

Article

A Roadmap for High-Integrity Soil Organic Carbon Sequestration in Mineral Soils: From Potential to Verified Storage

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Abstract

This study provides a structured operational-to-financial roadmap for soil organic carbon (SOC) sequestration in mineral soils as a specific carbon-farming pathway. It integrates SOC management; Monitoring, Reporting, and Verification (MRV) execution; financial recognition; and farmer adoption barriers. A comparison of carbon farming pathways is first presented to investigate their strengths and limitations, highlighting the specific importance of SOC management in mineral soils. For high-integrity carbon accounting, SOC gains should be assessed not only for quantity, but also for additionality, permanence, uncertainty, leakage, lifecycle emissions, and transparent verification. Credible MRV frameworks operationalize this logic: monitoring quantifies SOC changes, reporting ensures transparency, and verification provides independent assurance for carbon credit issuance and financial recognition. However, MRV execution faces several challenges, including high spatial variability of SOC, slow accumulation rates, methodological uncertainty, and high costs that limit scalability and reduce trust among stakeholders. Financial incentives are available from both public and private sources, supporting long-term soil carbon stabilization, verified carbon removals, and corporate insetting projects. Yet, adoption remains constrained by uncertain payments, poor transparency, contract and permanence concerns, as well as learning and operational costs for farmers. Addressing these bottlenecks is essential for transforming mineral-soil SOC sequestration into a scalable, high-integrity climate and economic opportunity.

Keywords: sustainable agriculture; carbon farming pathways; MRV; carbon credits; financial incentives; carbon market integrity; farmer adoption barriers



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1. Introduction

Climate change constitutes one of the most pressing issues of the current era. Evidence illustrates that average temperatures are increasing faster than ever before [1,2]. This

warming is driven predominantly by the escalating concentrations of the major anthropogenic greenhouse gases (GHGs), including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) in the atmosphere. GHGs are released via the combustion of fossil fuels and biomass. A smaller contribution comes from natural sources, but emissions are considerably amplified through the microbial decomposition of organic material across terrestrial environments [3]. Indicatively, the United Nations Environment Programme (UNEP) Emissions Gap Report [2], which was released in 2025, presents an alarming 8% growth of global GHG emissions as compared with the 2010–2019 decade average. Remarkably, agriculture and land-use change result in 19% of total emissions, second only to the power sector (27%), which is the largest single contributor.

Focusing on the agricultural sector, significant GHG emissions originate from: (a) enteric fermentation in livestock (CH₄) [4]; (b) manure management (CH₄, N₂O) [5]; (c) liming (CO₂) and urea application (CO₂); (d) conversion of forests, grasslands, or wetlands to cropland (CO₂, N₂O) [6]; (e) anaerobic conditions in flooded paddies (CH₄) [7]; (f) application of nitrogen-based fertilizers (N₂O) [8]; (g) conventional tillage relying on heavy plowing and soil turnover (CO₂) [9]; (h) crop residue burning (CO₂, CH₄, N₂O) [10]; and (i) combustion of fossil fuels for machinery, greenhouse heating, and irrigation (CO₂) [11]. Indicatively, a report focusing on US agricultural decarbonization [12] highlighted that agricultural production emissions are dominated by non-CO₂ gases. When measured in CO₂-e, N₂O had the largest share at 43%, followed by CH₄ at 38%, while CO₂ represented 19% of total agricultural production emissions.

Nevertheless, agriculture plays a dual role in the global GHG balance, since it functions both as an emission source and as a promising path for carbon sequestration. In fact, carbon can be sequestered either in plant biomass or agricultural soil. The former refers to the process by which the CO₂ in the atmosphere is assimilated via photosynthesis and stored in the structural material of plants, including trunks, leaves, branches, and roots [13]. Perennial crops and agroforestry systems have a high capacity for carbon sequestration as they accumulate stable biomass over multiple years [14,15]. In contrast, soil carbon sequestration is the process by which atmospheric carbon dioxide is captured and stored in soils [16]. In fact, soil represents the largest terrestrial carbon reservoir, as it stores an estimated two to three times more carbon than the atmosphere and approximately four times more than all aboveground vegetation [17]. This remarkable storage capacity makes agricultural soils, especially those of intensively managed cropping systems, a significant potential source of carbon loss and, at the same time, a major opportunity for carbon sequestration. In other words, when cropping systems are subjected to activities that disturb the soil, carbon that has accumulated over decades can be released rapidly. On the contrary, targeted agronomic interventions have the potential to enhance soil carbon stocks.

Strategic agronomic practices that aim to enhance soil carbon sequestration and/or reduce GHG emissions, thus mitigating the sector's climate impact, are collectively referred to as “carbon farming” [18]. Carbon farming involves a wide spectrum of practices, from land use changes to technological solutions that can deliver several co-benefits in four key areas. First, it provides environmental benefits, such as improvement of water quality and decrease in soil erosion and nutrient losses. Second, diversified rotations, cover crops, and reduced chemical inputs increase above- and below-ground biodiversity and strengthen essential ecosystem functions like natural pest regulation. Third, increasing soil organic matter improves soil structure, water retention capacity, nutrient availability, and biological activity which enhances resilience to climatic and agronomic stresses. Finally, it creates economic value for farmers through incentives from public programs and carbon-credit schemes that reward carbon farming practices [19,20]. Monetizing carbon farming can

serve as an incentive for farmers to adopt sustainable practices, while opening the door to a new and growing market that rewards climate initiatives.

In summary, carbon farming offers a sustainable and scalable pathway to mitigate climate change and generate economic value. However, large-scale adoption is currently hindered by critical challenges such as the high cost and complexity of accurate Monitoring, Reporting, and Verification (MRV), the permanence of stored carbon, and the demonstration of additionality [21,22]. Existing literature often draws broad conclusions from diverse ecosystems, frequently conflating GHG emission reductions with active carbon sequestration. These two pathways, however, present distinct carbon dynamics and sustainability co-benefits, while they differ significantly in their mitigation potential and specific market requirements. This lack of specificity creates an “operational gap” that hinders the transition from theoretical research to certifiable carbon removals.

This paper does not aim to serve as a conventional review of carbon farming, nor does it empirically validate a new MRV protocol through a specific case study. Instead, it focuses specifically on mineral soils, as they constitute a major share of agricultural land and are directly affected by routine cropland and grassland management. They also support soil organic carbon (SOC) maintenance and enhancement through targeted agronomic interventions. Contrary to organic soils and peatlands, where mitigation mainly depends on avoiding large emissions after drainage or degradation, mineral soils involve gradual SOC accumulation, strong spatial variability, site-dependent sequestration potential, and reversal risk. These characteristics make mineral soils particularly important for investigating how carbon sequestration potential can be converted into verified storage. Accordingly, this study aims to bridge the gap between theoretical research and operational implementation by providing a structured roadmap for SOC sequestration in mineral soils.

To gain a comprehensive understanding of the topic, the manuscript first provides a comparative analysis of diverse carbon farming pathways to evaluate their specific mitigation mechanisms and system-level impacts. It distinguishes between preventing GHG emissions and actively sequestering carbon to expand mineral-soil stocks. It systematically breaks down the “Monitoring”, “Reporting”, and “Verification” pillars to demonstrate how they transform biophysical soil processes into transparent carbon assets. The main contribution of this work is an interdisciplinary framework that brings together SOC management, MRV implementation, certification requirements, financial recognition, and farmer participation barriers. This integration represents the study’s key innovation, as it clarifies the operational conditions required for SOC sequestration to become credible, verifiable, economically recognizable, and practically attractive for farmers.

In this context, Figure 1 provides an overview of the proposed roadmap and serves as a conceptual guide for the sections that follow. It synthesizes the main components into an operational pathway from site-specific sequestration potential to verified storage and financial recognition. The roadmap is further supported by cross-cutting integrity safeguards that apply across all stages, although their operational emphasis differs across the process. These safeguards include uncertainty quantification, conservative carbon accounting, additionality, permanence, leakage assessment, transparency, data governance, and farmer participation.

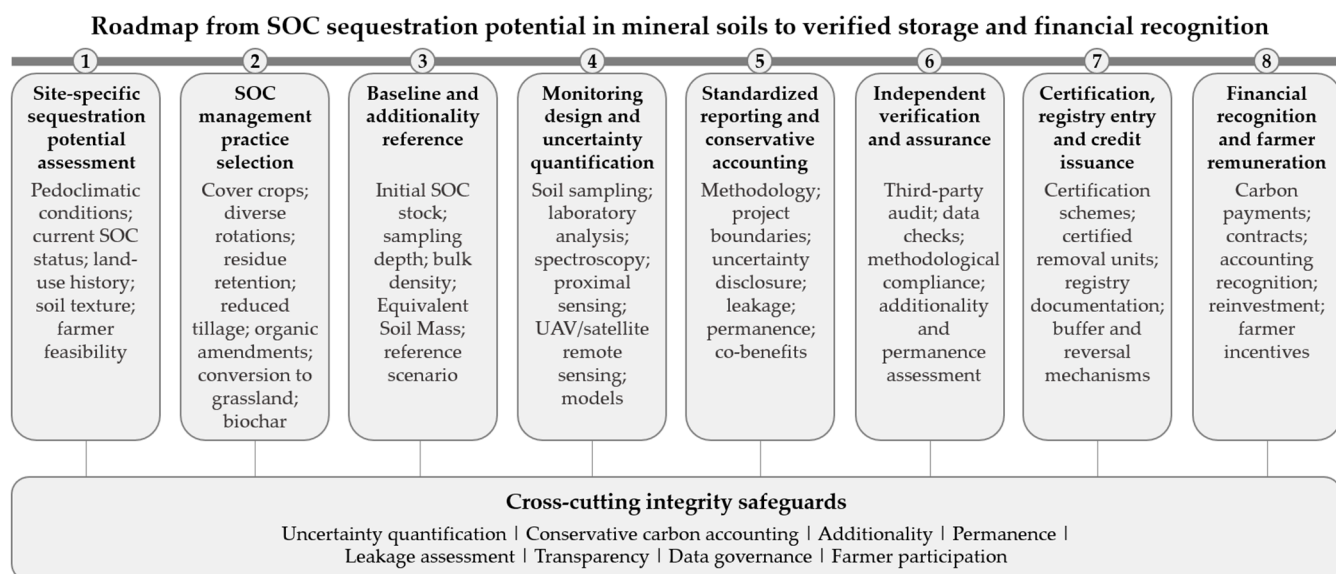


Figure 1. Roadmap from SOC sequestration potential in mineral soils to verified storage and financial recognition, showing the main implementation stages and cross-cutting integrity safeguards.

2. Carbon Farming Pathways, Mitigation Mechanisms and System-Level Impacts

Carbon farming is an umbrella term involving various approaches that operate through different pathways. Each approach can be either nature-based, such as peatland restoration, agroforestry and cover crops [23], or technological, such as the application of nitrification inhibitors and slow-release fertilizers [24]. A unique set of carbon dynamics, agronomic and environmental co-benefits, potential drawbacks, and safeguards is associated with each pathway. This section provides a brief comparative analysis of the five main categories of carbon farming options as defined in [25,26]. The discussion of pathways beyond mineral-soil SOC sequestration is included for contextual completeness. Importantly, the pathways are not assumed to operate through the same mitigation mechanism. Some pathways primarily reduce GHG emission flows, such as livestock and nutrient-management interventions, whereas others mainly increase or preserve carbon stocks, such as agroforestry and SOC management in mineral soils. Understanding this broader landscape is of major importance for the purpose of elucidating the subsequent, more detailed analysis of SOC management in mineral soils.

2.1. Carbon Farming Pathways Beyond SOC Sequestration in Mineral Soils

For the purpose of improving comparability, each pathway is discussed according to four common dimensions: (a) carbon mechanism; (b) current status or implementation context; (c) management interventions; and (d) mitigation effectiveness or constraints.

2.1.1. Peatlands Management

Peatlands are waterlogged ecosystems characterized by the accumulation of large amounts of organic matter. As a result, they are critical for carbon storage. When drained, peatlands release the carbon they had previously stored, alongside other GHGs [27,28]. This makes drainage the central threat and hydrological restoration the key mitigation measure.

Indicatively, peatlands in Europe store four to five times more carbon than forests, making them an important carbon sink [29]. Reported mitigation effectiveness varies by baseline condition and restoration outcome. Drainage of peatlands in the EU was estimated to be responsible for 220 Mt CO₂-e per year, corresponding to 5% of the EU's total GHG

emissions in 2017. The maximum additional annual reduction that could be achieved through the removal and rewetting of organic soils in the EU could reach 51.7 Mt CO₂-e by 2030, with a further 9 Mt CO₂-e y^{−1} being avoided by halting peat extraction [30]. At the hectare level, Günther et al. [31] estimated that emissions avoided through rewetting could total up to 29 t CO₂-e ha^{−1} y^{−1}. In the same vein, the German MoorFutures carbon farming methodology indicates a possible range of 3.5–24 t CO₂-e ha^{−1} y^{−1} depending on prior land use and the final restored condition [32]. Beyond avoiding emissions, peatland restoration can contribute to sequestering some carbon, though at a modest rate of less than 1 t CO₂-e ha^{−1} y^{−1}. Although rewetting may increase methane emissions in the short term, the reduction in CO₂ emissions generally outweighs these effects, while the release of CH₄ can be minimized through adequate management, such as cutting and removing biomass before raising the water table.

The main practical management options for peatlands are composed of distinct, yet complementary strategies, which can be broadly classified as:

- Preventive hydrology management, such as maintaining wet peatlands and controlled water-table management in productive peatlands, aims at preserving saturated soils towards preventing aerobic decomposition and CO₂ emissions. This helps maintain the existing SOC [33].
- Restorative hydrology management comprises rewetting drained peatlands and restoration of degraded sites. Its objective is to raise the water table and restore vegetation in previously degraded peatlands, transforming them from net carbon sources to potential sinks [34].
- Productive use of wetlands (paludiculture) involves the cultivation of moisture-tolerant crops on rewetted peatlands. This allows for their economic use while, simultaneously, preserving carbon sequestration [35].
- Operational management practices, such as removing biomass or vegetation before rewetting, can help reduce labile carbon inputs that could otherwise lead to methane production in the early stages of rewetting.
- Avoided peat extraction refers to preventing peat harvesting for the purpose of conserving peatland carbon stocks and avoiding carbon losses and ecosystem degradation associated with peat extraction [36].

Healthy peatlands can offer multiple benefits, such as purifying water, maintaining biodiversity, and protecting shorelines. Rewetting and restoring drained peatlands can restore many of these benefits. However, restored habitats often do not fully match the biodiversity and ecosystem services of undisturbed peatlands. Notably, there is a potential risk of competition with bioenergy with carbon capture and storage (referred to as BECCS), agricultural land use, or afforestation, as peatlands cover a relatively small total area. As for the safeguards needed, rewetting should be resilient to climate change to secure the permanence of carbon storage. Care is also needed to prevent ecological leakage, so that rewetting in one region does not have negative impacts on hydrologically connected ecosystems elsewhere.

2.1.2. Agroforestry Management

Agroforestry systems integrate trees or shrubs with crop and/or livestock production. This allows carbon to be stored in both above-ground biomass and soil. Indicatively, in the EU, agroforestry accounts for approximately 8.8% of the utilized agricultural land, concentrated mainly in Mediterranean and southeastern regions. The majority of existing systems combine grazing, fodder production, or foraging with trees or other woody perennials. Several of them are long-established and adapted to local conditions, such as the

French bocage systems, montado in Portugal, dehesa in Spain, and meadow orchards in Alpine regions.

Reported mitigation effectiveness varies widely according to system type, climate, tree density, and previous land use. Agroforestry in the EU can approximately store between 0.03 and 27 t CO₂-e ha⁻¹ yr⁻¹ according to [37]. Another study on hedgerows reported SOC sequestration rates of 1.1–3.3 t CO₂-e ha⁻¹ yr⁻¹ over 20–50 years, comparable to forest systems [38].

Practices recognized in agroforestry research and international frameworks include:

- Silvo-arable and silvo-pastoral systems, which involve combining trees with annual crops or livestock, respectively [39].
- Woody linear landscape elements such as hedgerows, windbreaks, and riparian buffer strips also contribute to carbon sequestration. In short, hedgerows are lines of shrubs and trees planted along field boundaries [40]. Windbreaks (also known as shelterbelts) are strips of trees or shrubs oriented to reduce wind speed across fields, protect crops and soils, and enhance carbon sequestration and biodiversity. Riparian buffer strips are vegetated zones of trees, shrubs, and grasses established along rivers, streams, or other water bodies to filter agricultural runoff and provide habitat corridors [41].

Co-benefits of agroforestry systems include improved erosion control, flood protection, reduced nitrate leaching, improved soil health, and enhanced biodiversity by providing habitat for wildlife and pollinators [39]. Interestingly, fire risk is generally lower than in forests as crops act as firebreaks. In Mediterranean contexts, these effects have been observed and even promoted as part of regional land management strategies [42]. Overall, the mitigation potential varies depending on the type of system, climate, and previous land use. For example, poplar silviculture systems in the United Kingdom showed reduced crop yields and tree growth when combined [43]. In contrast, Arenas-Corraliza et al. [44] demonstrated that Mediterranean silvicultural systems may improve crop yields under conditions of repeated spring temperature increases. According to the Ecologic Institute and IEEP [45], agroforestry should be avoided on peat soils because of the risk of GHG emissions during tree planting.

2.1.3. Livestock and Manure Management

This approach includes all measures taken by livestock farmers to reduce emissions from their activities and applies to cattle, pigs, sheep, and others. This pathway mainly targets emission-flow reduction rather than long-term carbon stock accumulation. The main mitigation mechanisms include reducing enteric methane through feed additives and improved feed digestibility or efficiency [46]. They also include limiting methane and nitrous oxide emissions from manure through practices like anaerobic digestion (also known as bimethanization) [47].

Concerning the mitigation potential, research and practical experience with livestock carbon farming in Europe indicate that farms could potentially reduce emissions by 12–30% by 2030 [45]. This corresponds to an annual mitigation potential of 26–66 Mt CO₂-e. Moreover, according to the European Parliament’s committee on Environment, Public Health and Food Safety (ENVI) [26], confined operations, such as pig farms, and high-intensity systems, such as dairy, are more suited to implementing feed additives, or manure management practices. In contrast, low-intensity systems may find such measures less feasible but could adopt efficiency improvements and soil carbon sequestration strategies.

Key practical management practices include:

- Rotational grazing, which involves moving livestock between paddocks to allow pastures to recover [48].

- Mob grazing, which utilizes high stocking density for short periods, followed by extended rest periods, to improve forage utilization and support soil health [49].
- Low-intensity (or reduced-stocking) grazing, which applies lighter grazing pressure to encourage biodiversity and maintain soil cover [50].
- Conservation grazing, which uses livestock to manage habitats in line with ecological objectives, such as maintaining grassland biodiversity [51].

Actions such as improved feed utilization, herd management, and selective breeding often generate notable cost savings for farmers, while adjusting nutrient applications to fodder crops can enhance water quality and ecosystem health. Furthermore, optimal grazing practices can improve soil health, reduce water consumption, and support biodiversity [52]. However, some interventions may conversely increase electricity use or lead to nutrient pollution and soil compaction. There is also a significant risk that relying solely on efficiency gains, like reducing emissions per unit of meat or milk, could trigger a rebound effect where lower costs lead to increased output and higher overall GHG emissions [53]. Therefore, evaluations must consider animal welfare, life-cycle impacts to prevent carbon leakage from imported feed, and a shift towards rewarding farmers for absolute reductions in emissions.

2.1.4. Nutrient Management on Croplands and Grasslands

Nutrient management aims to reduce N₂O emissions caused by synthetic fertilizers. By planning more carefully and applying fertilizers only when and as needed, farmers can avoid waste. In this sense, nutrient management is mainly treated here as a GHG emission reduction pathway, rather than as a direct SOC sequestration pathway. However, some nutrient-related practices can also support SOC accumulation when they increase organic carbon inputs to soil or improve biomass return [54].

A representative estimation regarding the EU, conducted in [55], states that improved nutrient management could achieve a mitigation potential of 19 Mt CO₂-e per year. This assessment includes reductions in both direct and indirect N₂O emissions as well as CO₂ savings achieved by decreasing fertilizer production.

Key strategies include:

- Application of lower amounts of synthetic fertilizers based on different factors like crop demand, soil testing, and timing [56]. This contributes to avoiding overfertilization as well as reducing nutrient runoff and N₂O emissions.
- Partial or full substitution of synthetic nitrogen with organic sources. These involve manure, slurry, digestate, or nitrogen-fixing crops, which can improve nutrient cycling, enhance soil fertility, and microbial activity. Moreover, the addition of compost or biochar can also improve soil structure, water retention, and long-term productivity, while reducing dependence on synthetic fertilizers. Remarkably, compost also adds decomposed organic material that directly increases SOC. In turn, biochar provides highly stable carbon in soils, making it an effective approach for long-term sequestration of carbon [57].
- Application of chemical or biological compounds slow the conversion of ammonium to nitrate, thus improving nitrogen use efficiency and reducing N₂O emissions [58].
- Incorporation of crop residues and temporary grasslands into rotations enhances soil organic matter, retains nitrogen, and can break pest and disease cycles. It can also increase SOC by returning plant biomass and root material to the soil, which is gradually stabilized as SOC [59].

Despite the benefits mentioned above, nutrient management strategies may have some disadvantages. For instance, replacing synthetic fertilizers with organic inputs can lead to under-fertilization, which may reduce crop yields [60]. In addition, nitrification inhibitors

are generally more expensive than conventional fertilizers, which can constrain adoption, especially for small-scale farmers [61]. Also, their effect is temporary. Finally, practices like incorporating crop residues require additional labor, hence, increasing operational costs.

2.2. Maintain and Enhance SOC on Mineral Soils

2.2.1. Management Practices

Management of mineral soils aims to expand the terrestrial carbon “stock” instead of merely slowing the “flow” of emissions. In many intensive cropping systems, these soils are currently carbon-depleted because of decades of conventional tillage and low residue return [62]. This sequestration deficit represents a significant opportunity to transform vast land areas into active carbon sinks by shifting the soil’s metabolic equilibrium. While this approach is relevant across different land uses, the following analysis focuses specifically on the mechanisms and management of SOC sequestration within mineral soils under cropland and grassland systems. Importantly, SOC sequestration is not a single intervention but an outcome emerging from interacting management choices that control carbon inputs, stabilization processes, and losses through disturbance and erosion.

Agronomic interventions with the greatest potential to increase SOC concentration include a variety of land-use and management shifts. These can be broadly categorized into practices that increase biomass input and those that minimize soil disturbance:

I. Practices increasing biomass input and microbial activity

- Diversified cropping systems and intercropping: This category involves the sequential or simultaneous cultivation of multiple crop types, such as integrating leguminous and nitrogen-fixing species. These systems can optimize nitrogen availability as well as increase the diversity of carbonaceous inputs (various root types and plant tissues) [63]. This variety supports the microbial community, which is necessary to stabilize labile carbon, ensuring its long-term storage within the soil organic matter. Yet, diversification also increases management complexity [64] and may require additional machinery, agronomic knowledge, and adjusted harvest calendars.
- Continuous soil coverage (cover crops): Planting cover crops during fallow periods keeps the soil biologically active year-round. By maintaining continuous root systems, this practice supplies the soil with necessary organic substrates for carbon stabilization. Additionally, the vegetative cover protects the soil surface from wind and solar radiation that accelerate carbon degradation. Despite the benefits, many farmers avoid using cover crops because of high seed costs and extra labor. In dry Mediterranean climates, particularly vineyards and other perennial crops, there is also the risk that these crops might compete with the primary crop for limited soil moisture [65]. Because of this, choosing the right plant species and knowing exactly when to terminate its growth are the most important factors for successfully storing carbon.
- Crop residue management: Retaining stalks, leaves, and stubble on the field after harvest transforms “waste” into a carbon source. Instead of clearing away organic matter, leaving it in the field gives the soil what it needs to create humus. This process naturally locks carbon away and improves the soil’s physical health. Leaving residue in the soil is not always easy, as it can create a habitat for pests and diseases to persist around for the next season [66]. It often makes weeds harder to manage.
- Systemic organic management (compost and mulching): Switching to organic methods creates a perfect environment for long-term carbon sequestration. The external application of compost (pre-decomposed organic material) and

mulching (protective organic layers) enriches the soil with complex carbon compounds. These amendments improve water retention and microbial health. This creates an environment that favors the formation of mineral-associated organic matter (MAOM) [67]. The effectiveness of organic amendments depends on the type and maturity of the material and how much is applied. Costs and logistics can also limit their use at larger scales [68].

II. Practices minimizing soil disturbance and stabilizing stocks

- Conservation tillage (no-till/strip-till): These practices minimize or eliminate soil inversion. Conventional tillage oxygenates the soil, which triggers rapid microbial respiration and the subsequent mineralization of stored organic carbon. By contrast, no-till and strip-till keep the carbon “locked” in soil aggregates, slowing down the decomposition process and allowing the sequestration stock to accumulate over decades. However, reduced tillage is not universally beneficial. Indicative risks include soil compaction [69], slower spring warming, and difficulties using machinery for weed control. These issues vary by crop and local climate and can reduce the capacity of agricultural land to capture and store carbon effectively.
- Grassland preservation and conversion: Permanent grasslands are among the most stable carbon reservoirs. Maintaining these areas without tillage prevents the rapid mineralization of stored organic matter. Converting degraded arable land to permanent grassland creates a powerful carbon sink. By stabilizing the soil, this transition moves the land away from being a net carbon source and maximizes its capacity for long-term sequestration. This pathway is often limited less by biophysics than by economics and governance [68], since it may entail opportunity costs from reduced flexibility and loss of annual crop revenues.
- Regenerative grassland management: By managing grazing carefully, using the right number of animals and giving pastures time to rest, grasses develop deeper, stronger roots. Via this process, which is usually referred to as “adaptive grazing”, carbon is moved into deeper soil horizons. This reduces the risk of carbon loss from topsoil disturbances, effectively “locking” it away in a more stable and resilient sequestration sink. However, outcomes are highly management-dependent [51]. Notably, excessive stocking, mistimed interventions, or drought can quickly eliminate gains. This emphasizes the need for careful monitoring and effective management.
- Biochar application: This involves the incorporation of pyrolyzed biomass into the soil. In contrast to fresh plant residues, biochar is a stable carbon amendment that resists microbial decomposition. It acts as a long-lasting part of the SOC, staying in the soil for centuries. It also improves nutrient retention and water-holding capacity. The success of carbon sequestration through biochar is not universal. It depends on the feedstock used, pyrolysis conditions, application rate, and site-specific soil properties [70].

For the sake of clarity, Table 1 summarizes the key practice categories, their mechanisms of SOC sequestration, co-benefits, and associated risks or constraints analyzed above. Understanding these sequestration pathways and their limitations is the foundation for the next section, where we explain the strict MRV frameworks needed to verify carbon gains.

Table 1. Key practices for enhancing SOC in mineral soils, their mechanisms, co-benefits, and limitations.

Category	Practice	Mechanism of SOC Sequestration	Co-Benefits	Limitations & Risks
I. Increasing biomass input and microbial activity	Diversified cropping and intercropping	Increases diversity of C inputs; enhances microbial activity and conversion of labile C into stable SOM	Improved nutrient cycling; enhanced soil biological activity; increased ecosystem resilience	High management complexity; potential competition for resources
	Continuous soil coverage (cover crops)	Provides year-round root exudates; protects soil surface; deep-soil microbial C stabilization	Maintains soil biological activity; improved water infiltration; reduced nutrient leaching	Seed and labor costs; potential water competition in semi-arid zones
	Crop residue management	Retains stalks, leaves, and stubble to promote humification and aggregate formation	Enhanced soil structure; improved moisture retention; reduced erosion	Potential for pest/disease carryover; equipment constraints
	Systemic organic management (compost & mulching)	Adds pre-decomposed organic matter; promotes formation of MAOM	Improved soil fertility; enhanced water retention; nutrient recycling	Transport and labor costs; risk of nutrient runoff or heavy metal contamination
II. Minimizing disturbance and stabilizing stocks	Conservation tillage (no-till/strip-till)	Minimizes soil inversion; protects aggregates from microbial oxidation	Maintains soil structure; enhances soil biological activity; reduces erosion	Compaction risk; herbicide dependence; slower soil warming in spring
	Grassland preservation & conversion to grassland	Maintains perennial root architecture; prevents rapid mineralization	Long-term C stocks; supports biodiversity; improves water retention	Opportunity cost of forgone annual crop revenue; potential policy constraints
	Regenerative grassland management	Adaptive grazing stimulates deep root growth; promotes C deposition in subsoil	Restores degraded land; enhances forage productivity and soil health	Requires precise stocking control; high management expertise
	Biochar application	Introduces pyrogenic C highly resistant to decay; adsorbs DOC to further stabilize native C	Improves CEC; enhances soil microbial habitat; increases water retention	Cost-intensive; site-specific effectiveness; variable nutrient interactions

C: Carbon; CEC: Cation Exchange Capacity; DOC: Dissolved Organic Carbon; MAOM: Mineral-Associated Organic Matter; SOM: Soil Organic Matter.

2.2.2. Quantitative Evidence on Sequestration Potential

The capacity for additional SOC sequestration within EU croplands, for example, is subject to significant academic debate. In fact, the estimates range from 9 Mt CO₂-e yr^{−1} [71] to 58 Mt CO₂-e yr^{−1} [72] and up to 70 Mt CO₂-e yr^{−1} [55]. Apart from active sequestration, a central mitigation priority is the stabilization of existing stocks, since many mineral cropland soils are currently net sources of carbon, making the halting and reversal of these losses a decisive climate goal. For grasslands, Roe et al. [55] suggest that EU grasslands could sequester approximately 27 Mt CO₂-e yr^{−1}.

Recent evidence from site-specific modeling supports this cautious interpretation. For example, Prudil et al. [73], using the RothC model in a long-term Central European field experiment, found that straw incorporation combined with intercrops produced a moderate SOC sequestration rate of approximately $0.09 \text{ t C ha}^{-1} \text{ yr}^{-1}$. Less favorable management scenarios led to declining SOC stocks. Similarly, Tao et al. [74], using a Tier 3 RothC modelling approach for Finnish mineral croplands over 2021–2040, estimated average SOC sequestration rates of -0.03 , 0.007 , 0.05 , and $0.13 \text{ t C ha}^{-1} \text{ yr}^{-1}$ under business-as-usual scenarios and 5%, 10%, and 20% carbon-input increase scenarios, respectively. They also found that climate change could reduce SOC sequestration by an average of $0.28 \text{ t C ha}^{-1} \text{ yr}^{-1}$, indicating that feasible SOC gains are strongly constrained by climate dynamics, carbon-input availability, soil conditions, and sustained management adoption.

These findings are consistent with recent European-level evidence from the EJP SOIL CarboSeq project [75]. In its modeling approach, CarboSeq estimated that improved crop-residue management could lead to an average C accrual of $0.14 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ and 53 million $\text{Mg CO}_2\text{-eq yr}^{-1}$ at EU scale. A wider cover-crop implementation could reach $0.58 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ and 224 million $\text{Mg CO}_2\text{-eq yr}^{-1}$. However, the report also noted medium-to-low confidence in these modeling estimates due to limitations in data availability, quality, and quantity.

2.2.3. Current Limitations and Challenges

The above results highlight the uncertainty surrounding SOC sequestration estimates in mineral soils. Uncertainty arises from differences in baseline SOC stocks, soil texture, climate trajectories, carbon-input availability, management adoption rates, sampling depth, model structure, and assumptions regarding saturation and permanence. Therefore, the mitigation values reported above should be interpreted as indicative potential ranges and not as directly achievable outcomes under real-world adoption, cost, and policy constraints.

More broadly, the mitigation potential of mineral soils remains substantially more constrained and uncertain compared with other carbon farming pathways [76]. This heterogeneity is largely a function of site-specific variability, where sequestration rates fluctuate according to soil texture as well as climatic conditions and baseline organic carbon levels. Interestingly, soils with lower initial carbon stocks commonly demonstrate higher sequestration efficiency. Yet, the inherent spatial variability of soil carbon complicates accurate assessment and drives up the operational costs of MRV [77]. In addition, mineral soils have finite carbon storage capacity, as they can reach a saturation point where additional inputs fail to increase stocks. This physical limitation is compounded by the high risk of reversal. While woody biomass often benefits from legal protections, soil management remains largely unregulated. This means that years of accumulated carbon can be lost through a single season of intensive tillage. These biophysical challenges are further complicated by the scientific controversy around certain technological amendments. For instance, the net climate benefit of biochar remains uncertain when considered from a full life-cycle perspective. Also, the use of compost from cities can be risky, because it might contain pollutants like microplastics and heavy metals [78]. From a net-removal accounting perspective, gross SOC gains should be adjusted for upstream and operational emissions, including amendment production and transport, field application, machinery fuel use, and possible N_2O or CH_4 trade-offs [79]. Therefore, high-integrity SOC accounting should deduct relevant lifecycle emissions from gross SOC stock increases before certified mitigation claims are made.

2.3. Comparative Evaluation of Carbon Farming Strategies and Broader System Outcomes

The diverse carbon farming pathways discussed in the preceding subsections (Sections 2.1 and 2.2) operate through distinct biological and physical mechanisms. These range from emission avoidance to active sequestration. With the aim of providing a comparison of these strategies, Table 2 summarizes the key aspects of the pathways. In particular, it focuses on their climate impacts and the associated management strategies. It also includes their estimated mitigation potential (considering the European mitigation landscape [26] as a reference), co-benefits, and primary constraints. As shown in Table 2, the mitigation landscape is divided between “flow-based” avoidance and “stock-based” expansion. Strategies such as peatland preservation, nutrient optimization, and livestock management primarily address the agricultural GHG balance by reducing the “flow” of gases into the atmosphere. While peatland management delivers the highest estimated mitigation per hectare through the avoidance of massive CO₂ flows, mineral-soil management is unique in its focus on expanding the terrestrial carbon stock. By shifting the soil’s metabolic equilibrium, these practices, including cover cropping, diversified rotations, and regenerative grazing, aim to remediate the sequestration deficit found in carbon-depleted intensive systems.

Table 2. Comparative analysis of carbon farming pathways and system-level impacts.

Pathway	Climate Impact *	Key Management Strategies	Estimated Mitigation (CO ₂ -e ha ^{−1} yr ^{−1}) **	Key Co-Benefits	Primary Constraints and Risks
Peatlands	Preventing “Flows”	Hydrology (preventive/restorative); paludiculture; biomass removal	3.5–29	Paludiculture potential; biodiversity; flood and water quality regulation	Methane “spikes”; land-use competition
Agroforestry	Building “Stocks”	Silvo-arable/-pastoral systems; woody landscape elements (hedgerows)	0.03–27	Output diversification; microclimate stability; soil health and biodiversity	Yield trade-offs; planting-phase GHG risks
Livestock	Reducing “Flows”	Enteric reduction (additives); advanced grazing (rotational/mob); manure management	N/A	Lower input costs (feed/energy); improved soil health and productivity	Rebound effects; leakage from imported feed
Nutrients	Reducing “Flows”	Precision fertilization; organic substitution (compost/biochar); residue incorporation	N/A	Cost savings; reduced ammonia emissions and nutrient leaching	Under-fertilization risk; high labor costs
Mineral Soils	Expanding “Stocks”	Diversified rotations; continuous cover; regenerative grazing; organic transition	0.5–7	Enhanced water retention and workability; productivity; soil biodiversity	Permanence; saturation; high MRV costs

* “Flow” refers to the rate of GHG emissions entering the atmosphere, while “Stock” refers to the total carbon stored in biomass or soil. ** Mitigation estimates represent potential range of values specifically within the European Union as reported in [26].

However, the wide range of estimated mitigation values for mineral soils reflects the substantial uncertainty and site-specific heterogeneity inherent to this pathway. Unlike emission-flow reductions, which can often be inferred from activity data, SOC stock increases occur slowly and are highly sensitive to the primary constraints and risks listed in Table 2. These include biological trade-offs like moisture competition in semi-arid re-

gions, the management complexity of diversified systems, and the technical challenges of residue retention. Furthermore, these gains remain vulnerable to reversal from climatic disturbances or shifting management choices.

This complexity makes it clear that qualitative field assessments are insufficient. Instead, rigorous oversight is needed. Towards scaling soil carbon sequestration reliably, the focus must shift to the strict MRV frameworks described in the next section.

3. Governance of Soil Organic Carbon Sequestration

Before elaborating on MRV frameworks for SOC assessment, it is essential to briefly present a theoretical understanding of the biophysical drivers and processes governing SOC dynamics.

3.1. Biophysical Drivers and Dynamics of Soil Organic Carbon

The stability and accumulation of SOC are controlled by a continuous metabolic equilibrium between organic inputs, such as root exudates and biomass residues, and carbon losses driven by microbial decomposition and physical disturbance. Photosynthesis is the main portal for atmospheric CO₂ to enter the terrestrial biosphere. However, the long-term preservation of this carbon is concentrated mainly in the upper soil horizons, specifically within the first 40 cm. Global initiatives, including the “4-per-mille” framework, emphasize the potential of this reservoir. In fact, the above initiative suggests that even a marginal annual increase of 0.4% in global SOC stocks could substantially offset human-caused GHG emissions [80]. However, this target should be interpreted as an aspirational benchmark and not as a uniformly achievable sequestration rate across all mineral soils. Its feasibility depends on local soil and climate conditions, initial SOC levels, the availability of carbon inputs, saturation dynamics, land-management continuity, and potential trade-offs with other GHGs. Recent modeling evidence illustrates these limitations. Tao et al. [74] reported that even a 20% increase in carbon inputs would not be sufficient to reach the 4‰ annual SOC increase target in Finnish croplands over 2021–2040. Furthermore, climate change could reduce SOC sequestration by an average of 0.28 t C ha^{−1} yr^{−1}. Similarly, Bruni et al. [81] showed that, in European croplands, the carbon-input changes required to reach the 4‰ target can exceed projected changes in net primary productivity, particularly in regions with higher input requirements.

The effectiveness of carbon sequestration also depends on a complex interaction between soil structure and environmental variables. The physical protection of organic molecules in mineral soils is influenced by pedological characteristics, specifically soil texture and bulk density. Fine-textured clay soils, for example, essentially sequester SOC via adsorbing organic matter onto mineral surfaces, thus limiting its bioavailability to microbes. Conversely, management interventions such as no-till farming and the application of stable carbon amendments, like biochar, contribute to improved soil aggregation and porosity. These structural improvements are constantly challenged by climatic stressors, since environmental conditions present a dual influence on the soil carbon balance. In particular, optimal moisture and aeration accelerate the microbial turnover essential for carbon stabilization, whereas extreme weather conditions can cause this balance to be disrupted abruptly. Indicatively, the thermal acceleration of microbial respiration, combined with the erosive effects of extreme hydrological events, like floods and droughts, can rapidly transform soils from net carbon sinks to net carbon sources [82,83]. As a consequence, any assessment of carbon farming potential should take into account these site-specific biophysical constraints as a means of ensuring the permanence of sequestered carbon.

3.2. Definition of Monitoring, Reporting, and Verification for Soil Organic Carbon Assessment

The operational governance of carbon farming must be supported by reliable and scientifically sound MRV protocols that standardize the quantification of SOC stocks [84,85]. These protocols act as a set of rules so as to ensure that carbon removals are real, measurable, and verifiable. In short, as summarized in Figure 2, MRV frameworks consist of three main pillars:

- **Monitoring:** This step includes the application of scientifically grounded measurement approaches and modeling tools to assess the quantity of SOC sequestered by the practices. It establishes the baseline and quantifies changes in SOC stocks over time, often integrating field sampling with digital technologies.
- **Reporting:** The measurements collected are systematically documented in accordance with established protocols. This entails providing transparent details on project characteristics, applied methodologies, and outcomes, including the quantification of uncertainties to ensure the reliability of the sequestered carbon data.
- **Verification:** An independent, third-party verifier reviews the reported data and implemented methods to confirm compliance with specific MRV protocols. This phase often involves auditing ground-truth data to substantiate that the claimed carbon removals are accurate, permanent, and additional.

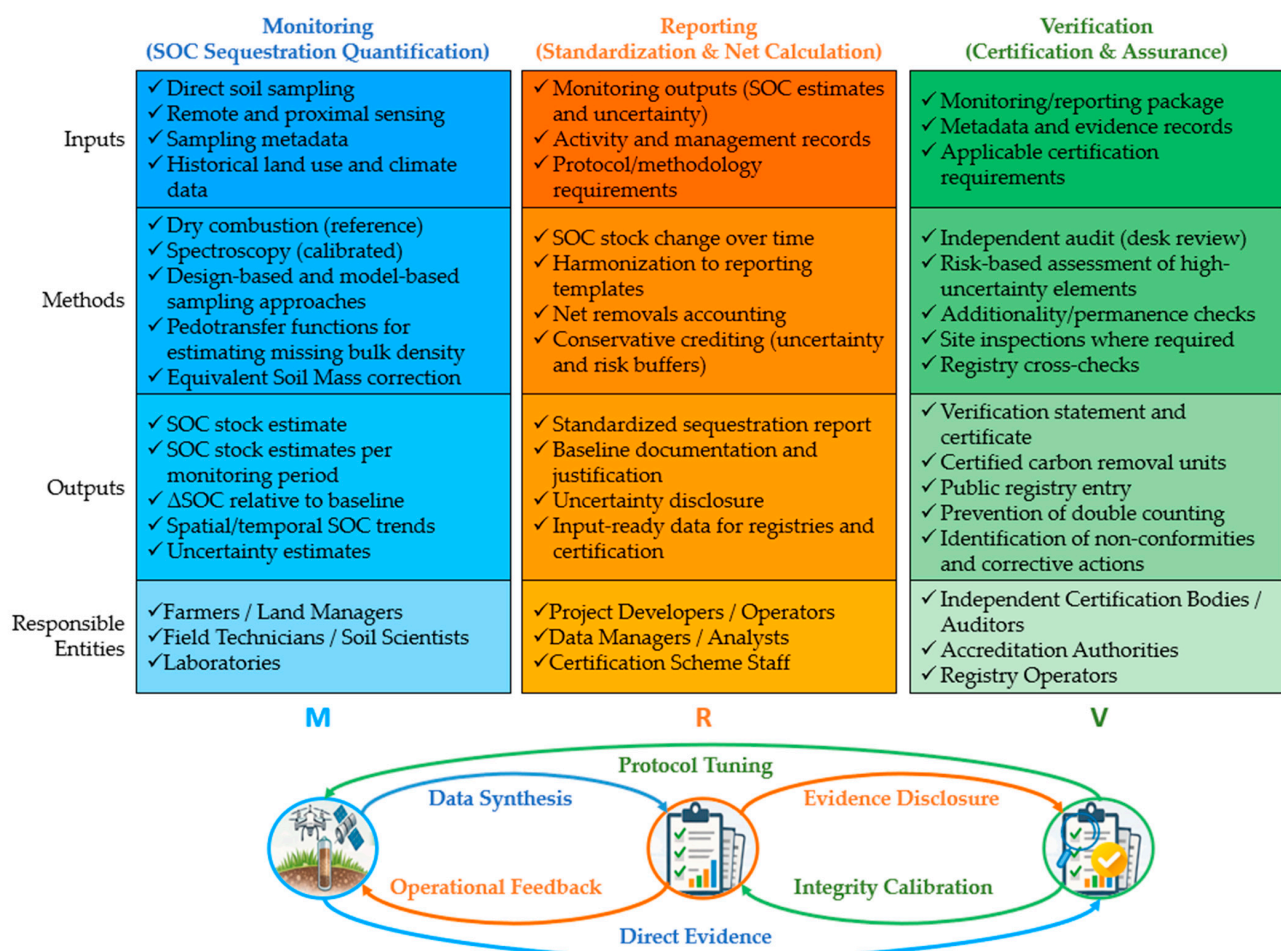


Figure 2. Monitoring, Reporting, and Verification (MRV) framework for SOC sequestration, including inputs, methods, outputs, responsible entities, and information flows. The dynamic flow is governed by six information vectors: the forward path (data synthesis, evidence disclosure, direct evidence) supports certification, while the feedback path (integrity calibration, protocol tuning, operational feedback) supports conservative crediting and continuous methodological refinement.

The above framework, which is illustrated in Figure 2, uses six information vectors to manage data integrity and feedback. The forward path handles the progression of data towards certification. In brief, “Data Synthesis” processes raw monitoring data into reporting outputs, while “Evidence Disclosure” conveys the finalized reports for verification. A dedicated “Direct Evidence” channel allows the verifier to access raw monitoring data directly, ensuring full transparency. At the same time, the feedback path enables systemic refinement. “Integrity Calibration” allows the verification phase to enforce conservative reporting. On a technical level, “Protocol Tuning” translates verification findings back into monitoring improvements to reduce uncertainty. Finally, “Operational Feedback” guarantees that the monitoring phase stays aligned with evolving compliance standards. To guide the discussion moving forward, Figure 2 also summarizes the primary inputs, methods, outputs, and responsible entities for each pillar, to facilitate a holistic understanding of the MRV process.

3.2.1. Monitoring

Monitoring is a significant element of MRV frameworks for carbon farming, as it enables the quantification of SOC stocks and the detection of their changes over time. In most applications, SOC stock changes are calculated by combining measurements of SOC concentration with soil bulk density over a defined reference depth, commonly the upper 0–30 cm of soil. Conceptually, SOC stock can be expressed as:

$$\text{SOC stock} = \text{SOC concentration} \times \text{bulk density} \times \text{soil depth} \times (1 - \text{coarse-fragment fraction}), \quad (1)$$

yielding a stock estimate per unit area [86]. To account for variations in soil compaction or expansion caused by management changes, the Equivalent Soil Mass (ESM) approach is increasingly utilized. In essence, ESM makes sure that SOC stocks are compared on a consistent soil mass rather than a fixed volume, avoiding the overestimation or underestimation of SOC stock changes [87]. For ESM-corrected comparisons, SOC stocks are recalculated for the same reference soil mass across sampling times or treatments, so that apparent SOC changes caused by management-induced changes in bulk density are not mistaken for real carbon gains or losses. This approach yields SOC stocks expressed as mass per unit area (e.g., t C ha^{−1}) and is consistent with international reporting standards, such as those recommended by the Intergovernmental Panel on Climate Change (IPCC) [88]. When physical sampling is not feasible, emission factor methods offer a low-cost alternative for regional reporting.

SOC monitoring in mineral soils can be understood as an operational sequence involving: (a) baseline setting, where the initial SOC stock and reference condition are defined; (b) sampling design, where the spatial scale, sampling depth, sampling density, and sampling strategy are selected according to site heterogeneity and cost constraints; (c) field sampling and measurement, where SOC concentration and bulk density are quantified through laboratory analysis and, where appropriate, supported by spectroscopy, proximal sensing, remote sensing, or model-based estimation; (d) SOC stock estimation and upscaling, where plot- or field-level measurements are converted into standardized stock estimates and extended to farm or landscape scales; and (e) uncertainty handling and reporting-ready synthesis, where sampling error, analytical error, spatial variability, and model uncertainty are quantified and propagated into SOC stock-change estimates. Uncertainty in SOC stock change should be treated as an error budget, including sampling-design variance, laboratory or assay error, bulk-density and coarse-fragment uncertainty, and model uncertainty where applicable. These uncertainties should be propagated into confidence intervals before credit issuance. Where projects are designed for credit issuance, power analysis and minimum detectable change calculations can further support cost-effective

sampling, compositing, and assay selection under realistic farm-budget constraints [89]. In calcareous, arid, or semi-arid soils, inorganic carbonate-derived carbon should also be distinguished from SOC. This is because soil inorganic carbon can represent an important carbon pool in these environments and may otherwise confound SOC-based sequestration estimates [90]. The resulting outputs should be documented with metadata, confidence intervals, methodological assumptions, and conservative estimates suitable for reporting and verification.

Strategic decision-making pertaining to the scale and scope of a survey is also important to SOC monitoring, since it determines the spatial and temporal boundaries necessary for a representative assessment. As far as the sampling scale is concerned, it may range from local or farm-level assessments to regional or national surveys that can inform policy and reporting. Notably, focusing on the local scale is valuable for carbon farming strategies, as it enables the capturing of site-specific soil properties and variances. This can lead to practical and pertinent solutions that consider the unique challenges of each site. Concerning the sampling scope, it further specifies whether the purpose of monitoring captures baseline conditions, long-term SOC trends, or shorter-term variability associated with management practices or seasonal dynamics. Moreover, temporal resolution should be explicitly considered depending on the technology applied. This can include periodic measurements for laboratory analyses, seasonal measurements for spectroscopy and UAVs, and frequent measurements for satellite remote sensing [21].

Beyond horizontal scale, vertical precision is of major importance. Because carbon concentrations decrease as we move from surface soil to deeper layers, sampling commonly follows the 0–30 cm reference depth used in many reporting frameworks, including IPCC-aligned inventories. However, extending to 50 cm or deeper can provide additional information on subsoil carbon redistribution, saturation dynamics, and the long-term permanence of sequestration [75]. Handling this intensity demands a calculated compromise between sample size and cost-effectiveness. In this context, success is not guaranteed by volume alone; the rigor of field protocols, including accurate coordinate recording and strategic seasonal timing, is also significant. Depth coverage differs between methods. Laboratory and design-based approaches capture 0–30 cm or deeper. In turn, most remote sensing and spectroscopy tools are restricted to the soil surface, requiring models to estimate stocks at required reporting depths.

Sampling design and measurement methods are also important factors towards determining the accuracy of SOC monitoring. Design-based approaches normally include random, grid-based, stratified, and balanced sampling schemes. Also, transect sampling is used, which is conducted along predetermined lines across the study area. The above methods are often structured around land use, soil type, or management zones to reduce spatial uncertainty. More advanced sampling methods, such as stratified, spatially balanced, or optimal design, can also be used when high-resolution covariates are available. This is particularly appropriate when fields contain distinct management zones, soil types, topographic locations, or covariate clusters derived from remote-sensing [91,92].

The selection of the most appropriate soil sampling strategy requires balancing the trade-offs between measurement accuracy, the effort required for sample collection, and associated costs [21]. For instance, random sampling improves statistical validity through minimizing bias. Nevertheless, it requires a large, resource-intensive sample size that may still fail to provide representative results. Regarding grid and transect sampling, they are both suitable for uncovering spatial trends and SOC gradients. Yet, they can offer limited coverage that misses overall diversity. Finally, targeted approaches can reduce uncertainty when prior information on soil strata or management impacts is reliable. However, these

methods only work well if the land's history is already known. Otherwise, incorrect strata may be defined, or biased data may be introduced.

Recent reviews on SOC assessment, such as [21], indicate that design-based methods remain widely used. Nevertheless, an increasing number of studies are complemented by model-based approaches. These include geostatistical models, process-based soil carbon models and machine learning (ML). These models allow SOC to be estimated in unsampled areas by using remote sensing data or information on soil properties, land use, climate, and management practices [93]. However, model-based SOC estimates remain sensitive to calibration data, model assumptions, and transferability across soils and management systems. In other words, the prediction of SOC has evolved from traditional spatial interpolation to advanced modeling. This has been driven by the need to process large-scale environmental data. ML algorithms, like Random Forest and Support Vector Machines, are now favored for identifying complex variable relationships [94,95]. However, Kriging remains a reliable method, because of its ability to interpret geographic proximity and spatial autocorrelation [96]. Towards compensating for missing bulk density measurements, pedotransfer functions (PTFs) are commonly incorporated into these models to estimate soil physical properties from available chemical information [97]. Recently, explainable artificial intelligence (XAI) models have been utilized to investigate the drivers of SOC stock prediction [98,99]. These models, like those using SHapley Additive exPlanations (SHAP), have become an essential tool in recent soil and agricultural science research since they can address the so-called “black box” nature of ML models [100].

Laboratory measurements constitute the reference standard for calibrating other measurement approaches. These methods can be roughly classified into oxidation-based and combustion-based techniques. Oxidation-based methods chemically oxidize organic carbon and estimate carbon content based on the resulting chemical reaction [101]. In contrast, combustion-based methods involve heating soil samples to high temperatures, typically with a dry combustion analyzer, converting carbon to CO₂. This is then quantified to determine total organic carbon [102]. These traditional laboratory techniques provide high accuracy, but they are often labor-intensive and time-consuming. Hence, they limit their throughput in large-scale applications. To overcome these limitations, spectroscopic approaches have become increasingly popular [21]. Techniques such as visible and near-infrared (VNIR), near-infrared (NIR), and mid-infrared (MIR) spectroscopy offer rapid, non-destructive estimates [103,104]. Other techniques, like X-ray fluorescence, gamma radiometry, diffuse reflectance infrared Fourier-transform, and laser-induced breakdown spectroscopy, provide additional information [105,106].

Finally, remote sensing has become a useful tool in SOC research as it supports detailed monitoring of expansive regions. These approaches use sensors mounted on satellites, aircraft, and unmanned aerial vehicles (UAVs) that can capture the reflectance of soil and other energy signals from various spectral bands. This allows for the indirect estimation of SOC via relationships involving spectral responses and soil properties. However, remote-sensing and field-spectroscopy estimates remain sensitive to vegetation cover, surface residues, soil moisture, roughness, and calibration quality. Moreover, most spectral signals mainly represent the exposed soil surface, requiring models to infer SOC stocks at depth [107]. In this context, multispectral and hyperspectral imagery are very important, because they can detect even slight variations in soil composition and organic carbon levels [108]. In particular, satellites are widely applied as they cover large areas and provide regular, long-term data. This makes them essential tools for identifying trends and monitoring changes in SOC over time across entire continents [92,109]. Airborne platforms can be flown exactly when and where they are needed for specific studies [110], while UAVs provide a cost-effective way to

collect high-resolution imagery at the farm level [111]. The high resolution of UAVs brings significant data processing complexity compared to automated satellite workflows [21].

In summary, these technologies are rarely used in isolation. They are integrated to achieve high-accuracy monitoring. Within MRV frameworks, laboratory measurements serve as the reference standard to calibrate spectroscopy and remote sensing. Ground-truthing connects field data with digital imagery to ensure maps reflect physical reality. This integrated system balances resolution and cost, making it powerful for large-scale carbon farming. However, integrated approaches must manage high system complexity to successfully fuse multi-source data for reliable MRV applications. The main SOC monitoring approaches are summarized in Table 3, which includes the type of method, main applications, spatial and temporal scale, advantages, limitations, depth coverage, cost/practicality, and integration potential within MRV frameworks. Table 3 is synthesized mainly from Petropoulos et al. [21], complemented by the method-specific references discussed in the surrounding text. The cost classification is qualitative and relative rather than a standardized monetary estimate, because actual costs depend on several factors. Therefore, the cost categories should be interpreted as indicative levels of resource intensity and operational feasibility, rather than fixed standard costs. In short, the relative costs and operational feasibility of each method vary. Laboratory analyses are accurate but resource-intensive, expensive, and difficult to scale across large areas. Spectroscopy and proximal sensing are moderate in cost and practicality, while remote sensing approaches offer easier deployment at scale but require strong calibration and careful interpretation.

Table 3. Summary of SOC monitoring methods and technologies, including their applications, scale, advantages, limitations, cost, practicality, depth coverage, and temporal resolution within MRV frameworks.

Method/ Technology	Purpose/ Application	Scale	Advantages	Limitations/ Considerations	Cost	Practicality/ Feasibility	Depth Coverage	Temporal Resolution
Lab (oxidation/ combustion)	Reference SOC; calibration	Plot/Field	High accuracy, especially for dry combustion; reference method	Costly at scale; labor-intensive; sample-preparation sensitive; inorganic C interference	H	D	0–30 cm (can extend to 50 cm)	Periodic/ baseline
Spectroscopy	Rapid SOC screening	Plot/Field/ Farm	Fast; minimally destructive; medium throughput	Calibration- dependent; affected by moisture, texture, and instrument transferability	M	M	Air-dried/sieved sample or exposed topsoil; depth depends on sampled layer	Seasonal
Proximal Sensing	Soil property characteriza- tion/SOC proxies	Plot/Field/ Farm	Detailed characterization; supports models	Specialized equipment; calibration required; sensor response affected by moisture, texture, roughness, and surface conditions	M–H	M	Surface/topsoil; sensor- dependent	Limited
RS: Satellites	Large-scale SOC mapping	Regional/ Continental	Large coverage; repeatable; long-term	Surface only; affected by vegetation & moisture; needs calibration	M	M	Exposed surface; depth inferred by models	Frequent
RS: Aircraft	High-res targeted mapping	Local/ Regional	Flexible timing; high spatial resolution	Expensive; smaller coverage; affected by vegetation, moisture, and acquisition timing; requires ground calibration	H	M	Exposed surface; depth inferred by models	Flexible
RS: UAVs	Farm-scale high-res SOC	Local/Farm	Very high resolution; cost-effective for small areas	Limited coverage; weather & calibration dependent; high data-processing burden	M	E	Exposed surface/topsoil; depth inferred by models	Flexible

Table 3. Cont.

Method/ Technology	Purpose/ Application	Scale	Advantages	Limitations/ Considerations	Cost	Practicality/ Feasibility	Depth Coverage	Temporal Resolution
Design-based Sampling	Statistical SOC estimation	Plot/Field/ Farm	Minimizes bias; supports spatially representative estimates	Cost-intensive; design-sensitive; may require prior stratification	M–H	M	0–30 cm or deeper, depending on sampling protocol	Periodic
Model-based	Estimate SOC in unsampled areas; integrate multi-source data	Field/ Landscape/ Regional	Handles large datasets; accounts for spatial patterns; BAU comparisons possible	Depends on calibration data, covariate quality, model assumptions, and transferability; risk of bias outside training domain	M	M	Depends on input data and model structure	Flexible/ scenario- based
PTFs	Estimate bulk density/soil properties	Point/Plot	Fills data gaps; supports modeling	Accuracy depends on calibration domain; may introduce bias when applied outside local soil conditions	L	E	N/A	N/A
Integrated Approaches	Combine sampling, sensing & modeling	MS: Farm to Landscape	Balances resolution, scalability, and cost; supports MRV	High complexity; requires robust data infrastructure, calibration, uncertainty propagation, and model-data fusion	M–H	M	Depends on sampled depth and model structure	Flexible
Ground- truthing/ Calibration	Validate remote sensing, spectroscopy & models	MS: All scales	Ensures accuracy & reliability	Requires rigorous field & lab sampling; weak ground-truthing propagates bias into sensing and model outputs	M	M	Depends on validation sampling depth	Periodic/ event- driven

BAU: Business-as-usual scenario; D: Difficult/operationally demanding; E: Easy; H: High; Lab: Laboratory; L: Low; M: Moderate; MS: Multi-scale; RS: Remote Sensing; SOC: Soil Organic Carbon; UAVs: Unmanned Aerial Vehicles.

As can be deduced from Table 3, the monitoring methodologies utilize a hierarchical order; from localized precision to broad geographic coverage:

- Point/plot scale focuses on specific geographic coordinates or small localized areas;
- Field/farm scale operates at the level of individual agricultural holdings;
- Landscape/regional scale extends across broader geographic boundaries;
- Continental scale provides “wall-to-wall” monitoring across entire nations or continents;
- Multi-scale integrates localized data within broader regional models, creating a hybrid approach.

3.2.2. Reporting

Although monitoring enables the quantification of SOC stocks, the resulting data remain ineffective in the absence of a structured reporting framework. In essence, reporting acts as the critical interface between the field and the market. It can be defined as the process by which raw scientific measurements are translated into standardized, comparable, and legally recognized claims. Without this process, monitoring data cannot be verified or traded, since there is no shared way to describe the permanence, ownership, or net climate impact of the sequestered carbon.

At the international level, reporting is essential for two key reasons, namely climate integrity and economic trust [112]. Global standards, such as those governed by the Paris Agreement (Article 6) and the IPCC Task Force on National Greenhouse Gas Inventories, rely on reporting to prevent “double counting”. This occurs when the same amount of sequestered carbon is claimed by both a private buyer and a host country. For the Voluntary Carbon Market (VCM), reporting is the mechanism that addresses the “information asymmetry” between the farmer (who knows the land) and the buyer (who typically operates in a remote jurisdiction) [113]. A strong report gives investors the confidence to invest in

sequestration. It provides clear, complete carbon data and shows the project's credibility and impact. Furthermore, timely and periodic reporting ensures that market participants have access to up-to-date information. This enables accurate credit issuance and ongoing evaluation of project performance.

Currently, reporting is shifting from scattered paper records to digital, auditable, and registry-based MRV systems. Global voluntary standards and registries, including Verra's Verified Carbon Standard, the Gold Standard, and the American Carbon Registry (ACR), provide standardized procedures for project registration, validation, verification, and issuance of carbon credits. In parallel, jurisdictional and public-policy frameworks have emerged or matured. Notable examples include Australia's ACCU Scheme, Canada's Federal Greenhouse Gas Offset Credit System, and the EU Carbon Removals and Carbon Farming Certification Framework (CRCF). The CRCF should be understood as an EU-wide voluntary certification framework for permanent carbon removals, carbon farming and carbon storage in products, rather than as a single soil-carbon methodology. Other regional or bilateral mechanisms, such as the Asia Carbon Institute and Japan's Joint Crediting Mechanism, further illustrate the diversification of carbon-crediting architectures.

A useful qualitative comparison of ten soil-management crediting approaches, based on guiding questions, is provided by Siemons et al. [114]. The comparison covers various aspects including methodological scope, quantification of emission reductions or removals, additionality, non-permanence, double counting, environmental and social safeguards, and governance. Within the methodologies most relevant to agricultural soil carbon, the report shows clear differences in MRV design. For example, the Gold Standard SOC Framework is described as allowing different SOC quantification approaches, such as on-site measurement, model- or dataset-based estimation using peer-reviewed sources, and IPCC Tier 1/2 default-factor approaches. Verra VM0042 is described as offering different quantification pathways, including measure-and-model, measure-and-remeasure, and calculation-based approaches—with sampling used differently across these options. The CAR Soil Enrichment Protocol is discussed as using specific non-permanence mechanisms, including Project Implementation Agreements and buffer-pool contributions, to address reversal risk. These examples indicate that existing soil-carbon crediting methodologies differ substantially in how they operationalize measurement, modeling, uncertainty, baseline construction, additionality, leakage, permanence, reversal liability, safeguards, and governance.

At the same time, there is a trend to report lower values when data are uncertain [97]. This conservative approach ensures that uncertainties in data do not lead to overestimating climate benefits. Hence, this prevents “phantom credits” from being created, ensuring that every credit issued represents a real and reliable amount of carbon removed from the atmosphere. Moreover, reporting is becoming more holistic, including co-benefits like soil health improvement and biodiversity. These are increasingly considered as high-quality indicators of credible sequestration [115].

Among the aforementioned frameworks, the EU CRCF stands out as a particularly relevant example. It is the first legally binding, government-led EU framework specifically designed for the voluntary certification of permanent carbon removals, carbon farming, and carbon storage in products. It may also serve as a reference point for emerging international certification approaches. Briefly stated, under Regulation (EU) 2024/3012 [116], the EU CRCF moves carbon-removal and carbon-farming certification towards a more harmonized and quality-controlled system, while maintaining its voluntary nature. To that end, four Q.U.A.L.I.T.Y. criteria, based on Articles 4 to 7 of the CRCF, are used, the content of which is summarized in Figure 3.



Figure 3. The QU.A.L.I.TY framework under the EU Carbon Removal Certification Framework. The framework establishes four essential criteria, Quantification, Additionality, Long-term Storage, and Sustainability, to ensure the transparency of certified carbon sequestration units.

In short, the “QU.A.L.I.TY” acronym stands for four pillars aiming to ensure the integrity and transparency of carbon removals:

- **QUantification:** This is the process of measuring the net carbon removal achieved by a carbon farming activity, determining which removals can be certified. Accurate measurement is essential, especially when removals are used to offset emissions, because overestimating them would harm the credibility of the system [117]. For carbon farming, the quantification task is difficult, because carbon accumulates slowly and varies widely between sites and management practices. Small changes in soil carbon relative to natural variability make measurements uncertain and costly. The EU CRCF addresses these challenges by requiring removals to be measured in a relevant, accurate, complete, consistent, comparable, and transparent manner. Uncertainties must also be accounted for by implementing recognized statistical methods. Data collection should also be in line with national GHG inventories. Concerning net carbon removal, it is estimated by using three components: (a) a baseline which represents standard or individual removal performance; (b) the total removals achieved; and (c) any emissions caused by the activity, including direct and indirect emissions. The framework encourages the use of digital tools like satellites, geographic information systems, and online databases to make tracking easier and cheaper.
- **Additionality:** This means that carbon removals or GHG reductions occur because of the incentives provided by the policy, such as the EU CRCF. In other words, these removals or reductions would not have occurred without the framework. If the removals occurred by other means, they are non-additional. Rewarding them would not create real climate benefits. Additionality is especially important when removals are used for offsetting. Specifically, if non-additional removals are counted as offsets, it allows emissions to increase without equivalent reductions. This weakens the credibility of the system. This rule is also important for cost-effectiveness. It ensures that funding is only spent on projects that achieve real results, either by capturing

extra carbon or by lowering emissions beyond what would have happened anyway. The EU CRCF utilizes a standardized baseline, which represents the typical carbon removal and emission reduction performance of similar farms, to help determine whether an activity is truly additional.

- **Long-term storage:** Also known as permanence, this refers to keeping carbon removed from the atmosphere stored for a long time. On the contrary, non-permanence occurs when carbon removals (or emission reductions) are later released back into the atmosphere. This could happen as a result of natural events or human actions, including land conversion or mismanagement. These challenges are common for all mitigation-based carbon farming activities. The EU CRCF addresses this by requiring operators to demonstrate that activities aim for long-term carbon storage. Operators must monitor and reduce the risk of carbon release during the monitoring period and are subject to liability if stored carbon is lost. In carbon farming, the carbon removed is assumed to be released back into the atmosphere at the end of the monitoring period, unless ongoing monitoring shows that it is still stored. Geological storage, by contrast, is treated as permanent as it is expected to remain stable for several centuries. These rules highlight that carbon farming removals are temporary by nature and require active management to maintain storage over time. Structured reporting of permanence data allows auditors to verify these claims and ensures that temporary removals are tracked and disclosed transparently.
- **Sustainability:** This criterion guarantees that carbon farming activities provide climate benefits without causing harm to the environment or society. In broad terms, carbon farming activities can influence biodiversity, water quality, soil health, farmer incomes, and rural communities. However, some activities, under certain circumstances, may generate risks. Indicatively, nature-based solutions can have negative effects in case they are poorly designed [118]. For instance, a project might prioritize rapid carbon sequestration through monoculture tree planting. This can actually decrease biodiversity [115] and make the land more vulnerable to pests. Furthermore, without strict sustainability safeguards, there is a risk of “greenwashing” [119]. This means that projects exaggerate their environmental benefits. This can lead to unintended consequences, such as higher operational costs, temporary reductions in crop yields, or negative ecological and social impacts. The EU CRCF addresses sustainability aspects by requiring that carbon removal activities have proven neutral or positive impacts on all sustainability objectives. These include climate, water, biodiversity, pollution, and circular economy. This is often called the “do no significant harm” principle [120]. For this purpose, operators must meet minimum sustainability standards, which are defined in certification methodologies. The framework also encourages activities that deliver additional co-benefits beyond the minimum requirements, such as ecosystem restoration. In addition, the EU CRCF ensures the integrity of carbon sequestration by incorporating the sustainability benchmarks for bioenergy set by the Renewable Energy Directive (EU) 2018/2001 [121]. It also aligns with the Common Agricultural Policy (CAP) by requiring rules that protect carbon-rich grasslands and peatlands [122]. Overall, this framework functions as a cohesive component of the EU Green Deal, specifically complementing the Farm to Fork Strategy to align sequestration certification with broader sustainable land-use goals [123].

In conclusion, structured and transparent reporting ensures that the data collected from carbon farming projects are consolidated into a verification-ready format. By integrating localized monitoring into standardized disclosures, the reporting stage serves as the final evidence-based record of sequestration. This provides the necessary transparency to

support the eventual issuance of certified removals, bridging the gap between raw field data and formal certification.

3.2.3. Verification

The final pillar of MRV determines if reported SOC removals can be formally recognized as credible, compliant, and certifiable climate outcomes. Specifically, verification provides the independent institutional assurance that these estimates are methodologically rigorous, conservatively quantified, and consistent with applicable regulatory standards. In mineral soils, this function is essential to account for the slow, variable, and reversible nature of SOC sequestration under changing management and climatic conditions.

At a functional level, verification is performed as an independent check by a third party. This assessment confirms that the carbon farming activity was actually carried out as reported. It also ensures that any carbon sequestration claims meet specific legal, technical, and sustainability standards. Unlike monitoring, verification does not generate new primary data. It evaluates the integrity, consistency, and credibility of monitoring and reporting outputs. Towards that direction, verification transforms scientific measurements into legally and economically actionable carbon removal units. Verification also evaluates how uncertainties in SOC measurements and model predictions are quantified and propagated into final carbon removal estimates.

Taking the EU CRCF as an indicative example, a highly structured verification architecture has been introduced. It is operationalized through a multi-layered institutional system involving operators, certification bodies, certification schemes, Member States, and the European Commission. In brief, the verification process, described in Article 9 of the CRCF, begins when an operator or group of operators submits an application to a recognized certification scheme. Once the project is accepted, the operator submits a detailed report of the sequestration activity to an independent certification body. The latter must be accredited by a national accreditation authority in accordance with Regulation (EC) No 765/2008. Certification bodies are required to be institutionally independent and impartial in relation to the operators they assess. Member States retain supervisory authority over the operation of these certification bodies, reinforcing regulatory oversight.

The certification body conducts a certification audit. Based on this, a certification audit report is produced, while an official certificate of compliance is issued. Both documents are subsequently reviewed and controlled by the certification scheme and made publicly available through a registry. As a means of ensuring continued compliance, periodic re-certification audits are required, although the specific frequency is to be defined in implementing acts. This iterative audit structure has been designed to match the dynamic nature of SOC sequestration, which depends on consistent, long-term land management instead of just one-off actions.

In practice, verification follows a structured audit workflow combining desk-based assessment with risk-based validation procedures. The audit begins with a comprehensive review of project documentation. This usually includes monitoring plans, baseline definition, sampling design, laboratory and analytical methods, modeling approaches, and uncertainty analysis. Verifiers evaluate methodological consistency with approved certification methodologies and examine the traceability and completeness of data. These involve metadata such as geolocation, sampling depth, timing, and analytical protocols. Because measuring SOC is naturally difficult and uncertain, the CRCF verification process focuses on finding major errors or false claims in the data. Key high-risk factors include how the baseline is chosen, the number of soil samples taken, how soil density is estimated, the assumptions used in models, and how missing information is handled. When necessary, certification bodies conduct physical inspections and check management records or land-

use history [124]. They may also perform direct ground checks to make sure the reported farming practices match what is actually happening on the land. Critically, verification is not limited to technical accuracy. It also checks whether operators followed the rules. This includes using approved methods, sticking to the required monitoring schedules, and meeting all documentation and transparency requirements [124].

The verification process is completed with the issuance of a certificate containing standardized information including:

- The specific name and geographical location of the sequestration project;
- The exact timeframe during which the activity was tracked;
- The specific approved method applied to the project;
- The calculated baseline and the total amount of carbon removed;
- Any GHG emissions generated by the activity itself;
- Net carbon removal benefits, adjusted to account for measurement uncertainty;
- Positive environmental or social impacts beyond carbon storage;
- References to any other carbon removal certifications held by the project.

Although most of these data come from the operator's own reports, they only gain legal and economic value once they have been checked and confirmed through independent verification [125]. In terms of MRV, the certificate represents a verification-validated reporting output. Public registries maintained by certification schemes improve transparency and integrity. This is accomplished by allowing carbon removals to be traced, publicly reviewed, and checked for double counting across different markets and jurisdictions. In particular, references to other carbon removal certifications serve as a verification safeguard to ensure compatibility with national inventories and international climate accounting frameworks, including the Paris Agreement.

Verification according to the EU CRCF differs from that of VCMs, even though both rely on independent third-party auditors. On the one hand, verification in VCMs mainly serves private offset buyers and often allows greater methodological flexibility to support market participation. On the other hand, CRCF verification is designed to meet public policy objectives, including compliance with EU climate law and alignment with national GHG inventories. As a consequence, the CRCF places a stronger emphasis on conservative quantification, explicit liability for reversals, regulatory compatibility, and public oversight. Despite these differences, the two systems are starting to converge. This is happening because both are using digital monitoring tools, risk-based audits, and standard ways to measure uncertainty.

In summary, verification serves as the critical safeguard that ensures SOC removals reported under MRV frameworks are accurate and credible. By combining independent audits, methodological checks, and adherence to regulatory and sustainability standards, verification transforms raw monitoring and reporting data into reliable carbon removal units. This process builds trust among stakeholders and improves the reliability and comparability of carbon farming projects. Ultimately, it supports the scaling of such projects in both voluntary and compliance markets. The key elements, actions, responsible entities, and intended outcomes of SOC verification are summarized in Table 4.

In this subsection, the EU CRCF was chosen as a representative example, as it provides a legally binding and highly structured verification system with accredited certification bodies, transparent certification schemes, and public registries. Different systems have different rules and setups. However, they all share core principles including independent checks, cautious carbon counting, and strong risk management. At the same time, CRCF implementation will still require operationalizing safeguards related to additionality baselines, reversal liability, long-term monitoring obligations, and the prevention of low-integrity

or greenwashing claims in practice [116]. Despite these implementation challenges, the shared values make it easier for voluntary, national, and EU systems to work together.

Table 4. Key elements of SOC verification under MRV frameworks, summarizing the main actions, responsible entities, and intended outcomes to ensure credible, compliant, and verifiable carbon removals.

Verification Element	Description	Key Actions	Responsible Entity	Purpose/Outcome
Documentation review	Evaluation of all project reports and records	Check monitoring plans, baseline definitions, sampling strategies, lab/analytical methods, and model inputs	Certification Body/Verifier	Ensures completeness, traceability, and methodological consistency
Risk-based assessment	Focus on high-risk areas prone to errors or bias	Evaluate baseline choice, number of soil samples, bulk density estimates, model assumptions, missing data handling	Certification Body/Verifier	Identifies potential errors or false claims in reported SOC
Physical/ground inspection	On-site verification	Inspect land management practices, sampling locations, field conditions, land-use history	Certification Body/Verifier	Confirms that reported activities match actual on-the-ground actions
Uncertainty evaluation	Assessment of how measurement and model uncertainties are handled	Check error propagation of SOC measurements and model prediction uncertainty into C removal estimates	Certification Body/Verifier	Ensures conservative, scientifically rigorous estimates
Certification audit	Independent audit by an accredited certification body	Combine desk review and field validation; follow approved methodology standards	Certification Body	Provides independent assurance that the project complies with MRV requirements
Certificate issuance	Formal recognition of verified C removals	Document project identity and location, monitoring period, methodology, net C benefits, and co-benefits	Certification Body	Transforms reported SOC data into certified and economically actionable C removal units
Periodic re-certification	Ensures continued compliance over time	Conduct recurring audits as defined by legislative implementing acts	Certification Body/Scheme	Maintains credibility, tracks long-term SOC trends, and addresses reversals
Public registry	Transparency and traceability	Upload certification outputs to publicly accessible registries	Certification Scheme/Registry Operator	Prevents double counting and allows public scrutiny
System alignment	Compatibility with broader frameworks	Check alignment with VCMs, national GHG inventories, Paris Agreement, or other certifications	Certification Body/Scheme	Facilitates harmonization and credibility across multiple C markets

C: Carbon; GHG: Greenhouse Gases; SOC: Soil Organic Carbon; VCMs: Voluntary Carbon Markets.

4. Discussion

The previous sections highlighted the biophysical capacity of mineral soils. However, this potential remains latent without a mechanism to convert biological data into economic trust. The historically ambiguous dividing line between avoided emissions and active sequestration, coupled with the absence of a standardized bridge to financial auditing, has created a systemic integrity gap. This disconnect means that even when sequestration occurs, it may remain invisible to traditional financial systems, trapping value in the soil and keeping institutional capital on the sidelines. To bridge this gap, the following discussion

first establishes the technical-to-financial nexus by linking MRV outputs to accounting recognition. It then evaluates the structural barriers within SOC-MRV frameworks before concluding with an analysis of financial incentives and the socio-economic barriers that currently limit market adoption and farmer participation.

4.1. Linking Monitoring, Reporting, and Verification Outputs to Financial Accounting Recognition

Carbon farming projects focusing on maintaining and enhancing SOC on mineral soils operate at the interface of environmental measurement and economic value creation. Notably, SOC sequestration can generate verifiable carbon credits and new financial incentives for farmers. Consequently, the effectiveness and credibility of the implemented practices depend, apart from agronomic performance, on whether their results can be turned into transparent and comparable financial information. In this context, MRV is more than just a technical tool. It provides the proof needed to translate stored soil carbon into financially recognizable credits.

Each element of the MRV framework can be aligned with financial reporting logic as follows:

- Monitoring generates project-specific, measurable data on changes in SOC stocks and related soil parameters. In accounting terms, this stage supports initial measurement of the underlying environmental asset, but it does not by itself justify credit issuance or financial recognition.
- Reporting organizes monitored results into traceable, transparent, and auditable documentation. In accounting logic, reporting supports an entity's claim to a measurable asset or revenue right, forming the basis for recognition once verification confirms its validity.
- Verification provides independent assurance that reported SOC increases comply with methodological and certification requirements. From a financial perspective, it is the checkpoint that enables eligible SOC credits to be recognized as inventory, intangible assets, or revenue, depending on their intended use or sale.

The financial relevance of MRV becomes clearest across the lifecycle of SOC credits, where verified evidence supports recognition, revenue, asset classification, impairment, and derecognition. This lifecycle is graphically illustrated in Figure 4.

The SOC credit lifecycle can be broken down into the following foundational stages:

- Recognition on generation (initial recognition): SOC credits can only be recognized in the accounting records after verification confirms that the measured SOC increases meet the criteria for issuance. Once verified, if the cooperative or farmer plans to sell the credits, they are generally treated as inventory. Under accounting principles, this inventory is often recorded at the lower cost or net realizable value. This means that high transaction costs, including MRV expenses, can negatively impact the project's profitability. If the credits are intended to be held long-term, for example, to support internal climate goals or prepare for future compliance, they are treated more like intangible assets. Since there is no dedicated accounting standard for carbon credits, the entity must justify the chosen classification based on the credit's intended use and economic substance.
- Recognition on sale (revenue): When credits are sold, the accounting recognition of revenue depends on the transfer of control to the buyer. In this context, MRV reporting and registry entry are not procedural details. They are conditions that enable the seller to prove that the credits exist and are uniquely identifiable. Therefore, the MRV provides the proof required to recognize revenue and verify the existence of the carbon credits being sold.

- Recognition on purchase (buyer perspective): For buyers, particularly firms acquiring credits to satisfy regulatory obligations or to meet climate commitments, purchased credits represent an expected future benefit. The MRV function is essential because it provides assurance that credits are valid, traceable and eligible for retirement. This supports recognition as an intangible asset until the credits are surrendered, as the credits provide the right/ability to reduce a future obligation or to demonstrate compliance.
- Surrender and derecognition (liability settlement and impairment): When credits are retired in the registry, the buyer removes the carbon credit asset from the balance sheet and reduces the corresponding emissions liability. MRV reporting provides the evidence that retirement has occurred and that the obligation has been settled. The MRV framework must also account for asset impairment. Specifically, if a carbon reversal occurs (e.g., carbon is released back into the atmosphere), the recognized asset must be written down or derecognized, reflecting the loss of economic value. This linkage is important to prevent environmental obligations from being addressed solely through narrative disclosure while remaining disconnected from the balance sheet. In other words, registry retirement provides the verifiable event that supports derecognition and liability reduction.

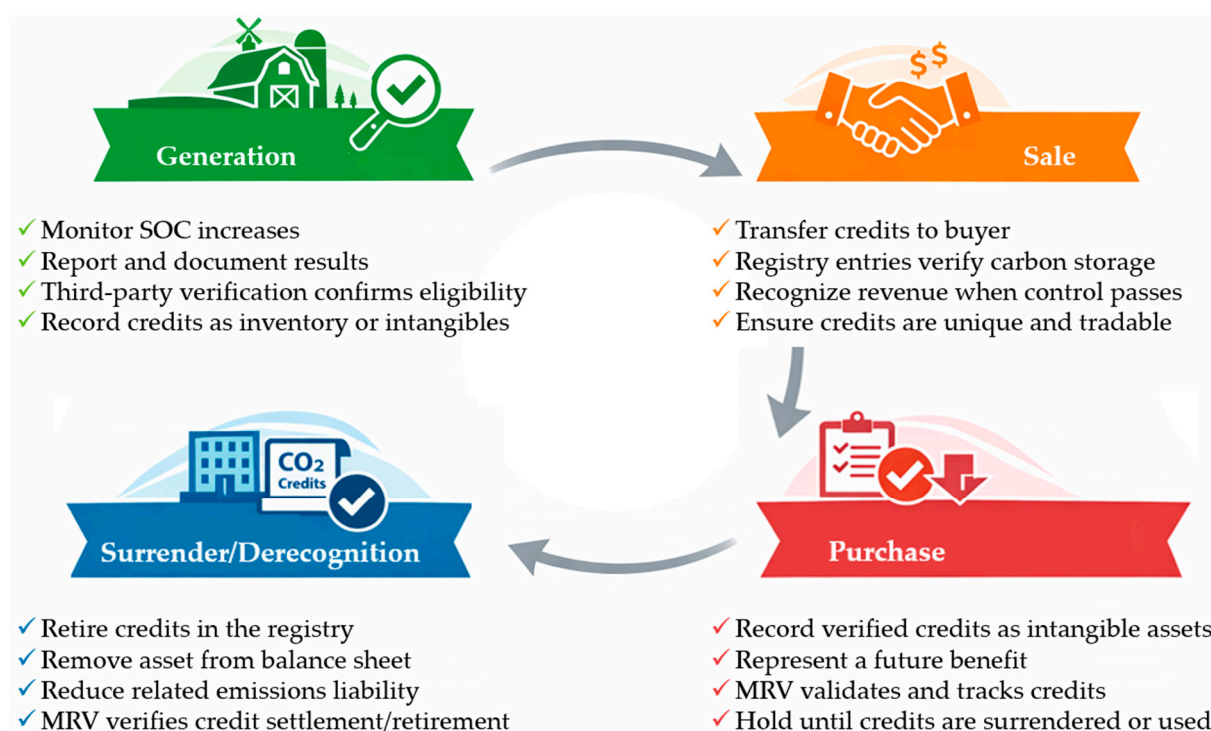


Figure 4. Lifecycle of SOC credits: from generation by farmers/cooperatives, through sale and purchase, to final surrender/retirement by buyers, highlighting accounting recognition and MRV at each stage.

4.2. Critical Challenges and Barriers in SOC-MRV Frameworks

MRV frameworks face multiple technical, methodological, and operational challenges which can limit their effectiveness and scalability. Table 5 details the main challenges to SOC-MRV, highlighting the affected stages and the strategic interventions used to mitigate implementation risks. The table breaks complex MRV challenges down into nine categories. These range from biophysical heterogeneity and slow SOC dynamics to model dependence, boundary issues, and data governance constraints.

Table 5. Primary barriers to SOC-MRV implementation: Core issues, affected stages, and strategic responses.

Barrier	Core Issue	MRV Stage	Impact on MRV Credibility & Implementation	Typical MRV/Policy Responses
SOC variability	Changes are slow and often smaller than measurement noise	M, V	High uncertainty; risk of “phantom credits”	Stratified sampling; ESM approach; uncertainty discounting
Temporal mismatch	SOC changes occur over decades, but markets demand periodic issuance	M, R	Delayed issuance; reliance on modeled estimates; risk of over-crediting	Hybrid MRV (models and sampling); dynamic baselines; tiered verification
Baseline & additionality fragility	Counterfactual baselines uncertain; risk of non-additional credits	R, V	Credibility loss; disputes; over-crediting	Standardized baselines; additionality tests; conservative assumptions
Permanence & reversal risk	SOC can be rapidly lost; liability allocation unclear	M, R, V	Invalidated credits; buffer depletion; weakened long-term integrity	Buffer pools; insurance; long-term monitoring; clear liability rules
High MRV costs	Sampling, labs, modeling, audits, and registry fees are expensive	M, R, V	Limits participation; favors large farms; reduces adoption	Project aggregation; simplified MRV tiers; advisory support
Methodological fragmentation	Different standards, assumptions, and protocols across programs	R, V	Inconsistent credit quality; registry incompatibility	Harmonized methodologies; standardized metadata; registry integration
Model dependence & transparency	Models rely on assumptions; black-box systems reduce reproducibility	M, R, V	Accountability gaps; systematic over/under-crediting	Model validation; transparent datasets; third-party review; uncertainty quantification
Leakage & indirect emissions	SOC gains may be offset by emissions elsewhere	M, R	Overestimation of net removals; phantom credits	Full GHG accounting; leakage deductions; conservative netting
Data governance & capacity	Sensitive farm data; limited lab and auditor availability	M, R, V	Participation barriers; uneven adoption; weaker trust	Data ownership agreements; anonymization; capacity building

ESM: Equivalent Soil Mass; GHG: Greenhouse gas; Lab: Laboratory; M: Monitoring; R: Reporting; SOC: Soil Organic Carbon; V: Verification.

The first set of challenges arises from SOC biophysical variability and weak detectability. Soil carbon is inconsistent across a field and changes so slowly that it is difficult for sensors to pick up real progress. This makes it challenging to track progress. If the monitoring is off, the carbon credits will be inaccurate, leading to farmers being overpaid or underpaid. Typical responses include dividing fields into management zones for sampling, using standardized protocols for soil depth and bulk density measurements, and explicitly accounting for measurement uncertainty in calculations. Temporal dynamics present another barrier. In practice, SOC sequestration is non-linear and eventually reaches saturation (meaning soil has a maximum storage capacity), while carbon markets require

periodic reporting. The monitoring and reporting stages are most impacted, as delayed detection or reliance on models can decrease credit issuance or cause overestimation in case linear accumulation is assumed. Solutions include combining models with periodic field sampling, using adaptive baselines, and extending monitoring over longer time periods.

Methodological fragility is also critical. Baseline and additionality uncertainties affect reporting and verification [126]. Weak baselines or stringent rules often ignore early adopters. This means farmers who have already improved their soil get no credit, while those who just started get paid. Furthermore, permanence and reversal risks must be managed across all MRV stages. Sequestered carbon can be rapidly released through management changes or natural disasters [127]. For this reason, programs require ongoing monitoring to detect reversals, transparent reporting of disturbances, and periodic verification to confirm the carbon remains in the ground. To mitigate these risks, programs employ insurance mechanisms like buffer pools, which are a reserve of non-tradable credits used to cover any unintentional carbon losses.

High MRV costs also represent a major barrier, since sampling, laboratory analyses, modeling, audits, and registry fees can be expensive, particularly for small farms [21,128]. Recommended approaches to mitigate these costs include aggregation through cooperatives, simplified MRV tiers for lower-cost verification, and advisory or technical support for participants. This approach maintains high standards but removes the financial and paperwork hurdles that usually prevent farmers from participating.

SOC-MRV increasingly relies on ML models and remote sensing. However, these usually depend on assumptions and “black-box” systems [129]. A lack of transparency makes it difficult to verify sequestration results and creates accountability gaps. Mitigating this challenge requires validating the models with real-world transparent data and ensuring third-party experts review the findings for accuracy [130]. Leakage and indirect emissions present additional challenges. SOC gains may be offset by increased N₂O emissions, additional fuel use, or displaced production. These can lead to “phantom credits” [131]. Solutions involve full GHG accounting, adjustments for leakage, and conservative netting approaches when calculating final credits. Finally, MRV requires sensitive farm data (inputs, yields, geolocation). Nevertheless, privacy concerns can restrict participation and reduce trust. Responses include establishing data ownership agreements, anonymizing sensitive data, building capacity for laboratories and verifiers as well as providing detailed reporting templates.

4.3. Financial Incentives and Market Barriers to Soil Carbon Farming Adoption

4.3.1. Funding Sources

Scaling SOC sequestration in mineral soils depends on methodological credibility as well as the availability and structure of financing mechanisms that can compensate farmers for transition costs, yield risks, and long-term commitments. In practice, funding for soil carbon farming originates from two main sources: (a) public finance, primarily through agricultural and climate policy instruments, and (b) private finance, mainly through VCMs and corporate supply-chain programs.

Public funding increasingly supports the accumulation of certified SOC in mineral soils through research programs, policy frameworks, and government incentives that treat soil carbon as a critical component of climate strategy. In the EU, programs such as Horizon Europe “Mission Soil” 2026 and the LIFE Programme provide substantial grants. These programs involve large-scale institutional funding for consortia developing regional MRV networks and “living labs” that monitor and stabilize SOC in mineral soils [132]. They also facilitate the integration of mineral-soil carbon stocks into national GHG inventories. In the United States, agencies like the United States Department of Agriculture (USDA) offer

loans, grants, and technical support to farmers and land managers [133]. Moreover, the Department of Energy (DOE) funds public–private partnerships and research projects to scale technologies that enhance carbon mineralization and deep-soil storage.

Private finance, currently, is moving away from simply paying for “good farming practices”. Instead, it focuses on high-integrity carbon removals, where investors pay for the amount of carbon credibly quantified, verified, and stored in soil. In addition, companies are shifting towards insetting. This means they invest directly in their own supply chains to store carbon. Investors, including climate-focused venture capital firms, are increasingly supporting mineral soil projects because they store carbon more securely and with less risk of loss than surface biomass. This trend is accelerated by the 2026 rollout of the EU CRCF and the first UN-backed credits under Article 6.4 of the Paris Agreement [134]. These frameworks may support the treatment of verified carbon credits as financially recognizable assets, depending on accounting rules, ownership, intended use, and contractual arrangements. Leading agri-food corporations are also directly funding projects that reduce carbon in their supply chains. For this purpose, they give farmers money upfront to plant deep-rooting crops and add minerals that keep carbon in the soil for decades.

4.3.2. Socio-Economic Barriers to Market Adoption and Institutional Constraints on Farmer Participation

Although MRV is commonly regarded as the main bottleneck for scaling SOC sequestration crediting, practical implementation shows that adoption is also limited by several barriers. These are associated with market design, contract rules, and farmer risk perceptions. SOC sequestration in mineral soils can only create financial value once measured outcomes are translated into verified credits. Nevertheless, farmers rarely join sequestration projects when the financial rewards are small and the legal obligations are unclear. Therefore, the scalability of soil carbon farming depends strongly on whether programs provide attractive and operationally feasible incentives.

The economic barriers discussed below are directly linked to the technical MRV constraints outlined earlier. In short, practices with slow or spatially heterogeneous SOC responses increase sampling, modeling, and verification costs. Practices with high reversal risk require longer monitoring, buffer pools, or insurance mechanisms. Uncertain baselines and weak additionality claims tend to reduce buyer confidence and credit value [135]. Finally, practices involving organic amendments, crop residues, or biochar require lifecycle-aware assessment of upstream emissions, non-CO₂ GHG trade-offs, and processing losses before net-removal claims are made [75].

Recent MRV cost modeling provides quantitative support for this constraint. In [136], MRV costs were estimated for a carbon-farming project consisting of 20 farms, each covering 65 ha, over a five-year monitoring period. In their base scenario, total MRV costs per farm were €4179 for decision-support tools, €5718 for process-based models, and €4472 for direct soil measurement, corresponding approximately to €12.9, €17.6, and €13.8 ha^{−1} yr^{−1}, respectively. The same study also showed a strong scale effect: single-farm projects incurred €5554–€6445 higher MRV costs per farm than 20-farm projects. Expanding from 20 to 100 farms reduced per-farm costs only modestly, by up to €321. Moreover, average MRV costs per hectare decreased as farm size increased, indicating that MRV requirements may disproportionately burden smaller farms.

A key barrier is the low and uncertain compensation currently offered for SOC sequestration. Voluntary demand is rising. However, buyer willingness to pay depends on whether credits are perceived as credible, additional, and permanent. If credit integrity is questioned, prices and farmer incentives decline. Vanderheyden et al. [136] further illustrate this economic constraint through a farm-level viability comparison. Assuming

an optimistic SOC-storage potential of up to $1.4 \text{ tCO}_2\text{e ha}^{-1} \text{ yr}^{-1}$ and a carbon price of $\text{€}30/\text{tCO}_2\text{e}$, reported by the authors as currently paid in the Label Bas Carbone scheme, a 65-ha farm participating in a 20-farm project could recover the MRV costs of process-based models, but not in all scenarios. In contrast, direct soil measurement would become viable only at approximately $\text{€}100/\text{tCO}_2\text{e}$, while smaller farms of 40–65 ha may require carbon prices of approximately $\text{€}60\text{--}100/\text{tCO}_2\text{e}$ to compensate for MRV costs. This indicates that low credit prices can directly undermine the economic viability of SOC crediting, particularly where MRV costs are high or farm size is small. Thompson et al. [135] further support this interpretation. They showed that the payment level offered was the main reason preventing farmer enrolment, followed by legal liability, skepticism about sequestration viability, and previous use of eligible practices. This illustrates the “early-adopter penalty”, which was reported as a participation barrier by 22% of surveyed producers who had engaged in carbon-market discussions.

Permanence and contract duration remain major obstacles in carbon sequestration projects. Short-term agreements often conflict with the long-term nature of carbon storage, providing insufficient climate security. In turn, perpetual contracts introduce financial and legal risks that can deter farmer participation. Farmers are especially concerned about liability for reversals beyond their control. This involves accidental plowing during wet seasons or other unforeseeable disturbances. The combination of non-compliance risk and the absence of affordable, precise measurement and verification tools creates a trust gap that limits project scalability, even when financial incentives are offered. Consequently, the structural mismatch between the temporal realities of carbon storage and the practical constraints of agricultural management continues to impede widespread adoption.

Another barrier is limited market transparency [137]. SOC programs vary widely in baselines, crediting periods, and how they handle uncertainty. Thus, farmers remain unsure about carbon prices and whether they are being treated fairly. This uncertainty is exacerbated by the rules of additionality. Specifically, most programs only reward the adoption of new carbon farming practices, excluding farmers who were already using no-till or cover crops, for example. Since SOC sequestration is finite and the same carbon can effectively be sold only once, such constraints further limit the scalability of carbon storage initiatives [138]. Collectively, these factors can delay participation, as farmers may prefer to save their limited sequestration potential for future markets that may offer higher prices.

Finally, implementing SOC sequestration practices requires learning new skills and acquiring knowledge about carbon farming mechanisms. These requirements create learning costs that necessitate specialized training, technical guidance, and hands-on demonstrations [139]. The risk of making a technical mistake that could lead to a “carbon loss” or a “contract violation” is simply too high to justify the transition for many farmers.

5. Conclusions and Future Directions

5.1. Concluding Remarks

This study addresses the gap between theoretical SOC sequestration potential and operational implementation in mineral soils by integrating agronomic practices, MRV requirements, certification requirements, financial recognition, and farmer-adoption considerations into a unified roadmap. Rather than treating SOC sequestration only as a biophysical process, the study shows how site-specific mineral-soil management can be connected to baseline setting, monitoring, reporting, independent verification, credit issuance, market incentives, and farmer remuneration. In this way, the proposed roadmap clarifies the pathway through which SOC sequestration can move from a theoretical climate-mitigation opportunity to an auditable, certifiable, and financially recognizable outcome.

To provide a holistic picture, this study first conducts a comparative assessment of carbon farming pathways, focusing on their distinct carbon dynamics, agronomic and environmental co-benefits, potential drawbacks, and safeguards. Notably, SOC management in mineral soils offers substantial mitigation potential. However, it requires accurate MRV to ensure that gains are measurable, site-appropriate, and durable over time. In particular: monitoring establishes baselines and quantifies SOC stock changes, reporting converts these measurements into transparent and auditable records, and verification provides independent assurance that reported outcomes comply with methodological and certification requirements.

Despite its central role, implementing MRV faces technical and operational barriers including:

- High variability and slow detectability;
- Temporal mismatch;
- Baseline and additionality uncertainty;
- Permanence and reversal risks;
- High implementation costs;
- Methodological fragmentation;
- Model dependence and limited transparency;
- Leakage and indirect emissions;
- Data governance and capacity constraints.

Even with strong MRV, scaling SOC sequestration depends on market design and farmer participation, which remain constrained mainly due to:

- Low and uncertain financial incentives;
- Limited market transparency;
- Additionality-related eligibility constraints;
- Permanence and contract concerns;
- Learning and technical barriers;
- Structural mismatch with agricultural realities;
- Exacerbated burden for small farms.

5.2. Future Directions for Orchestrating Technical Innovation and Financial Integrity in SOC Markets

Based on the findings of the present study, closing the systemic integrity gap in SOC markets requires coordinated technical, financial, and governance actions. Future research aimed at unlocking the full potential of SOC management in mineral soils should therefore focus on the following aspects:

- Developing scalable, cost-effective SOC-MRV approaches that fuse power-based sampling design, remote sensing, proximal sensing, digital MRV platforms, ML, and targeted field sampling.
- Prioritizing methods like XAI will be essential to eliminate the “black-box” nature of current ML models, ensuring the transparency required for independent audit.
- Harmonizing international protocols and providing open-source modeling tools to ensure reproducibility. Standardizing these “rules of the game” is a prerequisite for the global comparability of carbon credits.
- Establishing flexible baselines that account for historical management and local SOC trajectories. Moving towards adaptive reporting intervals allows the system to better reflect the non-linear nature of soil carbon accumulation.
- Establishing dedicated protocols for the valuation, classification, and derecognition of SOC assets on corporate balance sheets. Aligning MRV outputs with financial

reporting logic ensures that verified SOC gains in mineral soils can become high-integrity and financially recognizable climate assets.

- Developing standardized farm-level financial simulation cases that connect measured SOC increases, uncertainty deductions, MRV costs, credit prices, reversal-risk deductions, and net farmer revenue.
- Expanding buffer pools, specialized insurance mechanisms, and contractual arrangements to manage reversal risks. These tools are vital to provide financial security for farmers and maintain market confidence in the face of climatic or management disturbances.
- Designing payment schemes that accurately reflect opportunity costs, transition risks, smallholder participation barriers, and ecological co-benefits. This includes refining additionality rules to avoid the “early adopter penalty”, supporting equitable access for smaller farms, and avoiding trade-offs with food security and biodiversity.
- Providing targeted technical guidance and demonstration projects to reduce learning barriers. Future efforts should promote digital data aggregation to lower the MRV burden for small farms while ensuring robust data ownership and privacy.
- Aligning voluntary and compliance markets with national GHG inventories, evolving CRCF certification rules, and international carbon-crediting frameworks. Linking SOC sequestration to broader biodiversity and water management objectives will maximize the multi-functional value of mineral-soil management.

In conclusion, SOC sequestration in mineral soils offers substantial climate mitigation potential. This potential can only be realized under credible technical, financial, and governance conditions. Public funding is increasingly supporting the long-term stabilization of carbon within mineral soil matrices through research grants and national climate policies. Meanwhile, private investment is expanding through supply-chain “insetting” and high-quality carbon markets that reward verified carbon storage in agricultural soils. However, this transformation is credible only when gross SOC gains are supported by robust MRV, lifecycle-aware net-removal accounting, transparent reporting, independent verification, financial recognition, and supportive market design. Emerging digital MRV tools, proximal sensing, remote sensing, ML, and XAI can reduce monitoring burdens and improve transparency, but they must remain anchored in reliable field data, calibration, and uncertainty documentation. Integrating these elements can transform SOC sequestration from a theoretical opportunity into a scalable, auditable, and financially recognizable solution that delivers both climate and economic benefits.

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