reductions in fossil fuel emissions, supportive policies, adequate financial incentives, and long-term monitoring of forest carbon stocks.

10. Future Research Directions

Future research on **carbon dynamics in forest soils** should focus on developing long-term, site-specific approaches for understanding and enhancing stable soil carbon sequestration under changing climatic and management conditions. Greater attention is needed to distinguish between relatively active carbon pools such as particulate organic matter and more persistent mineral-associated organic matter, while also quantifying the contribution of roots, rhizodeposition, microbial biomass and necro-mass to long-term carbon stabilization. Future

studies should integrate tree species composition, soil properties, stand density, harvesting intensity, fire regime and restoration history to develop more reliable estimates of carbon storage across different forest ecosystems. Advances in **remote sensing, GIS, digital soil mapping, modelling and long-term field monitoring** can improve the assessment and prediction of forest soil carbon stocks. Future forest-management strategies should prioritize mixed-species stands, appropriate planting density, moderate thinning, residue retention, reduced-impact harvesting, restoration of degraded forests and sustainable fire management. Greater emphasis should also be placed on improving the resilience of forest soils to drought, wildfire, pests and climate warming. Integrating soil-carbon conservation with biodiversity protection, adaptive management, community participation and supportive climate policies will be essential for achieving persistent carbon sequestration and maximizing the contribution of forests to climate-change mitigation.

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