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Effects of agroforestry on soil carbon and nutrient cycling: A review

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Abstract

Agroforestry systems are multifunctional and well recognized for their ability to trap carbon and improve nutrient cycles. This research synthesizes information to date on the impact on soil C dynamics and nutrient fluxes of integrating woody perennials with annual crops or grazing. The main mechanisms of carbon acquisition are enhancement of organic matter turnover and enhancement of soil aggregation as a result of enhanced aboveground litter intake and belowground root biomass by the plants. Empirical data show that many agroforestry systems accumulate greater soil organic carbon stocks than surrounding croplands, notably in the topsoil, but subsurface responses are varied. Trees provide a large quantity of organic inputs to soil via litterfall and fine root turnover. This similar way helps to increase nutrient cycling. Nitrogen fixing plants provide nitrogen to the soil, deep roots recycle phosphorus and potassium and varied biota speed up mineralization. Microbial biomass and mycorrhizal abundance are often higher, indicating the presence of superior carbon sources. Agroforestry influences greenhouse gas fluxes, with increased sequestration associated with declines in CO₂ emissions per unit area, lower N₂O emissions due to reduced fertilizer requirements and better absorption and maybe greater CH₄ uptake rates in well-drained soils. Important management issues include tree species (legume vs. non-legume), planting density, pruning regimes, fertilizer use and tillage techniques. Soil carbon buildup trajectories are influenced by temporal issues such as years following establishment and previous land use histories. The relative effect of tropical, temperate and dry systems varies geographically with temperature and baseline fertility.

Keywords: Agroforestry, litterfall, nitrogen, emissions, tropical, fertilizer requirement

Introduction

Agroforestry is the deliberate cultivation of trees in combination with crops or animals on the same piece of land. This approach yields multi-layered vegetation which may have an impact on activities that occur below the surface. Incorporation of woody biomass, deep roots and perennial cover into agricultural systems may affect soil C and nutrient dynamics compared with conventional agricultural or grassland management ^[1, 2]. Under these ecological circumstances organic matter input to the soil occurs mainly in three ways: leaf litter, stem wood debris and fine root turnover. Some of them include increased carbon sequestration in the soil, enhanced soil structure and enhanced nutrient recycling. There are a number of advantages ^[3]. We reviewed agroforestry processes and impacts on soil carbon stores and nitrogen cycling. This article discusses the functions of litterfall and roots, the effects on aggregation, the changes in distributions of nitrogen, phosphate, potassium and micronutrients and the consequences for microbial communities and emissions of greenhouse gases ^[4]. An analysis is carried out of the effect of several management choices (species selection, planting density, pruning, fertilizer and tillage) on the soil results. Studies are done to understand the time dynamics, which include the annual variation of carbon and nutrients after planting and the variation between climatic zones, which include tropical, temperate and desert ^[5]. Trees and shrubs provide aboveground soil inputs in the form of litterfall, branches and even leaves. When they decay they provide organic carbon to the soil. Both coarse and fine roots are withering simultaneously, which causes carbon molecules to leak out and increases belowground inputs ^[6].

Trees with deep roots are able to translocate photosynthates into subsurface layers, enabling them to deposit carbon below the topsoil. Fine root turnover in many situations is a continual process and it serves to accelerate the formation of organic materials in the soil ^[7]. Bacteria in the soil feed on root exudates and in the process they transform additional carbon into stable forms. These inputs accumulate over time and enhance the organic matter content of the soil. Agroforestry also influences the microclimate ^[8]. Shaded soils are less heated and retain moisture, which retards the decay of organic matter and supports its preservation. More litter and root residues also lead to a

richer and more diversified microbial population (see below for more details) that helps to stabilize carbon in soil aggregates ^[9]. These inputs and activities together increase the amount of carbon stored in organic matter pools associated with mineral and particle surfaces. Pruning and coppicing are two practices that give further benefits to the carbon content of the soil. Such approaches include returning biomass to the ground or mulching it. This is more than the amount of organic carbon preserved on the land by annual crops when the biomass is harvested. However, compared to traditional monocultures, agroforestry systems have a net decrease in carbon emissions ^[10, 11].

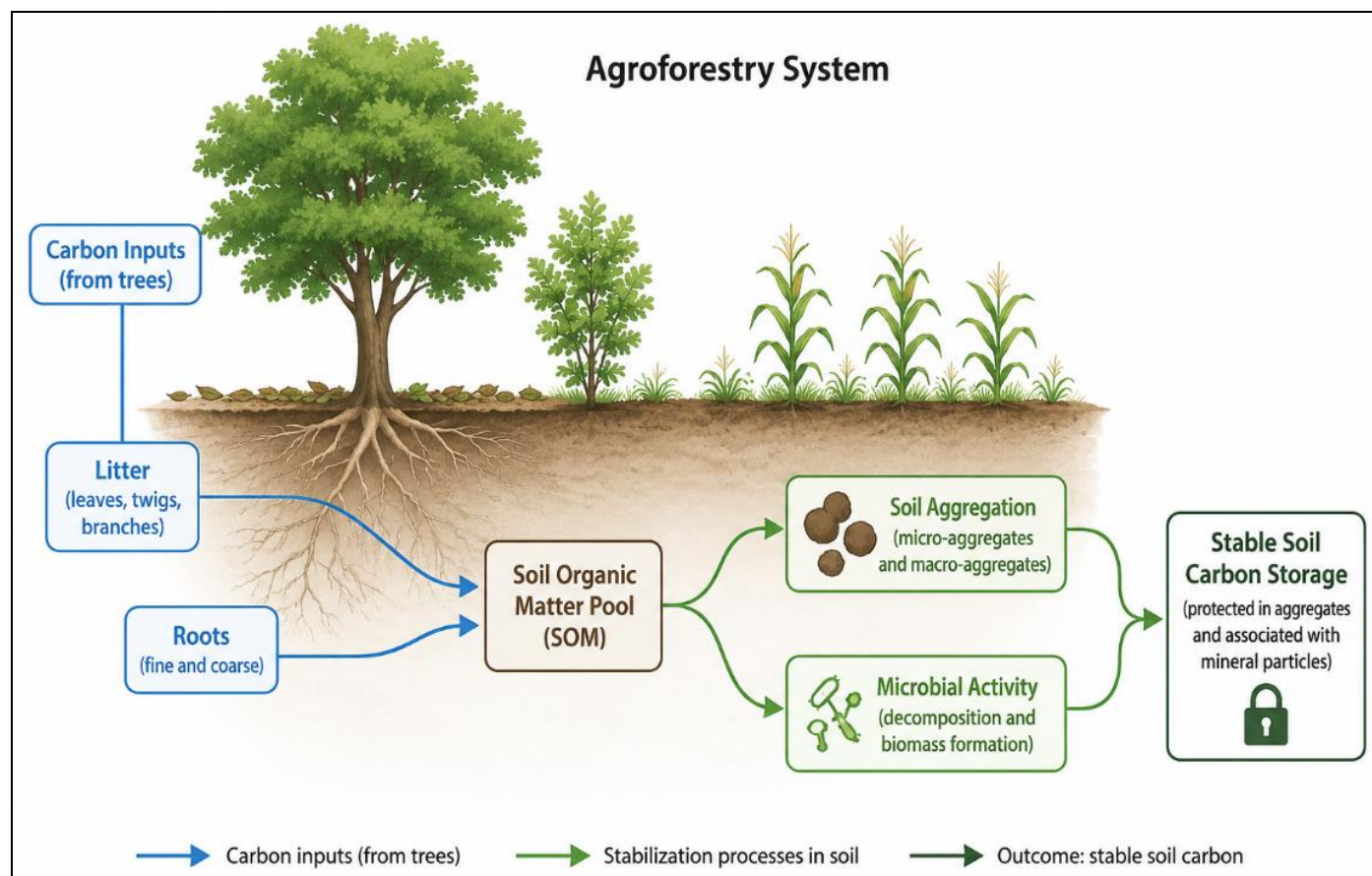


Fig 1: Agroforestry system

Soil aggregates generation is an essential stabilizing activity. Root hairs and fungal hyphae bind soil particles into small aggregates which help to physically protect organic carbon from destruction. Different root systems (e.g. taproots, fibrous roots) create pores and biopores which promote aeration and minimize compaction ^[12]. This improved structure allows more organic substances to be occluded inside aggregates and so reduces turnover. The accumulated carbon is resistant to mineralization because it is bound to microbial by-products and root-derived humus. Additional layers of tree litter and surface mulch serve to further reduce erosion and runoff, so further retaining soil carbon on site. Over decades these processes tend to accumulate larger stocks of SOC in agroforestry soils compared to adjacent agriculture ^[13].

Effects on Soil Organic Carbon Stocks

Agroforestry systems (AFS) maintain higher soil organic carbon (SOC) stocks than traditional agriculture in general, although outcomes are context specific. Table 1 summarizes selected results, with many research showing considerable increases in topsoil SOC under tree-integrated systems ^[14]. For example, a cocoa plantation intercropped with bananas (20-year-old) had SOC ~85 Mg C/ha in 0-30 cm compared with 50 Mg/ha in neighbouring monoculture (a 70% increase). Similarly, a coffee plantation with Inga shade trees (15-year-old) contained 75 vs. 45 Mg/ha in 0-20 cm ^[15]. Also temperate examples exhibit increases. For silvopasture (alder plus pasture), the SOC was slightly higher than for open pasture (42 versus 40 Mg/ha at 0-30 cm after 12 years). The highest benefits tend to be in legume-based systems or those with substantial tree biomass ^[16].

Table 1: Agroforestry systems (AFS) and conventional cropland (or pasture) [5, 10, 17, 18, 19, 20, 21, 22]

Location	Agroforestry system	Depth	Years	Management
India (subtropical)	Poplar + wheat alley vs wheat	0-15 cm	10	15 m tree spacing
Vietnam (tropical)	Rubber + fruit trees vs rubber monocrop	0-20 cm	20	Low-density planting
Brazil (tropical)	Acacia + maize alley vs maize monocrop	0-15 cm	8	Annual pruning, no-till
USA (temperate)	Silvopasture (alder + grass) vs pasture	0-30 cm	12	Managed grazing
India (subtropical)	Leucaena alley vs maize monocrop	0-20 cm	6	Pruned biomass retention
Canada (temperate)	Hazelnut orchard vs cropland	0-50 cm	30	Organic management
Spain (Mediterranean)	Olive orchard vs adjacent field	0-30 cm	25	No-till, organic amendments
China (temperate)	Walnut orchard vs rain-fed crops	0-30 cm	20	High tree density
Italy (Mediterranean)	Poplar alley vs arable crops	0-20 cm	18	Flood irrigation
Brazil (tropical)	Gliricidia + corn alley vs monocrop	0-15 cm	7	No-till management
India (tropical)	Multi-species agroforest vs cropland	0-45 cm	12	Multi-story canopy

The biggest variation is most often seen in the topsoil (0-20 or 0-30 cm) where litter and root inputs are highest. Some studies also reveal subsurface benefits. For instance, one Canadian hazelnut orchard stored 91 vs. 63 Mg C/ha in the 0-50 cm profile [20]. In contrast, a mature olive system in Spain (0-30 cm) conserved 40 vs. 32 Mg C/ha compared with an adjacent field. Percentage improvements are frequently on the order of ~5% to >50%. However, there is substantial variation: certain agroforestry soils show minimal improvement if baseline SOC was already high, or if management (e.g. intense tillage) counteracts inputs [17]. Overall, assessments report mean SOC gains in agroforestry compared to agriculture of about 10-40% depending on system and environment [21].

Litterfall, Root Biomass and Turnover Contributions

In agroforestry systems, trees create leaf litter and woody debris, both of which decay in situ. Litterfall inputs may be higher than yearly crops, many tree species drop biomass on a regular basis therefore contributing large carbon [22]. For example, intercropping maize with *Leucaena* may generate 2-5 Mg dry leaf mass per hectare per year, depositing carbon and nutrients. Banana and tree litter may provide >3-4 Mg/ha-year in mixed cacao systems. Woody prunings (twigs, branches) also provide lignin-rich organic materials [23]. The aboveground litter decays and contributes to the soil organic carbon reservoirs. Another important input is roots [24]. Long-lived trees have deep, wide root systems. Fine roots die back and regrow each season, with high turnover rates, pushing carbon deeper into the soil profile. For example, roots of cocoa and oil palm extend to 2-3 m and are continuously adding to soil organic matter [25]. Coarse roots die more slowly, but nevertheless provide carbon for years. Estimates imply that fine root carbon inputs in mature agroforests may be 30-50 % or more of total organic inputs. Living roots exude root exudates (sugars and organic acids) to nourish microbial populations and enhance the creation of stable soil carbon (by microbial biomass death and exudate humification) [26].

These inputs build throughout time as humus and particle organic materials. In long-term systems, soil carbon accumulation may reach a plateau, representing a new equilibrium between inputs and breakdown. Information on the rate of root turnover is less frequent, although if measured (e.g. in silvopastures or alley crops) fine root turnover may contribute greatly to SOC [27]. Tree rows frequently have a spatial distribution of roots which may contribute to soil carbon heterogeneity. Tree canopy regions usually contain more SOC than alleyways. Earthworm activity and tillage may incorporate organic ingredients and distribute these inputs more evenly [28]. Both woody plant litter and roots greatly increase the organic matter inputs to the soil, in summary. This is in contrast to

monocultures, where only agricultural leftovers (typically eliminated or reduced in quantity) contribute [29]. Agroforestry provides organic inputs throughout the year, which makes the carbon sequestration more continuous by smoothing the plant cover. Many studies estimate the contribution of trees in the order of half of the yearly organic matter returned to soil in these settings, indicating the significance of trees for SOC accumulation in quantitative terms [30].

Soil Aggregation and Stabilization

Agroforestry improves soil aggregation and stability of organic carbon. Mineral particles are bound into aggregates by tree roots, fungal hyphae (particularly mycorrhizae) and microbial glues made from exudates. These aggregates provide micro-environments in which organic stuff is shielded from fast degradation [31]. In reality, soils under trees have greater aggregate stability and bigger mean aggregate size than soils under annual cropping. Improved aggregation improves pore connection which improves water infiltration and reduces surface runoff. That means less erosion of carbon-rich topsoil [32]. The biological activity in agroforests also promotes aggregation. Tree systems tend to be fertile ground for soil fauna including earthworms since they consume leaf litter and organic-rich soil. Organic matter is further mixed and trapped in soil pores and aggregates by burrowing species. For example, earthworm biomass was 20-50% more in silvopastures or agroforests than in neighboring areas, perhaps because of enhanced habitat and food availability [33].

Further stability is obtained by mulching effects. Leaf litter and prunings produce a protective cover on the soil surface which reduces temperature changes and keeps soil wet. Cooler, moister soil limit the pace of breakdown, allowing carbon to be stored in more stable forms. Labile carbon is being transformed into more stable humic compounds [34]. This leads to a higher proportion of SOC beneath trees being mineral-associated or chemically stabilized. Empirical research confirms these mechanistic insights: measurements demonstrate greater amounts of aggregate preserved carbon in agroforest soils [35]. For example, microaggregate related carbon (0.05-0.25mm fraction) might be increased 20-30% beneath trees. The overall result is that more SOC is in forms that flip over slowly. This structural enhancement also helps with soil fertility and water retention, generating a positive loop that may further boost tree growth and carbon inputs [36].

Nutrient Cycling (N, P, K, Micronutrients)

Agroforestry influences the cycling of major nutrients in several ways.

- Nitrogen (N) cycling is generally most affected. Leguminous trees (e.g. *Gliricidia*, *Faidherbia*, *Acacia*) fix

atmospheric N₂, adding fresh nitrogen to the system. Part of this fixed N is transmitted to the crops via breakdown of leaf litter and root turnover ^[37]. Thus, soil total N stores tend to be higher in agroforestry systems. In a number of tree-crop systems the soil N has been 10-50 kg/ha greater than in monocultures after a number of years ^[38]. For example, a *Leucaena* alley cropping system in Kenya had ~55 versus 35 kg N/ha ($\Delta+20$) in the topsoil. Also decreased fertilizer N need in agroforestry (due to tree N-fixation and better soil moisture) typically decreases N losses. This results in lower N₂O emissions (see below) and more N in the system to cycle between soil, microorganisms and crops ^[39].

- Agroforestry may also enhance the dynamics of phosphorus (P). Deep rooted trees (e.g. eucalyptus, certain acacias) may mine P from lower layers and recycle it to the surface via leaf litter and root exudates, making it accessible to shallow rooted crops ^[40]. Mycorrhizal connections typical in tree roots also boost P absorption and cycling. Soil studies generally demonstrate that agroforestry enhances available P. An Italian olive agroforest showed 25 versus 20 mg/kg ($\Delta+5$). These changes are less than for N, but indicate improved P retention. Continuous cover reduces erosion and leaching, therefore conserving soil P ^[41]. Tree roots may modify the chemistry of P binding in certain situations (exudation of organic acids might mobilize sorbet P) to facilitate absorption. However, in the absence of P fertilization and when soils are depleted, systems will eventually be P-limited in the absence of inputs ^[42].
- Micronutrients and potassium (K) in general also benefit from agroforestry. Deep roots tap K, Ca, Mg and micronutrients (Zn, Cu, Mn etc.) in subsoil or parent rock, returning them via litter. Several studies demonstrate increased soil K and Mg in tree lanes ^[43]. For instance, a research in Brazil revealed 10-15% greater exchangeable K in a *Gliricidia* alley than in the next field. Increased cation exchange capacity (CEC) beneath trees (owing to more organic matter) helps to retain K and other cations. Micronutrients associated with organic matter (e.g. Fe, Zn) tend to rise with SOC. Quantification of micronutrient cycling is less prevalent, but conceptual knowledge shows that agroforestry operates much like a “nutrient pump”, spreading elements geographically and temporal ^[44].
- Nutrient cycling in agroforestry is more efficient and closed than that of monocultures overall. Internal cycling of nutrients (trees recycle deeper nutrients and fix N) reduces requirement for external fertilizer. This leads to increased sustainability and a decreased loss of nutrients to the environment (runoff or leaching). Such preservation of nutrients may greatly improve soil fertility and crop production when inputs are modest (as is typical of tropical smallholds) ^[45, 56].

Soil Microbial Community Structure and Function

More and different microbes are supported by the changes in carbon and nutrient inputs in agroforestry systems. Microbial biomass carbon and nitrogen tend to grow with added organic matter ^[47]. Many studies have shown that microbial biomass in agroforestry soils was 10-50% more than in cropping soils. Community composition often moves to greater relative abundance of fungus (especially mycorrhizal) and bacterial groups that are suited to the breakdown of woody wastes. For example, arbuscular mycorrhizal fungi often flourish in the vicinity of tree roots, improving nutrient uptake ^[48]. As pointed out above the earthworm and mesofauna populations rise as well

and they affect microbial hotspots indirectly via bioturbation. Functionally, microorganisms in agroforests exhibit more enzyme activity in nutrient cycling. High levels of enzymes such as β -glucosidase (for carbon breakdown) and urease or nitrate reductase (for nitrogen transformations) are typical, showing active decomposition of complex inputs ^[49]. This results in a quicker mineralization of tree litter and root material than plain agricultural wastes. There is some evidence for a superior carbon usage efficiency of agroforest soils. Microbes may assign more C to biomass or stable humus rather than respiring it away, partially owing to constant substrate availability. Microbial communities in agroforestry soils also show higher resilience and buffering of seasonality. The mulch and shade minimize changes in soil temperature and moisture, giving the microorganisms more stable settings ^[50]. This may be of benefit to microbial activity during dry or hot times when agricultural soils might be dormant. The net consequence is a speeding up of nutrient turnover by microorganisms. Nitrogen immobilization during high-C litter decomposition is then alleviated as net mineralization, typically synchronized to crop need. Phosphatase-producing microorganisms help free P from trash. Interestingly, several studies indicate distinct microbial taxa linked with certain tree species (e.g. nitrogen-fixing bacteria in legume-tree rhizospheres) that are missing in cropping soils ^[51]. Although information on changes in microbial communities is relatively limited, it is apparent that agroforestry leads to a more complex soil food web that benefits the cycling of carbon and nutrients ^[52].

Greenhouse Gas Fluxes (CO₂, N₂O, CH₄)

Agroforestry affects soil greenhouse gas fluxes in multiple ways.

- A common finding in agroforestry is a reduction in CO₂ emissions from soil respiration on an area basis due to higher carbon storage in biomass and soil. In many systems the land is a net carbon sink because of yearly net ecosystem CO₂ uptake (due to biomass and SOC increase). Soil CO₂ flow (higher sequestration) after establishment is frequently 10-30% lower in agroforestry than cropland throughout literature. This is mainly because the wooded component is a sink of carbon, with some of this carbon being accumulated as SOC rather than respired immediately ^[53, 54].
- Overall, agroforestry compared to fertilize cropping results in reduced or constant N₂O emissions. Less fertilizer use (due to N-fixing trees) and enhanced plant absorption of soil N both decrease nitrate leaching and denitrification, therefore reducing N₂O losses. Examples demonstrate N₂O flow decreasing e.g. from 6 to 4 kg N/ha-yr beneath tree lanes. Some alley cropping experiments indicate up to 50% reductions in N₂O. In well managed agroforestry (with balanced N inputs) the improved microbial immobilization of nitrogen and absorption by tree roots compete with denitrifiers and reduce nitrous oxide emissions. This is different from highly fertilized systems that may nevertheless produce substantial N₂O if not adequately maintained ^[56, 57].
- Upland agroforestry Methane (CH₄) dynamics in upland agroforestry are generally small. Most non-flooded soils are net sinks of CH₄ because of methanotrophic bacteria. Trees may boost soil aeration which improves the CH₄ absorption (more negative flux). Some trees may minimize waterlogging and hence CH₄ emissions in wet or paddy settings, however these are context-specific. Changes in

CH₄ are often minor compared to the impacts of CO₂ and N₂O^[58].

- Agroforestry generally has a net benefit to the climate because soil CO₂ flow per crop production decreases and SOC accumulates, whilst N₂O emissions are reduced via ecological N cycling. The relative amount of GHG change is a function of management, with avoided excess fertilizer, maintenance of tree cover and minimization of soil disturbance all favouring lower net GHG emissions. But if land conversion includes ploughing existing forest or peatland, early CO₂ pulses may counteract gains. Therefore, the climatic benefit of agroforestry is a temporal benefit as tree biomass and SOC increase^[59].

Management Practices (Species, Density, Pruning, Fertilization, Tillage)

The outcomes of agroforestry depend strongly on management choices.

- Species choice is very important. Deeper species (eucalyptus, poplar) pump more C and nutrients from the subsoil, whereas legumes (gliricidia, acacia) fix N. Overall, mixed-species (multi-strata) systems provide higher overall biomass and nutritional diversity than monocultural tree stands^[60, 61]. Tree planting density influences the amount of light available for understory crops and the total biomass inputs. More dense plantings tend to sequester more carbon, but if plants are too dense they may shade out crops. Pruning regimes affect carbon flow. More frequent pruning recycles more biomass back to the soil as mulch, but also diverts carbon from stable wood pools. It is vital to keep the trimmed material on site, rather than removing it, for the most soil carbon benefits^[62, 63]. Fertilization and soil amendments modify the baseline conditions. Low fertilizer use (common in traditional agroforestry) indicates advantages of trees, however inorganic N or P inputs may confound. For example, the net value of P recycling from trees may be decreased in a tree-crop system with P fertilizer application. But little light fertilization with plants might boost total productivity without negating carbon gains^[64].
- Tillage matters too: low or no-till in agroforestry preserves soil structure and organic layers, enhancing carbon storage. Frequent tillage (e.g. in alley cropping without conservation tillage) may reverse certain SOC gains via collective rupture. Some studies have showed substantially higher SOC and aggregate stability in no-till alley cropping than tilled alley cropping. A second management issue is the incorporation of animals (silvopasture)^[65]. Grazing animals provide nutrients to the soil via dung, but overgrazing may lead to soil compaction and less carbon sequestration. Managed grazing systems that maintain a ground cover frequently increase the return of soil organic carbon and nutrients. Agroforestry is linked with typically lower disturbance, continuous cover and greater return of

biomass than conventional agriculture. These practices (matching species to the local climate/soil, using tree prunings as mulch and avoiding synthetic inputs) boost benefits to soil carbon and nutrients^[66, 67].

Temporal Dynamics and Land-Use History

- Responses of soil carbon and nutrients to agroforestry are time dependent. SOC tends to rise gradually when trees are established. There may even be temporary reductions in the early years if land preparation (plowing, integration of residues) is disruptive. After roughly 5-10 years many systems exhibit net SOC growth as tree biomass builds up. Carbon continues to accumulate for decades; a mature agroforest (15-20+ years) generally has substantially more SOC than upon planting^[68].
- Typically, the trajectory is sigmoidal: sluggish at first, fast growth when trees mature and then leveling out. This trend is a function of previous land use: conversion of degraded or nutrient-poor land to agroforestry results in rapid relative improvements (high percentage increases), whereas conversion of fertile pasture to an agroforest results in lesser relative benefits^[69].
- Temporal studies show delayed deep carbon accretion relative to surface increases. For example, an Indian agroforest had a considerable increase in SOC at 0-15 cm after 10 years, but 15-30 cm stocks only caught up after ~20 years. "So you need long-term monitoring to get the full benefit." Changes in nutrient stocks are likewise sluggish to accrue. Organic N and P pools often reach a steady state after a decade or more. The rates of change depend on the tree growth rates, the management (e.g. mulching frequency) and the environment (e.g. warm soils breakdown quicker)^[70].
- And the legacy of land use matters. Also, the conversion to agroforestry may not raise SOC and even decrease it due to lower density of trees, since the former wooded area had generally high SOC. In contrast, conversions of degraded farmland to agroforestry typically show considerable improvements in SOC (often comparable or surpassing residual forest levels within decades). And, past fertilization may carry over into present nutritional status. Soils that have been previously heavily fertilized with NPK may react less to tree-based nutrient inputs, whereas low-fertility soils benefit more^[71].
- Model simulations (e.g. RothC or Century models in agroforestry) show that SOC sequestration rates are on average in the range of 0.2-0.6 Mg C/ha/year in ideal systems but may be an order of magnitude lower in bad management situations. Because decades are required to store considerable carbon, agroforestry is best as a long-term solution. In planning, it is important to address transient dynamics: the initial carbon debt associated with land clearance (if any) has to be recognized before the net sink benefits can be realized^[72].

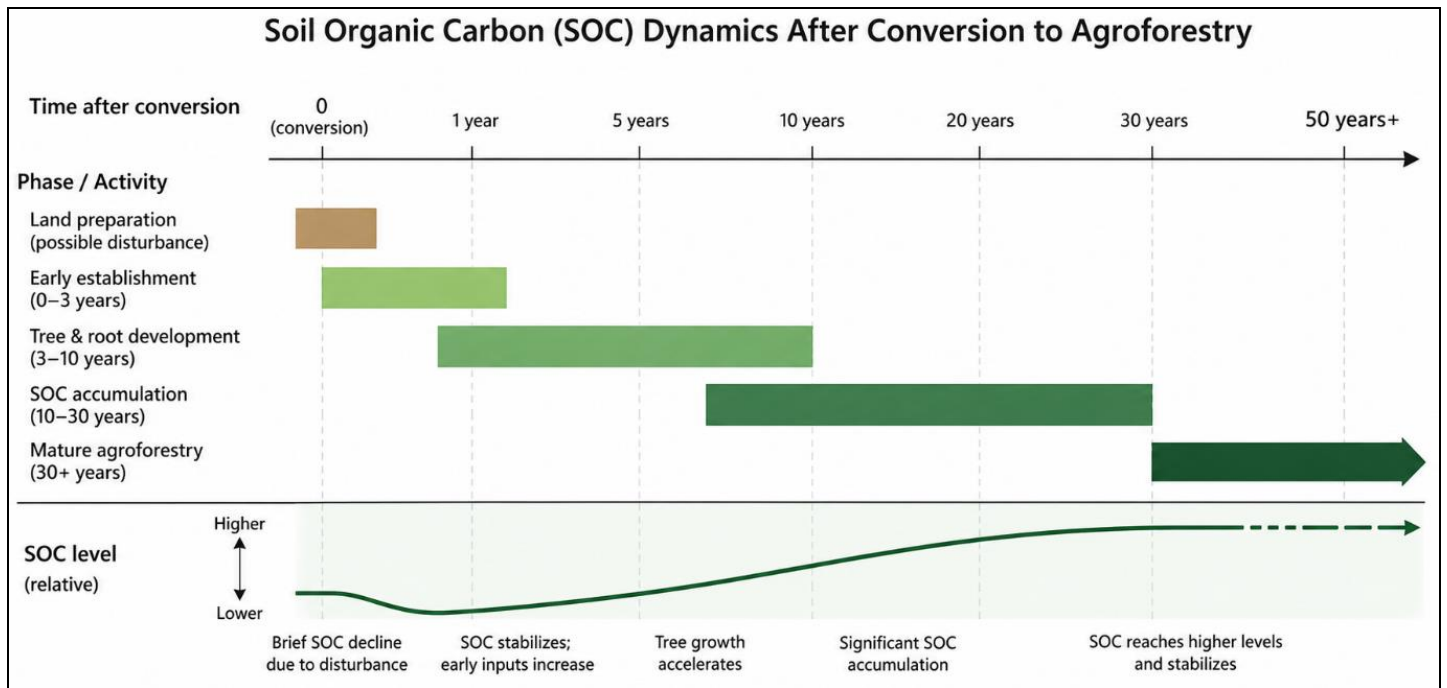


Fig 2: Soil Organic carbon and time taken for simpler breakdown

Regional Variability

Climate and ecological environment influence effects of agroforestry on soils.

Tropical regions: Tree growth rates are rapid in tropical places and baseline soil fertility is frequently poor, thus relative SOC and nutrient gains may be considerable. Many tropical field studies report 30-100% greater SOC under mature agroforests than under farmland. These increases are aided by rapid decomposition rates (which also need large inputs to maintain SOC) and persistent canopy cover. In hot wet climates, however, organic matter loss may be rapid and maintenance of litter layers is thus important in the tropics [73, 74].

Temperate climates: In temperate settings, advantages from agroforestry are usually modest. Cool winters reduce decomposition, enabling greater SOC build up from tree inputs yet tree growth (and biomass input) is slower than in tropics. Studies in Europe and North America indicate increases in SOC of 5-20% over a decade or more. For example, in North America, silvopastures with alder or black locust raised SOC marginally while improved water quality. In certain temperate soils with high starting fertility, the marginal benefit of SOC may be minimal [75].

Arid and semi-arid zones: Special problems exist in arid and semi-arid areas. Biomass production is limited by water and hence inputs of litter and roots are reduced. However, trees may still boost organic matter in soils by shading and lowering evaporation. Some agroforestry operations (e.g. *Faidherbia* biennial acacia) in the Sahel have improved agricultural yields and moderate SOC storage via improved microclimate and fertility. SOC stocks are still low (because to limited rainfall) but are a considerable fraction of baseline. Mediterranean climate research indicates dryland tree systems (e.g. olives, nuts) may slowly accumulate soil carbon, particularly with irrigation or cover cropping [76].

Soil type is important, too. Sandy soils with little clay concentration have less natural ability to store SOC, hence

absolute gains are less. The advantages of agroforestry are higher on soils with high clay content, which may store more organic carbon [77]. Topography and danger of erosion are important: agroforestry may considerably minimize SOC loss on slopes (eg hedgerows on the side of hills) and restore carbon in regions prone to gullying. Agroforestry has favorable impacts on carbon and nutrients worldwide, although the amount of these benefits depends on the location. The premise of 'trees provide carbon and nutrients' is true in all places but net results depend on local variables [90, 78].

- Quantifying changes in soil carbon and nutrients in agroforestry is difficult. Standard procedures involve bulk density and carbon concentration measurements by soil coring followed by elemental analysis (dry combustion) or wet oxidation (Walkley-Black). Reported SOC stocks are quite sensitive to the depth of sampling; many studies sample just 0-15 or 0-30 cm and may miss deeper accumulation [79]. Deep roots are important therefore it is desirable to have at least 0-50 cm sample. Others utilize separation of the clay fraction or density fractionation to separate stable pools of carbon. Root biomass measurements need labour demanding soil coring or ingrowth cores. Often litterfall is collected in baskets to measure inputs [80].
- Nutrient analysis also includes soil tests (Kjeldahl or Dumas for total N, Olsen or Bray for extractable P, exchangeable cations for K). Seasonal variation (e.g. before versus post rainy season) might impact nutritional measures [81]. Soil respiration and gas concentrations for GHG fluxes are often measured using static or automated chambers, while net ecosystem exchanges in larger plots may be measured using eddy covariance towers. These approaches include uncertainties: positioning of chambers (under tree vs open) and frequency of sampling (monthly vs continuous) impact flow estimations. Methane fluxes in uplands are tiny and unpredictable, making them difficult to detect [89, 82].
- High statistical variability owing to soil heterogeneity. Agroforestry fields often have uneven fertility (e.g. tree row versus alley). So, enough replication is necessary. Many

published research have low reproducibility, hence meta-analyses generally have high confidence ranges ^[83]. Uncertainty from land history: baseline SOC may be inadequately recorded. Models (e.g. Century, RothC) are occasionally used to model agroforestry effects, but need to be adjusted for perennial systems ^[84].

- Finally, although tools to measure impacts are available, care is warranted. In this assessment we presume that the observed changes are true, although the actual size may vary in every new project. Standardized sample techniques and long-term monitoring plots increase dependability of efforts ^[85, 86]. Remote sensing (e.g. LIDAR, satellite indices) for biomass estimation and inferential SOC is growing but not yet commonplace. Uncertainty is still a barrier for carbon accounting and meeting verification in carbon markets ^[87, 88].

Conclusion

The effect of agroforestry on the nutrient dynamics and carbon storage of soil may be explained by a lot of interrelated processes. These systems combine trees with crops or grazing and produce higher carbon inputs (litter and roots) and a more stable soil structure. They thus generate many scenarios in which the pools of soil organic carbon are higher than for traditional systems. Better nutrient cycling - nitrogen fixation by trees adds nitrogen to the soil, deep roots cycle phosphorus and potassium, and nutrient retention improves. Agroforestry encourages the growth of microbes in the soil which in turn aids in stabilizing organic materials. In more general terms there is an increase in GHG fluxes. Benefits include greater carbon sequestration and lower nitrous oxide emissions. The amount of these effects depends on tree type, management, temperature and the soil environment. For the best use of the advantages, it is required to use tactics such as the retention of prunings, minimal tillage, and the selection of appropriate species. SOC and nutrients fluctuate over years and need constant management. In temperate zones the advantages are minor but positive. In dry locations the absolute improvements are less. On the other hand, in the tropics the improvements are typically large since the soils are already poor to start with. The results are not consistent because of challenges experienced in obtaining measurements, although there are definite patterns. Agroforestry is a powerful tool to combat the consequences of climate change. Our research results suggest that in addition to the added benefit of enhancing soil fertility, integration of woody biomass into agricultural land might lead to storage of tens of milligrams of carbon per hectare over many decades. That promise may be realized via the creation of enabling policies, farmer incentives and the use of strong assessment techniques. Different interrelated processes underlie the effect of agroforestry on soil carbon sequestration and nitrogen cycling. These systems combine trees with crops or grazing and produce higher carbon inputs (litter and roots) and a more stable soil structure. They thus generate many scenarios in which the pools of soil organic carbon are higher than for traditional systems. Better nutrient cycling - nitrogen fixation by trees adds nitrogen to the soil, deep roots cycle phosphorus and potassium, and nutrient retention improves. Agroforestry encourages the growth of microbes in the soil which in turn aids in stabilizing organic materials. In more general terms there is an increase in GHG fluxes. Benefits include greater carbon sequestration and lower nitrous oxide emissions. The amount of these effects depends on tree type, management, temperature and the soil environment. For the best use of the advantages, it is required to use tactics such as the retention of prunings, minimal

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