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Knowledge gaps, research strategies and robust assessment methods for soil organic carbon storage in coffee production systems

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Abstract. Regenerative agriculture is increasingly promoted in the coffee sector as a strategy to enhance soil health and contribute to climate change mitigation through soil organic carbon (SOC) storage. However, robust evidence on the magnitude and drivers of SOC change in coffee production systems remains fragmented and methodologically inconsistent. We systematically reviewed 80 peer-reviewed studies assessing SOC stocks in coffee systems across major producing regions. Our analysis shows that the literature is dominated by synchronic (space-for-time) approaches (~91%), while true diachronic studies quantifying SOC stock change over time are rare. Only a minority of studies accounted for soil bulk density differences using equivalent soil mass (ESM) approaches, fewer than half sampled below 30 cm soil depth, and more than half did not report previous land use, an essential determinant of SOC trajectories.

Across studies, SOC stocks were generally higher in coffee systems than in annual cropping systems and lower than in natural forests, with agroforestry systems sometimes approaching forest SOC levels. However, reported management effects were highly context-dependent and often confounded by differences in soil type, climate, and land-use history. As a result, current evidence does not allow robust quantification of carbon removal potential in coffee systems, nor reliable attribution of SOC differences to specific management practices.

Based on this synthesis, we provide methodological guidance for rigorous SOC research in coffee systems, including recommendations on study design, sampling depth, bulk density correction, laboratory procedures, and reporting standards. We argue that future studies must explicitly define research objectives, baseline trajectories, and the spatial scale and context to which their findings apply and distinguish between SOC stock differences and true sequestration rates. Strengthening

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experimental designs, harmonizing methodologies, and improving data transparency are essential to generate credible, policy-relevant evidence on SOC storage and climate mitigation in coffee landscapes.

1 Introduction

Commitments to sustainable agriculture require clear guidance on research data collection as well as monitoring, evaluation, and reporting standards (Schreefel et al., 2024). Many actors in the coffee industry have made substantial commitments to regenerative agriculture, focusing on key environmental impact areas such as soil health, water, biodiversity, and climate (Pulleman et al., 2023). Soil organic carbon (SOC) stock, defined as the mass of SOC per unit of land area in a given soil depth or soil mass and normally expressed in Mg/ha (Box 1) is widely used as a key performance indicator, reflecting both the recognition that SOC decline is a major soil threat and the expectation that maintaining or rebuilding SOC supports multiple soil functions linked to soil health, including nutrient cycling, water regulation, habitat provision for biodiversity and climate regulation (Creamer et al., 2022). Thus, the importance of SOC as an integrated indicator of soil multifunctionality is well-established (Hoffland et al., 2020). On the other hand, caution is warranted to not treat SOC stocks as a direct, stand-alone proxy for broader outcomes such as biodiversity gains or climate mitigation, because correlations between SOC and soil functions are context dependent, and the translation of SOC stock changes into mitigation claims can be methodologically uncertain (Moinet et al., 2023; Powlson et al., 2011; Don et al., 2024). Moreover, although soils have considerable potential to store carbon, many are currently experiencing net carbon losses. In such cases, management measures aimed at increasing SOC may primarily reduce ongoing losses rather than result in net carbon sequestration (Don et al., 2024). Robust SOC assessment remains, nonetheless, an important part of evaluating regenerative approaches across contexts. However, assessing the effects of agricultural practices on SOC storage is not straight forward and can lead to biased conclusions. This is especially the case in perennial cropping systems such as coffee, due to a mixture of fundamental and methodological challenges. As a result, the scientific evidence on the relations between regenerative coffee production practices and SOC accrual across coffee production areas is ambiguous, limiting the possibility to prioritize management practices tailored to specific contexts.

Coffee is a global commodity and constitutes an important cash crop for millions of smallholder farmers across the tropics and is cultivated on approximately 12 million hectares (FAO 2025). Coffee is a tropical perennial woody plant, grown either as a sole crop, intercropped or in agroforestry systems, often on steep slopes in cooler mountainous areas in the case of *C. arabica* or on flatter lands in hotter environments in the case of *C. canephora*. While some coffee systems have been converted from forests, others were established on formerly grazed or cultivated lands, and the intensity of production varies widely. Approximately 95% of coffee farmers are smallholders managing relatively low-input systems. However, 40% of global coffee production comes from larger family-owned coffee estates and to a lesser extent from large coffee agribusinesses with more intensive management and high yields (Browning & Moayyad 2017). Major soil threats include soil erosion, the decline of soil organic matter and nutrient mining, particularly in low-input sole coffee crops and on steep

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slopes, whereas overfertilization and soil acidification are common causes of soil degradation in high-input systems (Giller et al., 2023). Nonetheless, soils under coffee cultivation have considerable potential to store and protect carbon as soil organic matter, especially when compared to annual cropping systems. As a perennial crop, coffee maintains continuous root-turnover, sustained soil cover and minimal soil disturbance. These characteristics favour higher SOC stocks and reduced SOC losses relative to arable systems, where most biomass is harvested and removed each year. When shade trees, cover crops or intercrops are integrated and/or significant quantities of organic amendments are applied, annual carbon input further increases, while SOC losses due to soil erosion decrease and high soil temperatures are moderated (De Souza et al. 2012; Pappo et al., 2025; Tinoco et al., 2026). Biomass input to the subsoil, primarily through root turnover, is expected to be particularly important for soil carbon accrual due to its higher residence time (Button et al., 2022; Sierra et al., 2024). Depending on the rejuvenation practice and coffee age/size, up to 75% of the root biomass senesce directly in the soil matrix (Defrenet et al., 2016), where the efficiency of organic matter stabilization is relatively high (Cotrufo et al., 2013). This can lead to an estimated 2 tons per ha of root biomass annually as an input in the 0-30 cm soil layer from coffee alone (Defrenet et al., 2016), on top of aboveground inputs due to coffee leaf litter. Carbon input from leaf litter has been estimated to be 2.2 and 3.1 tons per hectare per year in a sole coffee crop and in an agroforestry system in Costa Rica, respectively (Monge-Muñoz et al., 2025).

Research on SOC storage in coffee systems is complex because it is influenced by multiple interacting factors. First, the impact of agricultural practices on SOC storage can vary due to the large diversity of contexts in which coffee is grown (e.g., soil type, topography, altitude, climate, and land use history). The additional amount of organic carbon that any soil can store and stabilize depends on the soil's initial SOC content and on intrinsic soil properties that determine the soil's SOC saturation level (Schepens et al., 2025; Six et al., 2024) (Box 1). Second, the mechanistic understanding of SOC dynamics as a response to agricultural management in coffee systems remains limited. The complexity of the systems, with many components that directly or indirectly affect SOC dynamics, makes it difficult to disentangle interacting factors and infer causality (Müller et al., 2024). Moreover, coffee systems, particularly agroforestry systems, tend to show more spatial variation in soil and other environmental conditions and require longer time horizons than annual cropping systems to reach a new equilibrium of biomass turnover.

Third, assessing changes in SOC storage resulting from agricultural management entails a range of methodological challenges (Cardinael et al., 2025; Minarsch et al., 2025; Müller et al., 2024), and studies of coffee systems are no exception. These challenges include (i) the need for sampling designs that adequately account for the pronounced spatial and temporal heterogeneity of cropping systems, particularly in perennial crops and smallholder-dominated farming; (ii) the importance of using sampling designs that capture the entire soil profile potentially affected, as deeper soil layers (> 30cm) often contain substantial amounts of carbon and may stabilize newly added carbon for longer periods than topsoil (Segnini et al., 2011); and (iii) the use of standardized methodologies for the quantification of SOC stocks, to ensure comparability over time and across land uses and management systems that differ in soil bulk density (FAO, 2020; Cardinael et al., 2025).

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This review paper critically assesses the state of the art on soil organic carbon (SOC) storage in coffee systems with particular attention to the influence of agronomic management and methodological rigor. The specific objectives are to 1) define best practices for rigorous SOC research in coffee systems, including study design, sampling strategy, laboratory methods, SOC stock calculations, and reporting standards; 2) synthesize existing evidence on SOC storage in coffee systems, assessing reported effects of management practices while identifying methodological limitations that affect comparability and interpretation; and 3) propose roadmap to advance research on SOC quantification and strengthen the scientific basis for climate mitigation and soil health strategies across coffee growing contexts.

Box 1: Key definitions used in SOC studies

1) SOC stock: The mass of organic carbon per unit land area contained within a defined soil layer at a specific point in time, where the layer is delimited either by a fixed depth or by equivalent soil mass and is typically expressed in Mg C ha^{-1}.

2) SOC accrual: An increase in SOC stock per unit of land, starting from an initial SOC stock or compared to a business-as-usual (BAU) value. SOC accrual does not always result in soil C sequestration or climate change mitigation (based on Don et al. 2024).

3) SOC sequestration: The process of transferring C from the atmosphere into the soil through plants or other organisms, which is retained as soil organic carbon resulting in a global C stock increase of the soil (Don et al. 2024, based on IPCC, 2001). The rate of SOC sequestration is most often expressed in Mg C ha^{-1} yr^{-1}.

4) SOC equilibrium or steady state: In the context of SOC dynamics, equilibrium or steady state refers to a state of the system in which the rate of carbon inputs into the soil (e.g., from plant litter, roots, and organic amendments) equals the rate of carbon losses through processes such as decomposition and mineralization, erosion, and leaching. At this point, the total amount of SOC remains stable over time until a management change or environmental disturbance occurs.

5) SOC stabilization: Naturally occurring process, whereby the turnover of an organic particle is gradually reduced as a product of its interaction with the soil mineral matrix and decomposer organisms. As organic compounds are modified during decomposition, their affinity with soil minerals is modified, inducing a partial protection from further microbial decay (Kleber et al., 2021; Kögel-Knabner et al., 2023; Six et al., 2002).

6) SOC saturation: This concept describes that there is a limit to the capacity of a given soil to stabilize carbon through association with soil minerals where the SOC saturation limit depends on the chemical and physical properties of the soil mineral matrix. The theoretical limit is defined by the silt + clay content of the soil and the soil mineralogy, being greater for 2:1-clay minerals-dominated soils than for 1:1-clay minerals-dominated soils. Other aspects of soil mineralogy affecting the theoretical limit include the content of allophanic and amorphous clays in Andosols and metaloxides, which do play a dominant role in the mineralogy of many highly weathered soils (Six et al., 2024).

7) SOC storage: A broader concept than SOC stock, referring to both the amount of organic carbon present in soil at a specific time and the processes governing its accrual or loss over time. In methodological terms, SOC storage research therefore requires both accurate stock quantification and robust approaches to detect stock changes.

8) Climate change mitigation: An anthropogenic intervention that reduces the sources or enhances the sinks of greenhouse gases (Don et al., 2024, based on IPCC, 2021). In this sense carbon sequestration through SOC accrual may be compensated by increased emission of other GHGs such as nitrous oxide (N_2O). On the other hand, synergies may occur, where SOC accrual leads to a reduction in GHG sources.

2 Best practices for rigorous SOC research in coffee systems

A rigorous evaluation of the drivers of SOC storage across contrasting coffee-growing contexts requires robust experimental designs and sampling strategies, reliable and reproducible laboratory measurements, and transparent reporting standards. In addition, SOC stock estimates must explicitly account for soil mass equivalence to prevent systematic bias due to variability in soil bulk density when comparing management systems or assessing temporal changes. In the following sections, each of these methodological components is discussed in more detail, and common challenges, pitfalls and good practices are described.

2.1 Matching research objectives and study design

The design of SOC storage studies needs to be explicitly aligned with the research objectives and questions being addressed. Therefore, it is helpful to distinguish three major objectives for research on SOC storage in coffee systems : i) studying effects of land use change (e.g., conversion of natural vegetation, pasture, or annual cropping systems to coffee production); ii) production system comparisons (such as conventional versus organic and/or agroforestry versus sole coffee systems), and iii) evaluating the effects of individual management practices and their interactions. While system comparisons capture the

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integrated effects of multiple management practices or system components, they generally do not allow to disentangle the contributions of individual drivers of SOC stock change (e.g., tree species identity, planting density, spatial arrangement and pruning regimes, the use of cover crops, soil amendments and fertilizer applications). Furthermore, study design may differ depending on whether the objective is to assess changes in SOC stocks as indicators for soil quality or to quantify atmospheric CO_2 removal in the context of climate change mitigation.

Methodological approaches to study SOC stock change can be classified into i) diachronic approaches (i.e., time series or longitudinal studies) and ii) synchronic approaches (i.e., space-for-time substitution) (Petersson et al., 2024; Cardinael et al 2024). Diachronic approaches are primarily applied in controlled, randomized field trials but are also used in on-farm research to directly quantify temporal changes in SOC stocks. In contrast, synchronic approaches infer temporal SOC changes from observations across farms with different coffee system ages or time since adoption of management practices of interest. Synchronic approaches can further be subdivided into paired comparisons, chronosequences, and surveys. Chronosequences may be implemented as paired or unpaired designs, whereas surveys are inherently unpaired and rely on large numbers of farms or plots to statistically account for spatial variability in SOC stocks including relevant explanatory variables. Each of these approaches involves trade-offs between feasibility, control, and inferential strength, underscoring the need for complementary study designs rather than reliance on a single methodology. Importantly, research aimed at quantifying carbon sequestration must rely on diachronic approaches, as synchronic comparisons can only identify relative differences in SOC stocks between treatments and controls at a single point in time. They cannot determine whether systems with higher SOC stocks are losing carbon more slowly, merely maintaining existing stocks, or actively accumulating additional SOC compared to a baseline reference (Don et al., 2024; Petersson et al., 2024).

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Table 1: Methodological approaches for researching SOC storage and practical considerations (based on Cardinael et al., 2025; Petersson et al., 2024).

	Methodological design	Practical considerations
Diachronic approaches (i.e., time series or longitudinal study)	Controlled field trials	+ High internal validity + Highest interpretability - Costly, requires long term funding and therefore usually limited to few environmental contexts +/- Long-term institutional commitment required
	On-farm experiments	+ Greater representativeness of realistic farm conditions + Higher interpretability than synchronic approaches - Less experimental control, particularly to separate treatment effects from random spatial and temporal variation- Difficult to guarantee long-term commitment
Synchronic approaches / space-for-time substitution /	Paired plot comparisons	+ Results obtained in a short time, feasible across broad environmental contexts - Higher risk of bias due to confounding variables than with the diachronic approach - Only relative differences in SOC stocks between treatments and controls can be identified, which limits the interpretability of their actual carbon sequestration potential
	Chronosequence	+ Explicit consideration of temporal effects - Similar limitations to paired comparisons if reference plots are used but higher risk of bias due to confounding variables when not paired. - Only relative differences in SOC stocks between treatments
	(Stratified) random surveys	+ Broad environmental coverage - Large sample size required - High risk of confounding bias. - Only relative differences in SOC stocks between treatments

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2.2 Diachronic approach

When the objective of the researchers is to assess the effects of individual agronomic management interventions or system comparisons, the preferred research approach is the diachronic approach (Cardinael et al 2025)), applied in long-term trials (LT) with controlled field experiments or on-farm monitoring with documented management practices between sampling periods (Table 2). In controlled field experiments, treatments must be randomly assigned to plots and replicated across multiple blocks to account for spatial heterogeneity in soil and terrain properties and are compared against an appropriate control without the intervention of interest. This design enables SOC stock changes to be quantified over time in treatment plots relative to controls, while separating treatment effects from random spatial and temporal variation not directly attributable to the treatments (Brus, 2022).

When the objective is to compare effects, be it from individual agronomic management interventions or system comparison, across a wide range of environmental and management conditions, on-farm experiments, where the treatments are established on different farms, are a reasonable alternative (Table 2). However, while this might be more representative of realistic farm conditions and farm-to-farm variation, the drawback is more random variability or spatial autocorrelation that can complicate the interpretation of the results (Wartenberg et al., 2020). Such trade-offs must be carefully weighed when designing a research project.

System-level experiments, such as comparisons between sole coffee cropping and different agroforestry designs or conventional vs. organic systems, are often established on-farm (Hergoualc'h et al., 2012). However, systems can also be investigated through controlled field trials, including agroforestry contexts (Chavez et al., 2021; Kasmerchak et al., 2025; Noponen et al., 2013; Orozco-Aguilar et al., 2024). Further guidance on designing such experiments while accounting for the specific challenges of agroforestry systems is provided by Coe et al. (2003).

Many factors simultaneously influence SOC storage, including changes in the type and quantity of organic inputs, microclimatic conditions that regulate decomposition rates, root activity, and soil cover. In agronomic treatments that involve whole system designs, such as agroforestry, these factors inevitably change together, making it challenging to attribute observed SOC responses to any single driver. As a result, experimental designs should prioritize the collection and reporting of sufficient data to detect potential changes in key processes and microclimatic conditions associated with the system changes, in order to support robust interpretation of SOC responses at system-level (Coe et al., 2003; Dupraz, 1999).

The advantages of controlled LT trials for generating robust data of SOC stock dynamics attributable to specific management interventions or system designs are well established (Cardinael et al., 2025; Smith et al., 2020). Such trials provide the strongest basis for attributing the observed SOC stock changes to management effects. However, the availability of LT SOC stock data is limited to a small number of sites where LT experiments have been established, largely due to the substantial costs involved and the sustained institutional commitment required. The minimum time required to detect measurable changes in SOC stocks depends on carbon inputs and agroecological conditions but is generally in the order of 5-10 years (Smith, 2004). In perennial cropping systems, and particularly agroforestry systems with slow growth, this period

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can be longer due to the additional time required for tree establishment and biomass accumulation. Establishing, maintaining, and monitoring controlled field experiments over such timescales is resource-intensive, especially when multiple treatment levels are included. As a result, LT trials are typically confined to a limited range of soil types and climatic conditions (Chatterjee et al., 2019; Noponen et al., 2013; Chavez et al 2021; Kasmerchak et al 2025).

2.3 Synchronic approaches / space-for-time substitution

We differentiate between three types of synchronic approaches, namely paired comparisons, chronosequence and stratified random surveys (Table 2). Paired comparison studies represent one of the most practical approaches for assessing LT SOC stock outcomes in coffee systems, particularly under agroforestry management (Cardinael et al., 2025), and can ideally complement diachronic studies described above. Synchronic approaches facilitate the evaluation of land use and coffee management practices on SOC stock across a wide range of environmental and management conditions. However, as an observational approach, paired comparisons have important limitations, most notably the inability to unequivocally attribute observed differences in SOC stocks to specific management practices. To mitigate this limitation, the influence of confounding factors, such as soil texture, climate, and topography, should be minimized through careful site selection and, where sample sizes permit, explicitly accounting for them in the statistical analysis. At a minimum, these variables should be systematically reported to support interpretation of results and to enable robust synthesis in subsequent meta-analysis. Optimally, farms are selected where part of the field has changed management practices reflecting the treatment of interest (e.g., from sole coffee to agroforestry). In this case adjacent treatments are available with similar historical management.

The selection of farms is critical for synchronic approaches, especially when making use of pairing. Careful selection of reference coffee systems and the paired plots is essential to minimize bias. Ideally, a reference plot should be adjacent to the treatment plot, but even then differences in soil type, texture, depth and topography should be carefully checked to limit confounding effects (Rosinger et al., 2023). It is impossible to eliminate variability arising from inherent soil heterogeneity, historical land management and variation in individual farmers' behaviour. As a result, the differences observed in SOC stocks reflect both management-induced effects and potentially considerable random variation.

The required number of paired plots depends mainly on the magnitude of within-zone SOC variability and the minimum difference the study aims to detect and is often a compromise between statistical power and implementation costs or time. Given typical field-scale SOC variability in perennial systems (CV ≈ 15–30%) and realistic target differences of 10–20% between management systems, standard paired-sample power calculations (power = 0.8, α = 0.05) indicate that 15-20 paired plots per agroecological zone are required to robustly detect SOC stock differences. Increasing the number of paired farms further enhances statistical power and reduces the influence of unmeasured confounding factors, which is particularly important in heterogeneous landscapes typical of many coffee growing areas.

When the objective is to conduct a chronosequence study assessing SOC stock changes over time since conversion to coffee, or since management change, farms of different age in similar conditions are selected, ideally paired with a neighbouring control plot (Koorneef et al., 2024). In contrast, where the aim is to compare equilibrium SOC stocks under different management systems, farms should have been under coffee cultivation with practices comparable to current management for at least 20 years, which is consistent with the default 20-year transition period after land use changed used in the IPCC 2006 guidelines and several derived tools. Although this period does not guarantee that SOC has reached equilibrium (Poeplau et al. 2011; Emde et al., 2024), it helps minimize the effects of recent land use change (Laub et al., 2023). In tropical agroforestry systems, reaching a new theoretical SOC equilibrium may require 20-50 years due to the time needed for tree establishment, biomass accumulation, and associated changes in soil processes ((Ma et al., 2020; Poeplau et al., 2011). Therefore, when the objective is to evaluate the combined effects of land-use change and management practices, a chronosequence design represents a justifiable and pragmatic approach.

When unpaired farms are used (i.e., surveys), the number of replicates must be substantially higher than in paired plots. In such cases, model-assisted estimations can improve precision of comparisons by including potential confounding variables as covariates to account for differences in site conditions. Further stratification by agroecological factors such as soil type, rainfall, temperature, and topography can reduce the number of farms required and strengthen robustness of comparisons by explicitly accounting for environmental variability during the sampling design phase (Brus, 2022).

2.4 Defining sampling strategy at farm/field scale

Decisions on sampling strategy at farm/field level should consider the study's research questions, the existing spatial variation in soil properties, and the expected spatial heterogeneity of the effects of the management interventions under study. Spatial variation in soil properties is typically high in perennial crop fields and strongly influenced by environmental factors, such as slope (including erosion), hydrology, and coffee system design and management. Coffee farms show a large diversity in plantation size, planting schemes and shade tree cover. Agroforestry systems can be planted in a systematic way (e.g., alley cropping) with trees of similar age/size or trees can be scattered and include different species of various sizes (Pulleman et al., 2023). Together with the pruning management this variation defines the irregular distribution of plant litter and the associated heterogeneity of soil properties. Associated trees will affect SOC only up to a certain distance from the tree, whereby carbon inputs result from both aboveground (leaves) and belowground (roots), while also affecting the soil microclimate (temperature and humidity) and thus biological activity and decomposition rates. Application of soil amendments and fertilizers in coffee is typically heterogeneous both in space (under the dripline, half-moon shape application on slopes) and time, which depends on plant age and renovation cycles (Ortiz-Gonzalo et al., 2017; Tittonell et al., 2005). How to account for such complex heterogeneity is a key consideration when developing a proper sampling design (Coe et al. 2003; Wartenberg et al., 2020).

Guidelines on spatial sampling schemes for agroforestry systems are provided in Minarsch et al. (2025) and Rao & Coe (1991) and can also be applied to heterogenous sole coffee crops and intercropping. These authors agree with their recommendation to follow a similar transect sampling scheme for both treatment plots (e.g., an agroforestry plot) and the

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reference system or control plots (e.g., sole coffee crops) of the same study. The orientation, location and sampling positions along transects are important considerations to avoid biases (Minarsch et al., 2024). In agroforestry systems with more than one tree species, differences in tree species identity and management need to be taken into account (Chatterjee et al., 2019; Minarsch et al., 2025). Alternatively, the farm can be stratified by slope and vegetation structure as shown in Fig 1 (a and b) into relatively homogeneous areas. Importantly, the spatial sampling design needs to be well documented, which was a weakness of most of the SOC studies reviewed under objective 1.

Sample size (i.e., the number of composite samples, and the number of soil cores (or aliquots) per composite sample to be collected) is best determined from a stratified pilot sampling to first quantify within and between plot variability. Alternatively existing information collected in comparable settings can be used as an indication, when resources do not allow for pilot sampling. The number of composite samples per stratum can be calculated to meet a predefined precision (or minimum detectable change) using standard sampling theory (Brus, 2022), while the number of aliquots per composite needs to be selected to reduce within-plot variance to an acceptable level given budget constraint. As a minimum, the number of bulk density samples should equal the number of SOC composites.

2.5 Sampling depth

To determine the changes in SOC stocks due to land use change or management, sampling should go as deep as SOC changes are expected. This can be up to a meter or more, especially where trees, shrubs and deep rooting pasture species are present. Most SOC stock guidelines, including those of the IPCC and FAO (IPCC, 2006; 2019; FAO, 2020) and Monitoring, Reporting and Verification protocols (Dupla et al., 2024) require sampling soils to at least 30 cm, being the layer where most of the aboveground carbon inputs and most of the roots are located. However, in perennial systems, in particular when intercropped with shade trees or (cover)crops with deep rooting systems, the vertical root distribution of the coffee plants and associated crop/tree species should be considered (Cardinael et al., 2025, 2025; Coe et al., 2003). For coffee plants an average maximum rooting depth of around 300 cm has been reported (Barros et al., 1999), albeit with large variations among studies and sites due to variation in coffee variety, propagation method, soil depth, climate and soil characteristics (Defrenet et al., 2016). With regard to the vertical distribution of coffee (*C. Arabica*) root biomass, Defrenet et al., (2016) showed that 30–55 % of total root biomass was present in the upper 10–30 cm of the soil profile, around 70% in the top 50 cm, 78% in the top 60 cm and more than 80% in the top 100 cm. Moreover, even when the management practices being studied focus on superficial carbon inputs only, such as manure, biochar or compost, layers below 30 cm may eventually be affected, as was shown in LT maize cropping experiments in Kenya (Müller et al., 2024). For LT studies in general (i.e., > 20 years, irrespective of crop type), Raffeld et al., (2024), recommend sampling to 60 cm to capture changes in bulk density, potential SOC redistribution, and a larger proportion of the overall SOC stock. Nevertheless, for consistency among protocols including MRV protocols for SOC accounting (Dupla et al., 2024; FAO, 2020; Verra, VM42 Verra Methodology for

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Improved Agricultural Land, v. 2.0), a minimum depth of 50 cm may be an acceptable compromise to facilitate standardization.

In coffee systems, SOC stock assessment focusing only on the top 30 cm soil depth should only be used for short-term studies looking at agronomic management practices impacting only the upper soil layers. Assessment of deeper soil (at least 50 cm) is recommended for LT studies and system comparisons, including practices that are likely to significantly impact root turnover such as coffee pruning management (Defrenet et al., 2016). When coffee is intercropped with deep rooting trees or crops or when deep tillage is used for soil preparation, the recommended sampling depth is 100 cm. Acknowledging that increased intrinsic variability of deep soil layers may challenge proper interpretation and treatment attribution (Raffeld et al., 2024), baseline SOC stock assessments are strongly recommended.

The number of depth layers being separated has important impacts on research costs and is therefore another important choice to be made. While a single depth sample would be justifiable for SOC stock quantification perse, the chance of detecting early effects is higher when different depth layers are distinguished. Moreover, assessing changes in topsoil carbon has great relevance from a soil health perspective (Castellanos-Navarrete et al., 2012). Therefore, the recommendation is that SOC and bulk density measurements are separated into several continuous soil layers, ideally 0-10, 10-30, 30-50 cm, in line with (FAO, 2020; Cardinael et al., 2025) and, where applicable, 50-100 cm.

2.6 Sampling frequency

When SOC stocks are monitored over time (i.e., the SOC change or diachronic approach; Table 2), it is recommended that measurements are repeated every 5 years approximately (FAO, 2020). However, the optimal sampling frequency depends on the research question and the baseline soil conditions. The response to SOC enhancing practices is generally slow, especially in soils with high background amounts of carbon. As a reality check, a simple calculation can be made to check how long it could take before a measurable change in SOC stocks can be expected, based on the amounts of carbon inputs added per year and the assumed decomposition rate.

On the other hand, when the study focusses on carbon losses e.g., due to land use change starting from (relatively) undisturbed conditions, changes in carbon stocks are generally much faster (Laub et al., 2023).

Although not common in coffee production, when carbon stocks in tilled soil are being compared over time, it is best to sample the soil shortly before the tillage operations, because tillage will temporarily reduce the bulk density, and this has a strong impact on the soil mass sampled for a specific depth (Hauser et al., 2023), as described below.

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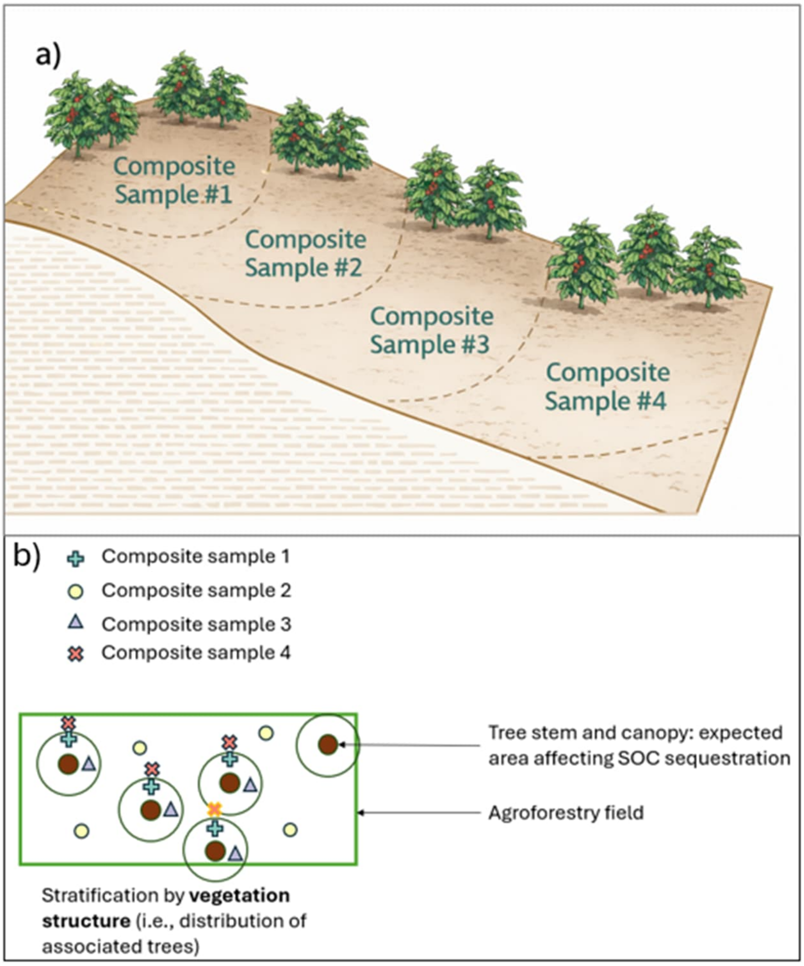

Figure 1: Example of stratified sampling based on a) slope and b) shade tree distribution.

2.7 Bulk density

Calculation of SOC stocks, expressed in Mg C ha^{-1}, requires information on SOC concentration and soil bulk density. However, one of the major challenges in SOC stock assessments is the representative measurement of soil bulk density (Boivin et al., 2025; Wendt & Hauser, 2013). Bulk density is commonly measured using small, undisturbed soil cores collected with the classical and widely accepted ring sampling method. This approach has several limitations, particularly in soils that are very dense or very loose, or that contain stones or coarse roots. The method is labour-intensive, prone to measurement error, and often requires excavation of soil pits, leading to substantial soil disturbance in experimental plots (Hauser et al 2023; Pepers et al., 2024). Consequently, the number of bulk density samples collected during SOC sampling campaigns is frequently insufficient to adequately capture spatial variability, both horizontally and vertically. Moreover,

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information on the number of samples collected is rarely reported (Annex 1). New methods are becoming available but require further testing such as seismology (Tsekhmistrenko et al., 2025) and gamma ray (Pepers et al., 2024).

2.8 Equivalent soil mass approaches

When bulk density differs between treatments or sampling times, SOC stock comparisons should be based on the equivalent soil mass (ESM) approach (Cardinael et al., 2025; Ellert & Bettany, 1995; Wendt & Hauser, 2013). Fixed-depth sampling is known to systematically overestimate SOC stocks in soils with higher bulk density and underestimate them in soils with lower bulk density (Boivin et al., 2025; Don et al., 2011; Raffeld et al., 2024), Nevertheless, many studies, including those in coffee systems, still fail to account for differences in sampled soil mass (Boivin et al., 2025; Cardinael et al., 2021; Dupla et al., 2024), despite reported bulk-density variations in the range of 15-25% due to land use, management, or temporal change, even in the absence of tillage (Boivin et al., 2025; Cardinael et al., 2025; Dupla et al., 2024; Youkhana & Idol, 2009). In fact, even when bulk-density differences are small and associated errors may appear negligible, reporting SOC stocks on an ESM basis is recommended to avoid difficulties in re-evaluating fixed-depth data already reported and to enable normalization of management effects in comparative analyses and meta-analyses (Wendt & Hauser, 2013).
Several methods exist to estimate ESM-based SOC stocks (Wendt & Hauser, 2013). In the original approach, soil mass is calculated from bulk density and sampling depth for each layer, requiring accurate and representative bulk-density measurements across treatments and depths (Ellert & Bettany, 1995). Alternatively, soil mass can be derived directly from sample mass using auger sampling with a known volume (Wendt & Hauser, 2013). This latter approach was shown to be reliable in Swiss soils (Boivin et al., 2025). Although it has higher relative uncertainty, this can be mitigated by increasing replications. Further testing in tropical coffee-growing soils is needed to strengthen confidence in its wider applicability.
Regardless of the method used, SOC stocks should be reported at the ESM at which they were calculated, as this approach is essential for accurately assessing the effects of management practices and land use on SOC storage within a given soil type. In addition, reporting SOC stocks at fixed depth intervals, at least in the supplementary material, is strongly recommended. Presenting both metrics enhances transparency, facilitates resampling, and supports comparison with data on rooting patterns or tillage depths, where applicable.

2.9 Lab analysis

Different methods for determining organic carbon concentration in soil samples exist. The dry combustion method using an autoanalyzer is the preferred method for the measurement of total soil C concentrations as it offers the highest precision. However, since dry combustion measures total carbon in the soil sample rather than organic carbon, prior removal of, or correction for inorganic carbon may be required (FAO, 2019, 2020; Koorneef et al., 2024). Presence of inorganic carbon is not common in soils used for coffee production. However, in soils with pH > 6.5 prior testing for the presence of inorganic

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carbon is strongly recommended (Gozukara et al., 2025). Due to the very small amount of samples used during dry combustion, sample preparation involves additional steps. In addition to the commonly used sample preparation procedures (crushing and homogenization using a 2 mm sieve), fine ball mill grinding is recommended to ensure the soil is well homogenized and high precision is achieved.

Special attention is also required when assessing SOC stocks in soils that have significant volumes of stones or rocks. In soils that contain a significant amount of coarse fraction material (>2mm), SOC analysis of the fine soil (< 2 mm) should always be corrected for the gravel and stone contents (> 2 mm) when calculating C stocks (Hauser et al., 2023). Not adjusting SOC stocks based on the importance of the coarse fraction can lead to significant overestimates (Poeplau et al., 2017).

2.9.1 Alternative methods for measuring SOC concentration

Due to the relatively high costs of autoanalyzers for total carbon content, the classic wet oxidation method using potassium dichromate and sulphuric acid (Walkley & Black, 1934) is still used in many laboratories, especially in the Global South where coffee is produced (37 of the reviewed studies use it; Annex 1). A major disadvantage of this method is that organic carbon recoveries are incomplete and inconsistent as the recovery percentage compared to dry combustion depends on soil type and depth. Moreover, stable organic carbon fractions like black carbon/charcoal do not oxidize and will thus not be included in the SOC quantification (Conyers et al., 2011). Therefore, relying on the wet oxidation methods for SOC stock assessments is discouraged (Cardinael et al., 2025; FAO, 2020).

Deploying adequate Quality Assurance/Quality Control (QA/QC) procedures is part of good laboratory practices (ISO, 2017). However, precision (reproducibility based on analytical replicates) and accuracy (recovery compared to certified reference samples of known SOC content) are rarely reported in scientific publications. Alternatively, internal reference materials or reference materials offered by specialized proficiency testing labs (e.g., WEPAL) can be used. Reference materials should be included in the whole analytical procedure, including the steps to remove or correct for inorganic carbon. Further details on laboratory quality control and quality assessment procedures for SOC quantification can be found in (FAO, 2019, 2020).

Finally, spectroscopic techniques have evolved as a more cost-efficient alternative to dry combustion analysis (FAO, 2020). Promising results have been obtained using lab-based MIR and FTIR spectroscopy, or laser-induced breakdown spectroscopy (LIBS) (Knadel et al., 2017; Senesi & Senesi, 2016), coupled with predictive modelling for estimating Total C, SIC, and SOC concentrations for regions where high quality spectral libraries exist (Even et al., 2025; FAO, 2020). However, to ensure the quality of predictions, models based on data from sample sets that include both reproducible spectra and high-quality dry combustion analysis are required to generate high quality libraries that are region-specific. Unfortunately, at the moment libraries are still lacking in most coffee producing countries. Portable scanners used directly in

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the field, based on VIS and NIR spectroscopy, have similar limitations and also lead to more variable results, depending on the samples' moisture and temperature, milling size, etc. (Dupla et al., 2024).

2.10 Reporting on contextual variables

Data related to carbon inputs, soil texture and soil mineralogy are important contextual variables that are very informative next to climate, topography (i.e., slope) and land use history. This data is often not easily available when working with many coffee farms and is difficult to collect but can greatly support a more mechanistic understanding of carbon dynamics rather than solely doing carbon stock accounting. Providing data on the amount of soil amendments applied rather to a specific soil than simply using binary information (absence / presence), is important for interpreting the results. It is recommended to include as many management variables as possible, such as the type of organic management, the type and amount of mineral fertilizers, pesticides, pruning practices, etc, particularly when the objective is to study the drivers of SOC storage. Information on soil texture and soil mineralogy is a major factor determining SOC stabilization (Reichenbach et al., 2023; Six et al., 2002, 2024). Cardinael et al., (2025) provide a checklist and description of variables that need to be reported to support interpretation of research studying SOC stocks.

3 Systematic literature review of existing SOC studies in coffee

3.1 Methodology

To address this objective, we systematically reviewed 80 publications assessing SOC stocks in coffee plantations globally, representing a wide range of soil types, climates, and management systems (see supplementary file). The following search code was used on February 2nd, 2026, in Scopus: ("Coffee" OR "Coffea") AND ("Soil") AND ("SOC" or "Carbon") AND ("Stocks" OR "Storage" OR "Sequestration") including searches in title, abstract, and keywords resulting in 242 articles published between 1974 and 2026. From these, articles were excluded that did not contain primary data on SOC concentration and soil bulk density or did not analyze SOC stocks in coffee systems.

Besides an analysis of the geographical origin and objectives of the available studies, the management systems or practices studied and the key findings reported, we conducted a systematic analysis of the research designs and methodological aspects. The latter allows us to evaluate the robustness of the studies, as well as any challenges that limit their interpretation or comparability. Our analysis was based on a number of key criteria as shown in Table 2.

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Table 2: Criteria used to compare methodological aspects of studies on SOC stocks in coffee systems

Criteria	Description
Country	
Research objective	• Land use change • System comparison • Management effects • Other
Land uses or management practices compared	
Coffee species	• *C. arabica* • *C. canephora* • *C. liberica*
Previous land use and time since conversion	
Soil type	
Study design	• Diachronic study • Synchronic or space-for-time substitution o Paired comparison o Chronosequence o Stratified survey
Years between sample collection	Only applies for stock difference method
Design of experimental trial	• Randomized block design, etc.
Number of replicates	
Sampling area of replicates	
Sampling scheme for soil sample collection	• Complete random sampling • Stratified random sampling • Transect sampling
Soil depth layers for SOC concentration and bulk density	
Number of composites and aliquots for sampling SOC concentration	
Laboratory SOC analytical determination	Dry combustion Walkley & Black Spectroscopy Other
Approach used for SOC stock calculation	Fixed depth Equivalent soil mass
Number of soil bulk density samples	
Correction for stones and coarse fragments	Not relevant

	Yes
	No
Information on contextual variables provided	Yes/no (for each variable ; Cardinael et al., 2025)

3.2 Key findings on limitations of available scientific research

Available scientific literature presenting primary data on SOC stocks is geographically concentrated in Latin America (n=36), followed by Africa (n=26) and Asia–Pacific region (n=18), with Ethiopia (n=18), Brazil (n=12), Peru (n=7) and Indonesia and Costa Rica (n=6) being the dominant countries. The majority of these studies focused on *C. arabica* (n=62), with 12 studies including *C. canephora* and one study *C. liberica*.

Most studies quantified and compared SOC stocks among different land uses and/or types of coffee production systems, including natural vegetation, annual crops, sole coffee crops and coffee agroforestry. These studies investigated how these systems affect SOC stocks by using synchronic / space-for-time substitution approaches (n = 70) focusing on land use change (n = 38) and/or system comparison (n = 33).

Evidence from diachronic studies based on medium-term (MT) ($\geq 5\ years$) to long-term (LT) ($\geq 20\ years$) experiments remain scarce. Only five identified studies were based on controlled field experiments using diachronic approach, and of these, just three covered periods of at least five years. Two MT controlled experiments monitored SOC stock dynamics for more than five years: one over nine years (Noponen et al., 2013) and another over 16 years (Chatterjee et al., 2019). Both studies evaluated different coffee agroforestry systems established after sugarcane as the previous land use. In each case, sole coffee cropping served as the control, and management practices compared conventional and organic systems. Another study assessed SOC stocks on the same plots after three years (Hergoualc'h et al., 2012). A further study examined the effects of applying *Leucaena* mulch over a two-year period (Youkhana & Idol, 2009, 2011). No other studies were identified which directly assessed the effects of individual management practices, such as cover crops, soil amendments, or specific conservation measures, using MT/LT nor controlled, randomized field experiments. Based on this, we identified a clear research gap limiting our capacity to attribute any measured SOC stock changes to specific practices or their interactions.

Only 42 studies assessed SOC below 30 cm and only 27 extended sampling beyond 40 cm. This is a notable limitation given that subsoils (i.e., soil layers below 30 cm) store approximately 50% of total SOC stocks (Müller et al., 2024) and have a greater potential for long-term carbon stabilization over decadal to millennial timescales (Balesdent et al., 2018; Müller et al., 2024; Rumpel & Kögel-Knabner, 2011). This aspect is particularly relevant for perennial systems such as coffee agroforestry, where deep rooting can enhance carbon inputs to subsoil layers (Defrenet et al., 2016). Among the few studies that examined deeper soil layers (> 40 cm) using diachronic or synchronic paired plot designs, management effects on SOC were generally not significant. However, several studies did not report land-use history, and all relied on fixed-depth sampling approaches, which may bias SOC stock comparison. More rigorous methodological approaches and LT are

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therefore needed to better understand SOC dynamics at greater soil depths, particularly in agroforestry systems relative to monocropping systems used as references.

Our review identified substantial research gaps and recurring methodological weaknesses that currently limit the generation of robust scientific evidence to inform decision making. In particular, these limitations constrain our ability to assess i) the quantitative potential of soils in coffee production systems for atmospheric carbon removal and ii) the agronomic and environmental factors that most strongly influence carbon sequestration. Of the studies using a synchronic approach, only few (19 out of 71) made use of a paired plot design using adjacent controls to minimize differences in environmental conditions and land use history. Instead, most studies selected different farms, whereby each farm represented a specific treatment, often located far away from the control. Nonetheless, many refer to the term SOC sequestration when identifying significant differences between land uses or management practices, even though the study design does not provide relevant information on SOC sequestration (Box 1). Hence research questions are often not aligned with study designs.

Robust sampling schemes are frequently lacking. Many studies do not adequately account for spatial variability, apply insufficient sampling depths, or fail to properly correct for differences in soil bulk density arising from land-use or management changes. These limitations introduce biases and reduce the reliability of SOC stock comparisons and change estimates. Finally, most studies provided limited information on key contextual variables, including detailed descriptions of production systems, soil properties, climatic conditions, and land-use history. The absence of systematic reporting of such variables hampers cross-study comparability and interpretability, restricting our ability to move beyond individual case studies toward a more generalizable understanding of SOC sequestration potential and its determining factors (Cardinael et al., 2025).

3.3 Key findings on the effects of coffee management on SOC stocks

As indicated above, there were only two studies that adopted a diachronic approach with more than 5 years between sampling campaigns (Chatterjee et al., 2019; Noponen et al., 2013). Noponen et al. (2013) found that SOC stocks declined over nine years following conversion from sugarcane to coffee, decreasing by 12.4% in Costa Rica and 0.13% in Nicaragua within the 0-40 cm soil layer. Notably, SOC stocks increased in the upper 10 cm but declined more substantially in the 20-40 cm layer. Organic management practices had stronger effects than shade type and were linked to organic matter inputs (e.g., soil amendments, shade tree pruning), rather than standing aboveground biomass. Because no significant changes in soil bulk density were detected, a fixed-depth approach was used.

Chatterjee et al., (2019), working at the same Costa Rican site as Noponen et al., (2013), extended the monitoring period to 16 years using a fixed-depth approach. Their results confirmed that organic matter inputs primarily affected SOC stocks in the upper 10 cm, with no significant effects observed in deeper soil layers and no relationship between aboveground biomass and SOC stocks, even after an additional seven years. However, it remains unclear whether changes in bulk density occurred over time, which would have necessitated an ESM-based correction.

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Across the broader literature, the fixed-depth approach was used in the majority of studies (n=63), whereas only eight studies applied the ESM approach; the remaining studies did not provide sufficient methodological detail to determine how SOC stocks were calculated. Furthermore, more than half of the studies (n=53) failed to report previous land use, limiting interpretation of SOC dynamics in relation to land-use history.

According to the observational studies, SOC stocks in coffee plantations were generally slightly lower than those under natural forest, although exceptions exist (e.g., Guillemot et al., 2018). SOC stocks typically decline following conversion from native vegetation to agriculture (Hombegowda et al., 2016) and sole coffee cropping (Belizário et al., 2018), but can recover to near forest levels with specific agroforestry designs (Guillemot et al., 2018; Hombegowda et al., 2016; Schmitt-Harsh et al., 2012). SOC stocks under coffee systems were consistently higher than those in annual or other perennial cropping systems (e.g., coconut and mango plantations (Hombegowda et al., 2016). Most studies examined systems-level management effects, such as organic versus conventional production, shaded versus full sun systems, and varying levels of diversification, but results are inconsistent and sometimes contradictory. While organic and shaded systems with greater plant diversity and biomass inputs tended to be associated with higher SOC stocks, these findings were largely based on observational comparisons and provided limited mechanistic insight or robust evidence of SOC sequestration.

Because SOC dynamics are strongly influenced by previous land use and the time elapsed since conversion, many studies have adopted chronosequence approaches (e.g.,Belizário et al., 2018; Hombegowda et al., 2016). However, these approaches rely on the assumption that sites share similar environmental baselines, an assumption that is often violated. Differences in soil properties and climate frequently obscure management effects, particularly in deeper soil layers where SOC changes occur slowly and legacy effects dominate (Chatterjee et al., 2019; Hergoualc'h et al., 2012). As a result, outcomes from observational studies cannot readily be generalized across contexts. Moreover, in many cases the conclusions of the studies attributing changes to differences in management are not supported by the data because of those confounding effects, something that the paired plot approach partly corrects for.

4 A research roadmap for robust SOC assessment in coffee systems

Our review demonstrates that current knowledge on SOC dynamics in coffee systems is insufficient to support robust claims about carbon removal, climate mitigation, or long-term soil regeneration. Moving forward requires a shift from descriptive stock comparisons toward clearly framed, hypothesis-driven, and methodologically rigorous research. Here we prioritize five recommendations that form the backbone of a robust research roadmap which aims at providing a more mechanistic and quantitative evidence for SOC storage potential and drivers, targeting researchers and actors in the coffee supply chain.

4.1 Explicit framing of research objectives and baselines

Future SOC studies in coffee systems must clearly define the research objective and clarify whether the aim is to assess soil quality or soil function, evaluate land use change impacts, compare management systems or management practices and whether the carbon sequestration in the context of climate change mitigation is of interest. Furthermore, the baseline or business-as-usual needs to be specified. Importantly, when the objective of the study includes carbon sequestration, SOC change can only be meaningfully interpreted relative to a defined reference trajectory using a diachronic approach. Only then can be clarified whether the baseline system is at steady state, losing carbon, or already accumulating SOC. Without this clarification, observed SOC differences risk being misinterpreted as carbon removal.

Findings must specify the inference domain, clarifying whether conclusions apply at the level of plot, farm, or agroecological zone. The inference domain defines the spatial and contextual scale at which the study's findings can be interpreted and applied. Clearly defining the inference domain is essential because SOC stocks and dynamics are strongly influenced by local factors such as soil type, climate, management history, and cropping systems. As a result, SOC differences observed in a particular study site may not necessarily represent outcomes that can be expected elsewhere. Explicitly stating the inference domain helps ensure that findings are interpreted within their appropriate context and prevents context-specific SOC differences from being generalized as universal carbon sequestration potential.

4.2 Strengthening experimental foundations

4.2.1 Expand long-term, diachronic experiments

Quantifying SOC sequestration requires repeated measurements over time (i.e., diachronic studies). A priority is, therefore, the establishment of new MT and LT (> 10-20 years) coffee trials across major coffee producing regions. These trials are essential for quantifying SOC sequestration rates and identifying causal relationships between management practices and carbon dynamics. Sites should ideally be selected in areas that have not undergone recent land-use change to avoid confounding legacy effects. At the same time, prioritizing degraded lands under long-term agricultural use would provide valuable insights into the regenerative potential of differently managed coffee systems. Attention could be given to management interventions with high carbon sequestration potential and co-benefits for soil health, such as the application of biochar derived from on-farm organic residues as a carbon removal strategy that may enhance nutrient retention and fertilizer-use efficiency. In regions where coffee has replaced pasture or other C_4 crops, stable isotope approaches may offer additional opportunities to trace SOC dynamics and distinguish newly sequestered carbon from pre-existing stocks. The establishment and maintenance of such trials, however, require substantial financial investment and long-term institutional commitment.

To maximize the impact of these efforts, it would be strategic to compile and maintain a global inventory of existing long-term coffee field trials, including information on site characteristics, treatments, available datasets, and associated publications. Providing an open platform where trial owners can share information would enhance visibility, foster

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collaboration, and help potential funders allocate resources more efficiently. Such an initiative could strengthen scientific exchange networks and reduce duplication of effort.

4.2.2 Complement with large-scale harmonized surveys

Complementary to long-term trials, coordinated surveys and chronosequence studies of coffee farms in prioritized regions and representative farm archetypes are needed to validate the applicability and scalability of experimental findings across broader environmental and socio-economic contexts. Engaging a large number of farms using harmonized and robust methodologies would generate datasets suitable for benchmarking and cross-site comparison. This data could also be used to parameterize and refine SOC models tailored to coffee production systems, explicitly accounting for site-specific environmental drivers of SOC accrual and stabilization. Once developed, such models should be tested and validated across expanded farm networks. It is important to recognize, however, that field surveys provide only a snapshot of SOC stocks at a given time and cannot determine whether systems are at equilibrium or transitioning toward a new steady state. For this reason, sites that have undergone recent land-use change should generally be excluded from such assessments.

4.3 Integrating whole-system climate and agronomic performance

Future research must also move beyond SOC stocks in isolation and adopt a whole-systems perspective on GHG dynamics. While many studies frame SOC storage in a climate change mitigation context, relatively few employ designs that allow true quantification of sequestration rates, and even fewer account for associated GHG fluxes. Coffee systems can influence emissions of other greenhouse gases, notably N_2O, and SOC gains may be partially offset by increased N_2O emissions, particularly in agroforestry systems that include nitrogen-fixing shade trees (Hergoualc'h et al., 2012). Evaluating net climate benefits therefore requires integrated assessments of SOC sequestration, GHG emissions, and agronomic performance. At the same time, improvements in soil health associated with higher SOC may enhance yields and fertilizer-use efficiency, potentially reducing the carbon footprint of coffee production. A comprehensive understanding of carbon dynamics in coffee agroecosystems thus demands integration across carbon stocks, GHG balances, and productivity outcomes in diverse environmental and management settings.

4.4 Methodological innovation and cost reduction

Methodological innovation will be critical to enable such integration at scale. The validation and deployment of cost-effective measurement techniques, such as alternative approaches to bulk density estimation (e.g., seismological or gamma-ray methods) and advances in spectroscopic techniques, could substantially reduce monitoring costs and improve feasibility in resource-constrained settings. Continued refinement, calibration, and inter-laboratory harmonization of these approaches will be essential.

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4.5 Data transparency, harmonization, and synthesis

Finally, improved coordination of data collection, standardization or reporting protocols, and open data sharing are foundational to progress. Systematic documentation of contextual variables, including soil properties, climate, management practices, and yield data, would facilitate benchmarking, meta-analyses, and model development. Greater transparency and interoperability of datasets will enhance reproducibility, accelerate synthesis, and ensure that investments in SOC research in the coffee sector translate into actionable knowledge.

Together, these efforts outline a pathway toward a more rigorous, collaborative, and impact-oriented research agenda capable of clarifying the true potential of coffee systems to contribute to climate mitigation and soil regeneration.

5 Conclusions

Given the relevance for soil health and climate impact, this study provides a systematic overview of the current state of knowledge on SOC storage in coffee systems, with particular attention to the research approaches and methodologies used to assess them. Our review highlights substantial variability in study design, measurement techniques, and reporting standards, which limits comparability across studies and constrains robust synthesis.

Further methodological advances are needed to improve the robustness, comparability, and efficiency of SOC assessments in coffee production systems. We propose practical guidelines for soil sampling and SOC determination aimed at enhancing cross-study consistency, while explicitly acknowledging trade-offs related to implementation costs and logistical feasibility. Adequate measurement and transparent reporting of key contextual variables and SOC baselines are essential to support sound interpretation and enable benchmarking, meta-analyses, and model development.

The central challenge is not to produce more SOC measurements, but to produce research that is better aligned with clearly defined objectives, baselines, and methodological standards. Without diachronic designs, equivalent soil mass corrections, appropriate sampling depths, and transparent contextual reporting, claims about carbon removal in coffee systems will remain scientifically fragile. Implementing the roadmap proposed here can transform fragmented case studies into a coherent, policy-relevant evidence base for soil regeneration and climate mitigation in coffee landscapes.

Supplement link

The link to the supplement will be included by Copernicus.

Author contributions

Eric Rahn: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, writing original draft, writing review & editing.

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Competing interests

At least one of the (co-)authors is a member of the editorial board of SOIL

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