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Review

Stabilizing Soil Organic Carbon Fractions as a Negative Emission Pathway in China: Mechanisms, Policy Drivers, and Systemic Innovations

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Highlights

- Separating POC from MAOC improves diagnosis of soil carbon persistence.
- Mineral saturation deficits guide sampling and regional practice selection.
- Paddy carbon gains require joint CH_4, N_2O, yield, and water.
- Pilot pathways require safeguards for yields, uncertainty, and reversal.

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Abstract

Background: Agricultural soil carbon sequestration can contribute to China's climate mitigation, but total soil organic carbon (SOC) gains alone do not establish durable net greenhouse-gas removal. This critical narrative review integrates evidence on particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) dynamics, regional soil constraints, agricultural management, carbon governance, and digital monitoring. **Methods:** A structured comparison of published management effects distinguishes carbon concentrations from stocks and China-specific evidence from global analogues. **Key Findings:** POC and MAOC provide complementary information about management response and persistence, although neither fraction defines a fixed permanence class. Paddy soils illustrate why fraction measurements must be evaluated alongside methane, nitrous oxide, crop yield, and water management. Mineral saturation deficits and high-resolution maps can guide sampling and prioritization, but do not independently establish additionality, detect stock changes, or authorize credit issuance. **Conclusion:** A conditional pathway from regional monitoring pilots to methodology evaluation were discussion, with safeguards for food production, farmer participation, uncertainty, and reversal liability. Fraction-informed assessment may strengthen future China Certified Emission Reduction (CCER) methodologies and ecological compensation, yet its financial benefits and institutional feasibility require empirical testing. The review connects soil mechanisms with governance and identifies evidence needed before agricultural carbon gains can support credible removal assets.

Keywords: soil carbon fractionation; mineral-associated organic carbon; particulate organic carbon; carbon neutrality; CCER; digital soil mapping; green finance

1. Introduction

China's carbon-neutrality pathway has moved soil carbon sequestration beyond the conventional domains of soil fertility and agricultural productivity. Because China is central to global mitigation, its pathway to peaking carbon emissions before 2030 and achieving carbon neutrality before 2060 has been analyzed as a systemic transition involving energy restructuring, negative-emission options, policy portfolios, market mechanisms, and regional governance (H. Duan et al., 2021; Y. Liu et al., 2025; Z. Liu et al., 2022). Within that transition, land and soil carbon sinks matter for two reasons. First, atmospheric and ecosystem studies show that China's terrestrial ecosystems have historically played an important carbon-sink role, although sink strength is spatially heterogeneous and sensitive to land-use and climate drivers (Piao et al., 2009; J. Wang et al., 2020). Second, natural climate solution assessments indicate that China's land-based mitigation potential is substantial but constrained by biophysical and economic conditions, meaning that soil carbon sequestration should be treated as a regionally differentiated pathway rather than a uniform national offset reservoir (Bossio et al., 2020; Lu et al., 2022). Agricultural soils are especially relevant because China's croplands store large SOC stocks and can respond to management (F. Chen et al., 2023; L. Chen et al., 2015; L. Feng et al., 2025). National-scale cropland evidence shows that residue return, livestock manure, fertilizer management, and improved agricultural practices have contributed to historical SOC gains and may continue to support future sequestration under appropriate scenarios (Beillouin et al., 2023; Berhane et al., 2020; Y. Wang et al., 2022; F. Zhang et al., 2017; Zou et al., 2024). Climate-smart soil management can affect soil condition and production as well as greenhouse-gas fluxes (Howari, 2026; Kichamu-Wachira et al., 2021; Paustian et al., 2016). These outcomes need not improve together; residue additions can support rice yields while increasing CH_4, and stronger drainage can reduce CH_4 while risking yield loss (Jiang et al., 2019; D. Liu et al., 2023). Yet these benefits do not make agricultural soil carbon a simple or risk-free negative-emission asset.

Whether soil carbon sequestration can function as a reliable natural negative-emission pathway depends on more than a measured increase in total carbon stock. Soil carbon storage is not a simple accumulation of plant inputs. It is a dynamic balance shaped by plant residue and root inputs, microbial processing, aggregate protection, mineral association, land-use change, and climatic disturbance (Cotrufo et al., 2022; Cotrufo & Lavallee, 2022; Dignac et al., 2017). China-scale evidence also shows strong spatial heterogeneity in SOC dynamics (H. Li et al., 2022b; S. Zhang et al., 2024, 2025a). Climate change, vegetation growth, land-use change, and management jointly affect SOC change across soil depths, while land-use and land-cover change can either strengthen terrestrial carbon sinks or cause SOC losses (Beillouin et al., 2022; Cheng et al., 2024; H. Li et al., 2022b). In cropland systems, straw return, conservation tillage, organic amendments, and nitrogen management can increase SOC or alter carbon source-sink balance, but their effects vary with region, soil depth, initial SOC status, and management combination (X. Dong et al., 2026; Kan et al., 2022; B.-J. Lin et al., 2023, 2024; Z. Lin et al., 2024b). For this reason, total SOC accumulation alone cannot answer whether newly stored carbon is stable, reversible, or climatically valuable over policy-relevant time scales. Recent soil organic matter research offers a mechanism-based way to address this accounting problem. Lavallee et al. (2020) argued that treating soil organic matter as a single homogeneous pool is insufficient for explaining its formation, persistence, and function, and proposed distinguishing particulate organic matter (POM) from mineral-associated organic matter (MAOM). Particulate organic carbon (POC) and mineral-associated organic carbon (MAOC) refer to the carbon contained in POM and MAOM, respectively. POC usually responds more rapidly to external carbon inputs and disturbance, and it supports short-term fertility, aggregate formation, and microbial activity (Y. Chen et al., 2021; Cotrufo et al., 2015, 2019, 2022; Fu et al., 2025b). MAOC is more strongly controlled by clay, silt, reactive minerals, Fe/Al oxides, calcium interactions, and microbial necromass stabilization, and it generally has longer mean turnover times and stronger physicochemical protection (Bramble et al., 2024; Canisares et al., 2023; Cotrufo et al., 2019; Sokol et al., 2019, 2022, 2024). At the same time, Angst et al. (2023) cautioned that an excessive focus on MAOC may underestimate the stock contribution, persistence, and precursor role of POM in some soils. The present review therefore does not treat POC as low-quality carbon or MAOC as permanent carbon. Instead, it uses the POC/MAOC distinction as a two-fraction framework for assessing carbon-sink quality, reversal risk, and management pathways.

This framework is especially relevant to China because the country has highly diverse soil types, climatic gradients, land-use histories, and agricultural management regimes. China-scale

fraction mapping has already estimated spatial patterns of POC and MAOC and shown that they are controlled by partly different factors. POC density is more strongly related to climate and vegetation processes, whereas MAOC density is more closely associated with soil properties such as clay content (Lugato et al., 2021; S. Zhang et al., 2024). Chinese cropland SOC mapping also shows that soil physicochemical properties, depth, and regional environmental conditions jointly constrain SOC stocks and future change (H. Li et al., 2022b; S. Zhang et al., 2025a, 2025b). Management-level evidence further indicates that straw carbon enters POC more than MAOC during early decomposition, and that conservation tillage, deep tillage, manure addition, and restoration can affect SOC differently across soil depths and fractions (Y. Li et al., 2024; Su et al., 2020; X. Wang et al., 2023; Zhao et al., 2025). If China's farmland carbon policy is to move from implementation of practices toward governance of carbon-sink quality, it must consider regional mineral saturation deficits, POC reversibility, MAOC formation efficiency, and the net greenhouse-gas consequences of management.

Institutional translation is the other major challenge. Soil organic carbon fraction must be expressed in the language of measurable, reportable, verifiable (MRV), and finance-recognizable systems. China's carbon-market scholarship shows that the national emissions trading system (ETS) and voluntary offset mechanisms are distinct but related governance channels. The national carbon market has been analyzed as a large, rate-based carbon-pricing system whose effectiveness depends on allocation rules, institutional design, and firm responses (Cui et al., 2021; Pizer & Zhang, 2018; X. Zhang et al., 2025). Studies of China's regional ETS pilots show that emissions trading can reduce firm emissions and induce low-carbon innovation, while also requiring careful design to avoid weak incentives (Cui et al., 2021; J. Zhu et al., 2019). For offsets, earlier and recent China certified emission reduction (CCER) studies show a transition from clean development mechanism (CDM)-style project generation toward domestic project-based carbon markets with mitigation, air-quality, and environmental-justice implications (Lo & Cong, 2017; Mei et al., 2026; L. Zhu et al., 2024). These studies support using carbon markets as an institutional bridge, but do not show that farmland POC/MAOC has already become an approved credit unit.

Green finance and digital monitoring add further translation channels. Empirical studies suggest that green finance in China can support renewable-energy deployment, emission reduction, industrial upgrading, and green technology innovation, although effects vary by region and mechanism (J. Huang et al., 2024; Ran & Zhang, 2023; Sun et al., 2022). At the same time, digital soil mapping, spectroscopy, and uncertainty propagation increasingly make fraction-oriented monitoring technically plausible. China-scale POC/MAOC mapping, global spectroscopy syntheses, and MAOC-deficit mapping studies show that fraction stocks and sequestration potential can be modeled, but only with calibration, uncertainty reporting, and repeated verification (S. Ding et al., 2026; Viscarra Rossel et al., 2024; S. Zhang et al., 2024). A credible pathway therefore requires a full evidence chain from fraction measurement to methodology design, credit-risk classification, and financial risk control.

Against this background, this review examines how POC/MAOC evidence can improve the assessment of agricultural soil carbon sequestration in China. It connects biogeochemical mechanisms and regional constraints with management responses, monitoring requirements, and the institutional conditions for credible climate claims (Figure 1). The review first evaluates fraction dynamics and reported management effects, then examines the relevance and limits of carbon-market and green-finance evidence, and finally discusses the technical and governance tests needed for fraction-informed accounting. Its contribution is a conditional assessment framework linking carbon quantity, fraction identity, persistence, uncertainty, and verifiability, rather than a validated credit methodology or a new national sequestration estimate.

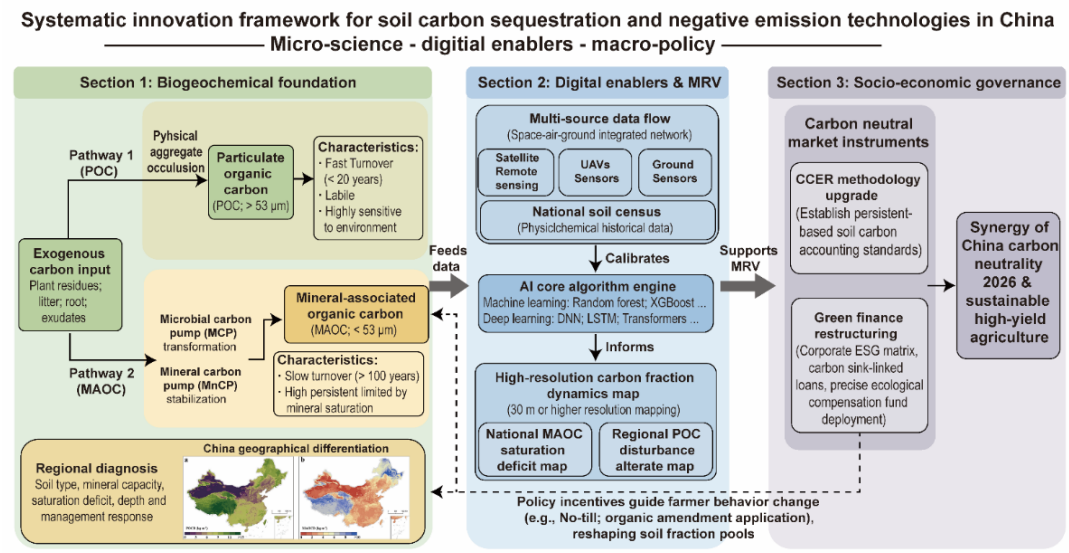

Figure 1. A systemic innovation framework integrating soil organic carbon (SOC) fraction, digital monitoring, reporting, and verification (MRV) enablers, and macro-climate governance in China.
Note: The dashed feedback loop highlights how policy incentives can induce behavioral shifts among land managers, which subsequently recalibrate soil carbon inputs and agricultural management practices. Abbreviations: particulate organic carbon, POC; mineral-associated organic carbon, MAOC; unmanned aerial vehicle system, UAVs; Chinese certified emission reduction, CCER; environmental, social and governance, ESG.

This study is a critical narrative review with a structured summary of published effects, not a systematic review or a new meta-analysis. The evidence base is the literature assembled for the manuscript on POC/MAOC mechanisms, Chinese agricultural soils, management responses, soil-carbon MRV, and carbon governance. During revision, this corpus was checked against accessible source texts and supplemented by targeted web searches of publisher and PubMed records on rice water management, straw return, methane, nitrous oxide, and yield, and by official Ministry of Ecology and Environment sources for institutional requirements. The revision search was conducted on 10 September 2026 using combinations of "*rice/paddy*," "*water management/alternate wetting and drying*," "*straw return*," "*methane*," "*nitrous oxide*," "*yield*," "*China*," and "*meta-analysis*." Sources were retained for their direct relevance to at least one link in the mechanism–management–accounting framework. Quantitative entries in Tables required an identifiable intervention and comparator, a stated geographic or soil context, a defined outcome, and a traceable numerical estimate; qualitative fraction evidence was retained where directly reported but not reduced to a common numerical metric. We distinguish concentration from stock responses, topsoil from deeper measurements, China-specific findings from global analogues, and biogeochemical evidence from institutional evidence. Missing soil specific estimates or confidence intervals were not reconstructed. When studies disagreed, differences in fractionation, comparator, depth, duration, climate, texture, and baseline carbon were considered before drawing a conditional conclusion. Reported estimates were not repooled because overlapping primary studies and inconsistent outcomes preclude treating the syntheses as independent observations.

2. Scientific Mechanisms: POC and MAOC Dynamics

2.1. Biogeochemical Distinctions Between POC and MAOC Cycling

Treating soil organic matter (SOM) as a single homogeneous pool is no longer adequate for explaining differences in SOM formation, persistence, function, and management response. Fraction-based sequestration analysis is therefore not a minor refinement of SOC accounting. It reframes soil carbon sequestration as a combination of carbon pools with different stability, risk exposure, and management sensitivity. POC is derived mainly from incompletely decomposed plant residues, root fragments, and organic particles colonized during early microbial decomposition (Table 1). Its formation is shaped first by vegetation inputs, crop-residue return, root turnover, and aggregate protection (Cotrufo et al., 2019, 2022). Because POM usually occurs as relatively large particles, it often contains a substantial share of plant-derived structural compounds, and its turnover is closely related to physical fragmentation, aggregate exposure, and microbial accessibility (Chi et al., 2022; T. Ding et al., 2025; Kravchenko et al., 2015; W. Yu et al., 2022). This does not

make POC irrelevant for sequestration. POC can respond quickly to external organic inputs, support microbial activity, regulate nutrient cycling, and contribute to soil structure. Stable-isotope evidence from straw decomposition shows this early response clearly. Su et al. (2020) found that, during the first 180 days of straw decomposition, a larger share of straw-derived carbon entered POC than MAOC, and that this allocation was linked to microbial community succession. In agricultural systems, POC is often the first observable response pool after carbon-input management and is an important contributor to short-term SOC increases (Table 1). The climate-governance value of POC, however, should not be equated with long-term negative emission value. POC persistence depends strongly on physical isolation, especially aggregate occlusion and pore-structure constraints on decomposer access (Chi et al., 2022; Simonetti et al., 2017). Tillage (Balesdent et al., 2000; Bayer et al., 2006; Guo et al., 2020), erosion (Deumlich et al., 2018; Jakab et al., 2014; H. Li et al., 2022a), drying-wetting cycles (Kholodov, 2013; Najera et al., 2020), warming (Y. Chen et al., 2023; Z. Chen et al., 2024; Hou et al., 2023), and other disturbances (Dar & Abhishek, 2020) can expose this carbon and increase mineralization risk. POC is therefore best interpreted as a relatively active, rapidly cycling, management-sensitive pool. It can improve soil fertility and supply substrate for later MAOC formation, but policies that treat short-term SOC growth or topsoil POC accumulation as durable sequestration may overstate the permanence of agricultural soil carbon sinks.

Table 1. Biogeochemical and accounting distinctions between POC and MAOC.

Dimension	POC	MAOC	Implication	Reference
Fraction definition	Carbon contained in POM-derived largely from recognizable plant and root residues.	Carbon contained in MAOM bound to fine particles or reactive mineral surfaces.	POM/MAOM describe organic matter forms; POC/MAOC describe the carbon fractions that can be monitored and accounted for.	Lavallee et al. (2020); W. Yu et al. (2022)
Dominant formation pathway	Direct residue input, root debris, aggregate occlusion, and early microbial colonization.	Microbial products, necromass and dissolved organic compounds associated with clay, silt, Fe/Al oxides, Ca bridges and mineral surfaces.	Total SOC accumulation should be partitioned by formation pathway before being interpreted as negative emissions.	Georgiou et al. (2022); Lavallee et al. (2020); Liang et al. (2017); Sokol et al. (2022)
Stabilization mechanism	Physical protection and limited decomposer access, especially through aggregation and pore structure.	Physicochemical protection through adsorption, complexation, co-precipitation, and organo-mineral interactions.	Persistence depends on protection context rather than intrinsic chemical recalcitrance alone.	Sokol et al. (2022); Wu et al. (2023); Xiao et al. (2023)
Management response	Often responds rapidly to straw return, reduced disturbance, restoration, and organic inputs.	Accrues more slowly and depends on mineral capacity, microbial transformation, and soil matrix conditions.	Management success should be evaluated by both short-term responsiveness and long-term stabilization efficiency.	Y.-m. Li et al. (2024); B.-J. Lin et al. (2023); Z. Lin et al. (2024b); Su et al. (2020)
Reversal and credit risk	More sensitive to tillage, erosion, drying-wetting, warming, and land-use change.	Generally lower reversal risk, but not risk-free because MAOM contains chemically and functionally diverse pools.	Credit standards should use differentiated monitoring and buffers rather than treating all SOC increases as equivalent.	Jilling et al. (2025); Matus (2026); Zhou et al. (2024)
Accounting role	Useful indicator of management response, soil fertility co-benefits and potential substrate for later stabilization.	More direct indicator of durable removal quality when verified under suitable mineral and depth conditions.	Fraction-informed accounting should combine quantity, fraction identity, stability and verifiability.	Georgiou et al. (2022); Lavallee et al. (2020); Sokol et al. (2022)

MAOC commonly forms when microbial products, necromass, and dissolved organic compounds interact with silicate clay, Fe/Al oxides, and other mineral surfaces through adsorption,

complexation, co-precipitation, and cation bridging (Kleber et al., 2021; Wu et al., 2023; Xiao et al., 2023; Table 1). In this pathway, persistence arises less from the inherent chemical recalcitrance of organic molecules than from physicochemical protection by mineral surfaces and limited microbial accessibility (Lehmann et al., 2020; Lehmann & Kleber, 2015). Global observations show that MAOC and POC have distinct stock patterns and turnover characteristics, supporting the need to represent the two fractions separately in soil carbon-cycle models and climate-feedback assessments (Zhou et al., 2024). MAOC is central to long-term sequestration discussions not because it is irreversible, but because it is generally more protected by mineral and microbial stabilization processes than POC (Table 1). This distinction changes the evaluation logic for agricultural soil sequestration. If SOC is the only metric, a rapid POC increase and a slower MAOC increase are merged into the same category of carbon accumulation. A fraction-based view requires three additional questions: i) does newly added carbon enter POC or MAOC? ii) can accumulated POC be transformed through microbial processing and mineral association into MAOC? iii) does the target soil still have sufficient mineral capacity to stabilize additional carbon? Georgiou et al. (2022) linked global MAOC stocks with mineralogical capacity and showed the mechanistic basis for discussing mineral constraints and saturation deficits across Chinese soil regions.

POC and MAOC therefore provide complementary evidence for evaluating agricultural carbon gains. POC often responds rapidly to management and supports agronomic functions, whereas mineral association can reduce microbial accessibility and influence persistence. These tendencies do not establish fixed formation rates or permanence classes; the outcome depends on inputs, mineral context, disturbance, and microbial processing. The relevant questions are how management changes each fraction, whether those changes increase total storage relative to a baseline, and whether the gains persist without offsetting greenhouse-gas or production costs (Georgiou et al., 2022; Lavallee et al., 2020; Sokol et al., 2022; Zhou et al., 2024).

2.2. Mineralogical Constraints and Carbon Saturation Deficits Across Major Soil Types in China

At the China scale, the spatial distributions of POC and MAOC are not simple reflections of the same environmental drivers. S. Zhang et al. (2024) combined a meta-analysis of 356 studies from Chinese terrestrial ecosystems with machine-learning models to estimate POC and MAOC density in the 0–30 cm layer. Their results indicate that POC is more strongly affected by climatic conditions, especially mean annual temperature, whereas MAOC is more strongly associated with soil properties, with clay content emerging as a key driver. This pattern is consistent with fraction carbon theory (Lavallee et al., 2020; Zhou et al., 2024). POC mainly reflects external carbon inputs, temperature, and decomposition conditions, whereas MAOC formation and persistence depend more on fine mineral particles, reactive metal oxides, exchangeable cations, pH, and soil matrix properties (King et al., 2023; Sokol et al., 2022; W. Yu et al., 2022; X. Yu et al., 2025). China's agricultural soil sequestration potential therefore cannot be assessed from total SOC or vegetation productivity alone. It must also ask whether additional carbon can enter the mineral-protected MAOC pool. Carbon saturation deficit provides one useful framework for evaluating that mineral-protection potential. W. Feng et al. (2013) defined saturation deficit as the difference between the current amount of stable carbon in fine mineral fractions and the theoretical maximum stable carbon, noting that fine-fraction organic carbon is generally more stable than coarse-fraction carbon. Georgiou et al. (2022) further connected MAOC stocks to mineralogical capacity and argued that soils farther from capacity may accumulate stable carbon more efficiently over relevant time scales. This concept should not be treated as a fixed ceiling that can be transferred to all soils. Six et al. (2024) showed that testing carbon saturation requires careful attention to measurement variables, units, dispersion intensity, soil type, clay type, and current saturation level. Begill et al. (2023) also did not identify a simple MAOC upper limit in temperate agricultural soils and emphasized that mineralogy, depth, and land use affect the detectability of an apparent ceiling. In this review, saturation deficit is therefore used as a diagnostic and prioritization concept, not as a direct conversion factor for carbon credits.

Northeast black soils illustrate a regional context in which high SOC stocks, intensive agricultural use, and substantial mineral capacity may coexist (S. Han et al., 2022; H. Li et al., 2015; G. Yu et al., 2006). If 2:1 clay-dominated soils are used as a mechanistic reference, their higher specific surface area and cation exchange capacity can favor organic matter stabilization through surface adsorption, cation bridging, and aggregate protection (Churchman et al., 2020; Kleber et al., 2021; Sarkar et al., 2018). Six et al. (2024) found that the estimated maximum mineral-stabilized carbon per unit silt-plus-clay can be higher in 2:1 clay-dominated soils than in 1:1 clay-dominated soils. For long-term cultivated black soils, the key question is not whether sequestration potential exists in general, but whether the existing MAOC pool is already close to mineral capacity and whether new straw, root carbon, and manure inputs can be microbially processed and transferred to unoccupied mineral sites (X. Liu et al., 2026; Ma et al., 2026; Shi et al., 2025).

Southern red soils and other strongly weathered soils reflect a different mineral constraint. Under intense weathering and leaching, 1:1 clays and Fe/Al oxides may be more informative than expandable clays as reactive interfaces for organic carbon protection (X. Duan et al., 2025; Y. Li et al., 2025; S. Ren et al., 2024). The comparison by Six et al. (2024) suggests that, when estimates rely only on silt-plus-clay quantity, 1:1 clay-dominated soils may have lower mineral-stabilized carbon capacity per unit fine fraction than 2:1 clay-dominated soils. This interpretation should not ignore Fe/Al oxides. S. Ren et al. (2024), using 341 Chinese soil profiles and a global synthesis, showed that Fe/Al hydroxides are important for explaining surface and subsurface SOC variation and that clay content alone is not always a reliable proxy for mineral-associated organic carbon. Q. Li et al. (2023) also reviewed adsorption, complexation, and co-precipitation mechanisms between iron oxides and organic carbon at soil microinterfaces. Southern red-soil regions should therefore not be characterized simply as low-capacity areas because they contain less expandable clay. Their sequestration potential should be evaluated through reactive Fe/Al phases, pH, redox fluctuation, moisture dynamics, and carbon inputs together.

Arid, semi-arid, and calcareous soils in northern and northwestern China face yet another set of constraints. In these contexts, the main limitation is often not simply a lack of mineral surface area. Water availability, vegetation productivity, fine-particle retention, calcium bridging, and microbial necromass formation jointly constrain MAOC accumulation. Mao et al. (2024) argued that, in arid ecosystems, silt and clay protect carbon not only through adsorption but also by altering water availability, pore structure, microbial activity, and microbial necromass formation. Peng et al. (2026), comparing typical steppe and desert steppe in Inner Mongolia, found that desertification reduced MAOC concentration and that the mechanism involved fine-particle loss, lower amorphous Fe/Al oxides, exchangeable Ca, and microbial community change, whereas POC differences were concentrated mainly in surface layers. Thus, even where a nominal mineral saturation deficit exists in arid and semi-arid regions, it may not automatically translate into realizable MAOC gains. Minerals can be used effectively only when water conditions, vegetation restoration, organic inputs, and fine-particle conservation improve together.

Paddy soils require a separate diagnostic because rice cultivation crosses mineralogical regions, including black-soil and strongly weathered southern landscapes. Flooding and drainage alter oxygen availability and microbial carbon processing; redox-sensitive mineral-organic interactions further complicate the use of a single mineral-capacity estimate (Hu et al., 2024; Kleber et al., 2021). Consequently, neither a high SOC concentration nor an apparent MAOC deficit demonstrates a net climate benefit in a paddy field. Straw return and irrigation can change CH_4 and N_2O emissions as well as carbon retention (Jiang et al., 2019; D. Liu et al., 2023). Table 2 therefore treats paddy management as a cross-cutting water-regime class rather than a mutually exclusive soil type. Fraction measurements should be paired with mineral characterization, sampling depth, water-regime records, and seasonal gas measurements before extrapolating upland stabilization relationships to rice systems.

Table 2. Mineralogical constraints and carbon-saturation implications across major Chinese soil contexts.

Soil or regional context	Main mineralogical or environmental constraint	Likely POC signal	Likely MAOC constraint	Implication for sequestration assessment
China-scale terrestrial ecosystems, 0–30 cm	POC and MAOC are controlled by partly different environmental drivers; clay content is more important for MAOC, while temperature is more important for POC.	More climate- and vegetation-sensitive.	More soil-property and clay-associated.	POC and MAOC should be mapped and interpreted separately rather than split from SOC by a fixed ratio.
Northeast black-soil and high-SOC cropland contexts	Potentially high fine-particle capacity and long cultivation history; actual MAOC deficit still needs direct regional quantification.	Management inputs may increase POC and aggregate-associated fractions.	Capacity depends on clay type, current saturation level, depth and long-term management history.	Treat as a high-priority diagnostic region, but avoid assigning a fixed MAOC capacity without local fraction and mineral data.
Southern red soils and strongly weathered soils	Fe/Al oxides, pH and redox/water fluctuations may be more informative than clay content alone.	POC response depends on carbon input and decomposition conditions.	Reactive Fe/Al interfaces can protect SOC, but acidification and moisture dynamics may alter protection.	Assess reactive mineral surfaces and Fe/Al-organic carbon interactions, not only silt-plus-clay quantity
Arid, semi-arid and calcareous northern/northwestern soils	Water and carbon-input limitation erosion and fine-particle retention; Ca interactions vary locally.	Surface POC responds to inputs and disturbance; grassland evidence is not automatically transferable to cropland	Apparent mineral deficit may remain inaccessible without adequate inputs water and reactive surfaces	Co-monitor water, salinity where relevant, fine particles, inorganic versus organic C, and depth-specific fractions; no fixed credit coefficient (Mao et al., 2024; Peng et al., 2026; Rowley et al., 2018)
Paddy soils across mineralogical regions	Flooding/drainage and redox-sensitive mineral interactions	Residue inputs and oxygen limitation can alter particulate retention and decomposition	Protection depends on mineral and redox context; a fixed saturation value is insufficient	Measure fractions with CH_4, N_2O, yield and water regime; high SOC alone does not establish mitigation (Jiang et al., 2019; Kleber et al., 2021; D. Liu et al., 2023)

Across Chinese regions, MAOC sequestration potential should be interpreted as the joint outcome of mineral capacity, effective carbon input, and environmental accessibility (Table 2). In Northeast black soils, the central issue is whether high background SOC still leaves usable mineral capacity and management deficits. In southern red soils, the key issue is whether Fe/Al oxide interfaces can maintain protection under acidification and water fluctuation. In arid and calcareous regions, the limiting issue is whether carbon input, moisture, and fine-particle retention are sufficient to activate potential mineral sites. This heterogeneity means that China cannot rely on a single SOC-growth coefficient for soil negative-emission assessment. It needs a regional diagnostic framework that jointly evaluates POC, MAOC, mineral composition, and saturation deficit. For policy and MRV systems, the central task is not to assign each soil type a fixed sequestration ceiling. It is to identify where additional carbon is more likely to enter a stable MAOC pool, where SOC gains are dominated by more reversible POC accumulation, and where mineral or water constraints limit the long-term climate value of management practices (Angst et al., 2023; Georgiou et al., 2022, 2025; Lugato et al., 2021; Peng et al., 2026; S. Ren et al., 2024; S. Zhang et al., 2024).

2.3 Land-Use and Management Modulations on POC and MAOC Regimes

Land-use change and agricultural management do not merely increase or decrease total SOC. They redistribute carbon between POC and MAOC by changing the amount of carbon input (Fujisaki et al., 2018; Lee et al., 2021; G. Wang et al., 2023), the position at which residues enter the soil (Canisares et al., 2023; Sokol et al., 2019, 2024), the intensity of physical disturbance (Bramble et al., 2024; M. Li et al., 2018; Pellegrini et al., 2026), microbial processing efficiency (Fu et al.,

2025a; N. Wang et al., 2024; Y. Zhang et al., 2024), and opportunities for mineral association (Boeddinghaus et al., 2021; Kleber et al., 2021; Wu et al., 2023). A meta-analysis of Chinese cropland (B.-J. Lin et al., 2023) found that chemical fertilizer combined with organic fertilizer, no-tillage, and straw return all increased SOC stock in the 0–20 cm layer, but that the management effect depended on climate, texture, initial SOC, and experimental duration. Figure 2 condenses the common management practices (including straw return, conservation tillage, manure application, and land restoration) into a qualitative synthesis. It emphasizes that the same management practice may increase SOC, change POC response, and alter MAOC formation opportunities at the same time. Practice implementation should therefore not be equated directly with stable negative emissions (B.-J. Lin et al., 2023; Z. Lin et al., 2024b; Su et al., 2020; Zhao et al., 2025). For negative-emission accounting, the key question is not only whether SOC increases. It is whether newly added carbon remains in the faster-cycling POC pool or is transformed into MAOC through microbial processing and mineral protection.

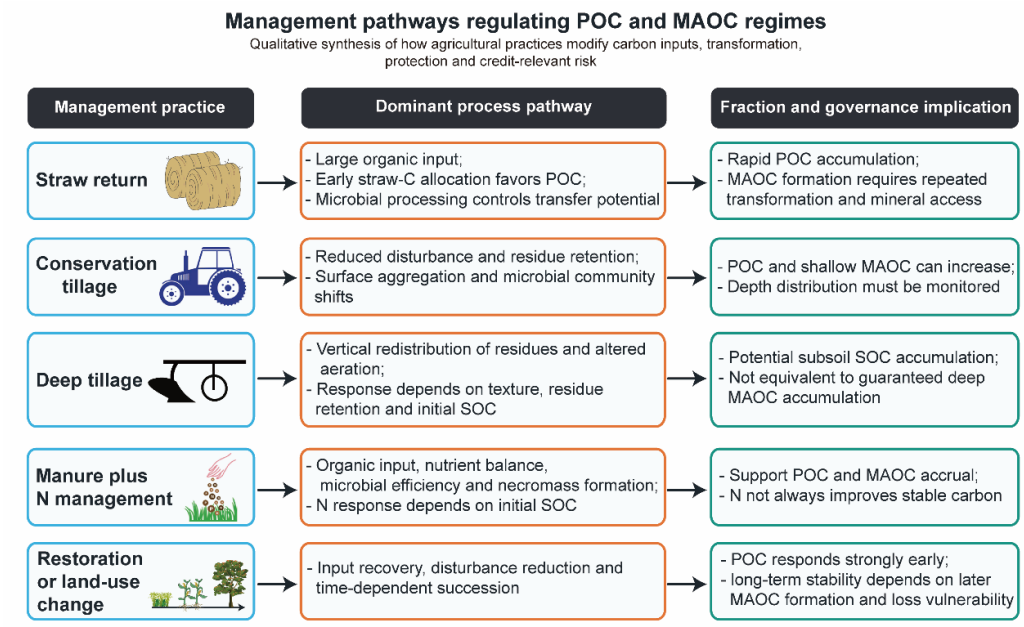

Figure 2. Management pathways regulating POC and MAOC accumulation.
Note: The figure summarizes reviewed evidence on straw return, tillage, manure and nitrogen management, and land restoration. Directional pathways indicate mechanisms and accounting implications; they do not assign universal response coefficients or credit weights.

Tillage systems regulate fraction carbon first by altering physical disturbance and vertical mixing. Conservation tillage usually reduces aggregate disruption and surface-residue disturbance, which can favor POC retention (H. Chen et al., 2009; Z. Han et al., 2024; Y.-m. Li et al., 2024). Fraction-specific evidence shows that its effects are not limited to POC. In a six-year field experiment on eolian sandy soil, Y.-m. Li et al. (2024) found that conservation tillage increased POC in the 0–30 cm layer and MAOC in the 0–20 cm layer compared with conventional tillage, and linked these changes to key microbial groups and aggregate formation. Reduced disturbance may therefore protect plant-residue carbon while also promoting shallow MAOC formation through microbial pathways (H. Chen et al., 2019; Chivenge et al., 2007). Deep tillage or subsoiling should not be interpreted as intrinsically better because it is deeper. Its value depends on whether carbon inputs and mineral sites are more effectively coupled. A meta-analysis of dryland wheat and maize systems in China (Islam et al., 2023) found that straw return under different tillage modes increased SOC, while deep tillage had a stronger positive effect on subsurface SOC in the 20–40 cm layer. X. Wang et al. (2023) also found that deep tillage increased SOC stock relative to conventional tillage, but that the effect depended on texture, precipitation, residue retention, multiple cropping, and initial SOC, with no significant increase below 40 cm. Tillage should therefore be evaluated as a practice that changes the spatial distribution and stabilization opportunities of carbon, not as a simple binary preference for no-tillage or deep tillage.

Straw return is one of the most important management pathways for increasing SOC in Chinese cropland, but its fraction effects are stage-dependent. Z. Lin et al. (2024b), using RothC simulations and long-term field experiments, showed that the increase in topsoil SOC across Chinese cropland over the past 40 years was related to higher organic carbon input, with straw return as a

key driver. Stable-isotope evidence indicates that fresh straw carbon initially enters POC more than MAOC. Su et al. (2020) traced straw-derived carbon across SOC fractions and found that, within 180 days, the proportion entering POC was substantially higher than the proportion entering MAOC, with allocation linked to microbial community dynamics. Straw return therefore first provides decomposable substrate and particulate carbon. Its long-term climate value depends on later microbial necromass production, aggregate protection, and mineral association. G. Ren et al. (2023) further showed that straw combined with appropriate nitrogen management increased SOC, dissolved organic carbon, POC, and MAOC and altered microbial communities, but that higher nitrogen under straw treatment did not consistently outperform moderate nitrogen. Straw-return policy should therefore evaluate not only the amount returned but also placement depth, decomposition environment, nitrogen ratio, and MAOC conversion efficiency.

Fertilizer management also cannot be reduced to the claim that more nutrient addition increases sequestration. A long-term black-soil experiment (Dou et al., 2016) showed that inorganic nitrogen or NPK alone did not significantly increase SOC stock, although they increased mineral-associated organic matter carbon within aggregates. By contrast, chemical fertilizer combined with farmyard manure increased carbon in the light fraction, intra-aggregate POM, and mineral-associated SOM, producing the highest SOC stock (Dou et al., 2016) . Manure acts not only by adding carbon, but also by improving aggregate structure, substrate quality, and microbial transformation. Long-term dryland experiments in China also indicate that NPK combined with manure or straw can increase SOC and labile carbon pools more effectively than mineral fertilizer alone, although the increase in active carbon declines with depth (Nazia et al., 2019). Ling et al. (2025) further identified an initial SOC threshold of about 15 g C kg^{-1} that changes the direction of nitrogen effects on POC and MAOC. In low-SOC soils, nitrogen mainly promotes POC accumulation through plant-derived inputs and aggregate formation. In high-SOC soils, nitrogen is more likely to promote MAOC accumulation through microbial metabolic efficiency and necromass stabilization. The effect of nitrogen on SOC fractions should therefore be interpreted through initial SOC, mineral capacity, and organic carbon input together.

Land-use change and ecological restoration reshape POC and MAOC over longer time scales. A global meta-analysis (Zhao et al., 2025) found that land restoration generally increased both MAOC and POC, while land degradation reduced both fractions, and POC was more sensitive to land-use change than MAOC. The same study (Zhao et al., 2025) reported that restored systems tend to have a higher POC proportion early in restoration, whereas the POC proportion declines and soil carbon stability increases with restoration duration. This mechanism helps interpret revegetation and land-restoration programs. Early SOC gains after restoration may mainly reflect surface POC and litter inputs and may not immediately represent durable carbon assets. Only when root inputs, microbial transformation, and mineral association continue over time can restoration progressively raise the MAOC share.

Paddy management makes the distinction between carbon accumulation and mitigation explicit. D. Liu et al. (2023), synthesizing 369 studies on China's three major grain crops, reported that straw return increased rice yield by 5.04% but increased CH_4 emissions by 72.01%, while rice N_2O emissions decreased by 11.43%. A global analysis of 201 paired observations from 52 rice studies found that non-continuous flooding reduced CH_4 by 53% and combined CH_4/N_2O warming potential by 44%, but increased N_2O by 105%; severe drying reduced yield whereas mild drying did not Jiang et al. (2019). The latter analysis does not establish a Chinese POC/MAOC stock response. Together, these findings support joint water, residue, and nitrogen management, with carbon-stock change, seasonal gases, and harvest measured within the same accounting boundary.

In summary, SOC fraction-informed management in Chinese croplands should move from increasing carbon inputs to improving stabilization efficiency. No-tillage and conservation tillage can reduce disturbance and retain shallow fraction carbon, but they may also create surface enrichment (H. Chen et al., 2009; Z. Han et al., 2024; Hou et al., 2023; Y.-m. Li et al., 2024). Deep tillage or subsoiling may improve subsurface SOC where residue input, texture, and initial SOC conditions are favorable (S. Chen et al., 2026; X. Wang et al., 2023). Straw return provides a large carbon source, but MAOC gains depend on microbial processing and nitrogen matching (S. Chen et al., 2026; Islam et al., 2023; Z. Lin et al., 2024b; Su et al., 2020; X. Yu et al., 2025). Manure combined with mineral nutrients is often more favorable for multi-fraction carbon accumulation than mineral fertilizer alone (Anthonio et al., 2022; Banger et al., 2010; Dou et al., 2016). Land restoration requires longer periods before its stabilization benefits become evident (Cheng et al., 2024; H. Li et al., 2015; Zhao et al., 2025). Negative-emission evaluation should therefore record not only whether a practice is implemented or whether SOC increases. It should monitor POC, MAOC, soil depth, and regional mineral saturation deficit to distinguish short-term fertility benefits, reversible particulate carbon accumulation, and more durable mineral-associated carbon accumulation.

Table 3 summarizes source-reported management effects by available geographic and soil context. Global fraction-concentration responses and Chinese SOC-stock responses are shown separately because they answer different questions. For example, a positive topsoil POC concentration response under no-till does not establish a whole-profile carbon-stock gain. The table also retains unquantified regional fraction responses as evidence gaps instead of assigning national means to individual soil types. The reported percentages are comparator-specific and are neither annual sequestration rates nor credit conversion factors.

Table 3. Source-reported management effects by available geographic and soil context.

Study/design	Geographic and soil context	Intervention/comparator; depth	Source-reported response	Interpretation and limits
(Prairie et al., 2023); global meta-analysis	Global croplands; mixed soils, not a Chinese soil-zone estimate	No-till/conventional tillage; 0–20 cm	Concentrations: SOC +11.3%; POC +19.7%; MAOC +8.5%	Positive topsoil responses; pooled subsoil effects not significant. Concentration changes are not stock gains.
	Global croplands; mixed soils	Cropping intensification/less intensive cropping; 0–20 cm	Concentrations: SOC +12.4%; POC +33.3%; MAOC +7.1%	Includes several intensification types; shares the preceding source and is not an independent meta-analysis.
(B.-J. Lin et al., 2023); meta-analysis, 2,301 comparisons/158 papers	Chinese croplands; mixed regions and textures	Chemical fertilizer plus manure/no fertilizer; 0–20 cm	SOC stock +31.8%; POC/MAOC not separately estimated here	The unfertilized comparator differs from the controls below; it is not the marginal benefit of manure over mineral fertilizer.
	Chinese croplands; arid, alkaline and fine-textured contexts identified as favorable moderators	No-till/plow tillage; 0–20 cm	SOC stock +9.98%; POC/MAOC not separately estimated here	National pooled value, not a numerical estimate for each listed moderator subgroup.
	Chinese croplands; mixed soil categories	Straw return/removal; 0–20 cm	SOC stock +10.84%; POC/MAOC not separately estimated here	Duration and initial SOC modify responses; not an annual rate.
(B. Huang et al., 2025); meta-analysis, 527 observations/140 publications	Northeast China; black-soil region	Conservation tillage/conventional comparator; multiple depths	SOC concentration +4.17%; POC +8.27%; crop yield +2.69%	POC is a reported ancillary carbon-pool response (Section 3.3), not a stock estimate; MAOC not synthesized. Surface and deeper SOC responses differ.
(X. Wang et al., 2023); meta-analysis, 447 observations	China; response modified by rainfall, texture and initial SOC	Deep tillage/conventional tillage; source-specific profile depths	SOC stock +7.36%; subsoiling +8.76%, deep ploughing +5.85%	No significant benefit below 40 cm; larger responses in fine-textured than sandy contexts. Not a POC/MAOC estimate.
(Y.-m. Li et al., 2024); six-year field experiment	Chinese eolian sandy soil; local experiment	Conservation/conventional tillage; POC 0–30 cm, MAOC 0–20 cm	Positive POC and MAOC responses; no numerical percentage transcribed	Direct local fraction evidence; does not quantify all arid or calcareous soils.

Table 3. *Cont.*

Study/design	Geographic and soil context	Intervention/comparator; depth	Source-reported response	Interpretation and limits
(Zhao et al., 2025); meta-analysis, 693 observations	Global land transitions; arid/carbon-poor and humid/carbon-rich contexts	Restoration or degradation/corresponding reference land use; variable depths	Restoration increased POC and MAOC; degradation reduced both; no common percentage transcribed	Larger restoration responses in arid or carbon-poor topsoil; forest/grassland conversion is not a production-compatible cropland practice by default.
(D. Liu et al., 2023); meta-analysis, 2,269 datasets/369 studies	China; rice systems across soil contexts	Straw return/corresponding no-return control; seasonal gases and harvest	Rice yield +5.04%; CH_4 +72.01%; N_2O −11.43%	No POC/MAOC effect estimated; gas percentages cannot be added to SOC percentages.
	China; upland wheat and maize	Straw return/corresponding no-return control	Wheat yield +8.09%; maize yield +8.71%; maize N_2O +14.69%	Wheat N_2O response not significant; crop-specific effects, not a common climate-benefit coefficient.
(Jiang et al., 2019); meta-analysis, 201 pairs/52 studies	Global rice paddies, including China; mixed soils	Non-continuous/continuous flooding; seasonal gases and yield	CH_4 −53%; N_2O +105%; combined gas GWP −44%; yield −3.6%	Mild drying did not significantly reduce yield; severe drying did. GWP covers CH_4/N_2O using source factors, not SOC or a complete life cycle.

Note: Values are published mean relative effects, not recalculated estimates. Multiple rows from one synthesis are not independent evidence. SOC stock and concentration are kept separate; percentages are not additive across outcomes or treatments. Significance and non-significance are reported only where stated by the source. Missing regional POC/MAOC effects are retained as gaps; the table is organized by available context, not a complete soil-by-region factorial classification. Jiang et al. (2019) calculated combined gas GWP with CH_4 and N_2O factors of 25 and 298, respectively; its GWP result is not a current project-accounting conversion. The other sources' original uncertainty and subgroup results should be consulted for interpretation.

3. Policy Drivers: Integrating Soil Carbon Sequestration into China's Climate Governance

3.1. Macro-Policy Landscape and the Limitation of Total Carbon Accounting

China is the world's largest carbon emitter, and its 2030/2060 transition pathway has been analyzed as a system-level challenge involving energy restructuring, industrial transformation, carbon pricing, regional development, and negative-emission options (H. Duan et al., 2021; Z. Liu et al., 2022). Recent modeling further suggests that mitigation policies interact with one another, so the timing and effectiveness of carbon neutrality depend on coordinated policy portfolios rather than isolated instruments (Y. Liu et al., 2025). This matters for agricultural soil carbon because soil sequestration does not replace energy and industrial mitigation. It functions as one component of a wider transition portfolio, where its contribution depends on measurement credibility, permanence, land-use compatibility, and institutional integration. Meanwhile, China has a significant terrestrial carbon sink, but its magnitude and distribution are uncertain and spatially variable (Piao et al., 2009; J. Wang et al., 2020). Natural climate solution assessments show that land-based mitigation in China is constrained by biophysical conditions, economic feasibility, and competing land-management objectives (Lu et al., 2022). Soil carbon is therefore best understood as a conditional mitigation pathway: it can contribute to carbon neutrality, but only when additional carbon storage is measurable, durable, and compatible with food security, biodiversity, water constraints, and farmer incentives (Bossio et al., 2020; Paustian et al., 2016).

Cropland studies make this conditional potential more concrete. Zuo et al. (2023) estimated large SOC stocks in China's croplands and projected that increased crop residue, livestock manure, and nitrogen management could make a measurable contribution to China's carbon-neutrality pathway. Y. Wang et al. (2022) further showed that future SOC sequestration potential depends on the interaction between climate change and agricultural management, indicating that carbon input alone is insufficient for predicting future gains. Historical cropland SOC analysis also shows that China's agricultural soils have changed under different bioclimatic and cropping conditions, reinforcing the need for regionalized accounting (Z. Lin et al., 2024b; Xie et al., 2021; F. Zhang et al.,

2017; S. Zhang et al., 2024). These studies support the policy relevance of farmland soil carbon, but they also show why aggregate SOC targets are not enough. A cropland can gain SOC while still differing in fraction allocation, depth distribution, reversibility, and net greenhouse gas balance. The limitation of total carbon accounting is therefore a scale mismatch between governance demand and biogeochemical mechanisms. Total SOC or net carbon sink support macro-level inventories and policy mobilization, but they cannot directly answer three questions that determine the quality of soil-based negative emissions. First, does new carbon enter POC or MAOC? Second, can management-induced POC be transformed through microbial processing and mineral association into more stable MAOC? Third, does the target soil have sufficient mineral capacity and environmental conditions to stabilize additional carbon? The POC/MAOC framework addresses these questions by separating fast, management-sensitive responses from slower, mineral-associated stabilization pathways (Fu et al., 2025b; Georgiou et al., 2022; Lavallee et al., 2020; Lugato et al., 2021; L. Zhu et al., 2024).

Recent agricultural accounting studies in China move in the same direction of refinement, although most do not yet reach the fraction level. Y. Chen et al. (2022) linked net carbon sequestration value compensation with paddy field management, food security, and farmer incentives. Z. Zhang and Qin (2025) incorporated carbon sinks into carbon-emission-efficiency assessment across China's major maize regions and emphasized regional differentiation. X. Dong et al. (2026) argued that conventional agricultural carbon accounting often treats farming systems as homogeneous wholes and proposed a management practice-based accounting system that disaggregates Chinese farming systems into more refined units. These studies show a shift from aggregate accounting toward regional, crop-specific, and management-specific accounting. The remaining gap is that most frameworks still use SOC change, net carbon sinks, or management coefficients rather than fraction identity, mineral saturation deficit, and permanence risk. For a review focused on soil fractions, the macro-governance implication is clear. Soil carbon governance should move from total carbon accounting to quality accounting. The basic accounting unit should not be practice implementation or short-term SOC gain alone. It should include the amount of carbon added, the fraction in which it is stored, the depth and mineral context of storage, the uncertainty of measurement, and the probability of reversal. This shift would make agricultural soil carbon more compatible with carbon-neutrality governance because it links the scientific quality of a removal with the institutional requirements of MRV, additionality, conservativeness, and credit-risk management.

Food production constrains which carbon-management options are acceptable. In North-east China's black-soil region, B. Huang et al. (2025) reported average increases in SOC and crop yield under conservation tillage, but responses varied with soil depth, climate, and practice combination; a regional mean therefore cannot guarantee a yield benefit on every farm. Rice water-management evidence likewise distinguishes mild drying from yield-reducing severe drying Jiang et al. (2019). We propose that pilot eligibility include maintenance of locally relevant staple-crop production and water availability, with adjustment or discontinuation when persistent yield losses occur. Residue and manure allocation should also consider competing uses and nutrient budgets. Additional fertilizer or irrigation introduced to maximize carbon inputs must be assessed for N_2O emissions, energy use, water stress, and farm costs. Restoration effects from land-use conversion should not be used to justify displacement of productive cropland without accounting for displaced production and leakage (D. Liu et al., 2023; Lu et al., 2022).

3.2. Market-Based Mechanisms: Transforming Fractionation Science into CCER and Green Finance

Market-based mechanisms matter because they convert scientific measurement into incentives, asset language, and risk allocation. The key issue is not whether all additional SOC can be marketed as a homogeneous offset. It is whether fraction-specific carbon gains can be validated, quantified, discounted for uncertainty, and classified according to permanence risk. China's carbon-market literature provides a useful institutional background. Pizer and Zhang (2018) described China's national carbon market as a large and distinctive carbon-pricing program based on a tradable performance standard design. Cui et al. (2021) found that China's regional carbon-market pilots reduced firm emissions, while J. Zhu et al. (2019) showed that pilot emissions trading induced low-carbon innovation. These findings support the broader claim that market mechanisms can shape mitigation behavior, but they also show that design quality matters.

The institutional pathway for agricultural soil carbon is more likely to pass through project-based voluntary reductions than through direct allowance trading. China's offset literature shows that domestic carbon offsetting emerged from the post-CDM context and shifted certified emission reductions toward domestic carbon-market use (Lo & Cong, 2017). Recent CCER scholarship describes a renewed voluntary reduction scheme and emphasizes the role of methodologies, project eligibility, additionality, and credit credibility (L. Zhu et al., 2024). Mei et al. (2026) further found

that China's CCER program reduced CO_2 emissions and PM2.5 concentrations and promoted environmental justice by narrowing air quality disparities. These studies justify treating CCER as a potentially important bridge between land-based mitigation and market governance. They do not, however, justify immediate crediting of farmland POC/MAOC. A soil fraction pathway would require a dedicated methodology that defines boundaries, baselines, eligible practices, measured fractions, uncertainty deductions, leakage treatment, and reversal response (Figure 3). SOC fraction can improve this methodology by differentiating credit quality. A project that increases surface POC after straw return or reduced tillage may deliver agronomic benefits and short-term carbon gains, but its reversal risk is higher because POC is sensitive to disturbance and management discontinuity (Fu et al., 2025b; Z. Lin et al., 2024b; X. Yu et al., 2025). A project that increases MAOC within a verified mineral context may provide a stronger basis for long-term removal claims (Begill et al., 2023; Georgiou et al., 2022; Ma et al., 2026), but it still requires repeated monitoring and risk buffers because MAOC is dynamic, heterogeneous, and not automatically permanent (Faust et al., 2021; Grant et al., 2022; Jilling et al., 2025; Matus, 2026). Therefore, a future CCER-oriented soil methodology should move from asking only how much SOC increased to asking which fraction increased, at what depth, under what mineral constraint, with what uncertainty, and with what reversal risk.

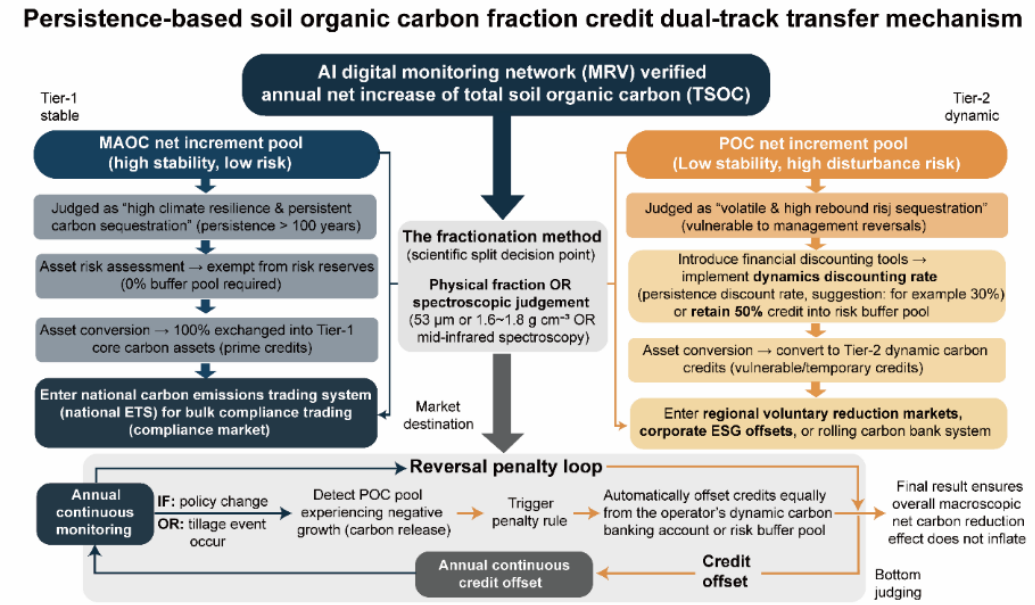

Figure 3. Schematic flowchart of the persistence-based dual-track soil carbon credit allocation and trading mechanism.

Green finance can use this differentiated information as a risk signal. Previous studies suggest that green finance in China can reduce emissions, promote renewable-energy deployment, support industrial upgrading, and foster green technology innovation (J. Huang et al., 2024; Sun et al., 2022; R. Zhang et al., 2023). For soil carbon, however, green finance should not finance generic claims of improved soil organic matter without verifying carbon quality. SOC fraction indicators could support more conservative asset classification. Verified MAOC accumulation with low model uncertainty and low disturbance exposure may support longer-term compensation or lower-risk credit products (Begill et al., 2023; Lugato et al., 2021; Matus, 2026). POC-dominated gains, highly reversible management practices, or projects with uncertain net greenhouse-gas effects should face shorter review intervals, higher buffers, or more conservative financial treatment (X. Dong et al., 2026; Kellner et al., 2025; Pellegrini et al., 2026). This does not require assigning universal prices to POC and MAOC. It requires using fraction identity, uncertainty, and permanence risk as asset-quality parameters (Figure 3). Green-finance evidence from renewable energy and industrial innovation is similarly indirect (J. Huang et al., 2024; Sun et al., 2022). Verified fraction measurements could inform an ecological-performance assessment, but lower borrowing costs, insurance premiums, or collateral values do not follow automatically from a larger MAOC share. Such outcomes would require lender acceptance, enforceable contracts, reliable cash flows, and evidence that the added monitoring cost is justified. Ecological compensation can in principle reward agreed management or soil-health outcomes without representing them as fungible offsets; any associated removal claim still requires separate carbon accounting.

Market design should therefore establish a continuous chain from SOC fraction measurement to methodology-based certification and then to financial risk management. The first link is scientific: POC and MAOC must be measured or predicted with calibrated uncertainty (Baldock et al., 2018; Fultz et al., 2014; Lavallee et al., 2020). The second link is methodological: project boundaries, baselines, eligible practices, monitoring periods, and uncertainty deductions must be standardized. The third link is market-based: certified units should be classified according to permanence risk and verification quality (Dynarski et al., 2020; L. Zhu et al., 2024). The fourth link is financial: banks, insurers, and compensation schemes can use these quality classes as risk parameters. This chain would make soil carbon more compatible with carbon-neutrality research because it connects mechanisms, policy design, markets, technology, and systemic innovation in one analytical framework.

4. Evidence Limits and Conditional Pathways for Implementation

4.1. What Digital Soil Mapping Can and Cannot Establish

Bringing POC and MAOC into climate governance first creates a scale problem. Physical fractionation can separate POC from MAOC, and laboratory measurements remain the benchmark for defining fraction identity (Lavallee et al., 2020). Yet fractionation requires sampling, pretreatment, size or density separation, carbon analysis, and quality control. It is therefore difficult to repeat at the density and frequency required for national monitoring or project-level carbon crediting. Carbon markets and agricultural carbon-sink programs require an evidence chain that is measurable, reportable, verifiable, conservative, and auditable. If soil accounting continues to extrapolate total SOC from sparse samples, it cannot determine whether new carbon has entered POC or MAOC, nor can it distinguish short-lived management responses from more durable stabilization processes (Thornbush & Govind, 2025; World Bank, 2021).

Digital soil mapping (DSM) provides the most practical route for scaling fraction measurements (S. Ding et al., 2026; Sun et al., 2023; Wadoux et al., 2020; Ye et al., 2025), but its role should be defined carefully. DSM does not make remote sensing a direct sensor of belowground POC or MAOC. Rather, it links standardized field and laboratory observations with environmental covariates, remote or proximal sensing, management records, and machine-learning models to predict soil properties in unsampled locations (Kellner et al., 2025). For fraction-specific monitoring, covariates should be selected according to mechanism rather than data availability alone. Bare-soil reflectance from Sentinel-2, Landsat, or high-resolution imagery can inform surface organic matter, soil color, moisture, and some mineral backgrounds (F. Liu et al., 2022; S. Wang et al., 2020; Xue et al., 2025; X. Zhang et al., 2024). Unmanned aerial imagery can supplement field-scale bare-soil windows and residue information (Flores Peña et al., 2025; Narzari et al., 2025; Suleymanov et al., 2025). Terrain variables, including slope, flow accumulation, and topographic wetness indices, help represent erosion, deposition, and moisture redistribution. Climate, net primary productivity, vegetation indices, crop type, fertilization, straw return, and tillage records can indicate carbon input and disturbance intensity. These variables are relevant because POC is strongly shaped by recent inputs and disturbance (Cotrufo et al., 2022; Fujisaki et al., 2018; Pellegrini et al., 2026; X. Yu et al., 2025), whereas MAOC is more constrained by texture, mineral surfaces, microbial processing, and hydrothermal conditions (Araujo et al., 2017; Cai et al., 2016; King et al., 2023; Sokol et al., 2024).

China's recent SOC mapping studies show that this transition from conventional soil maps to high-resolution, data-driven soil information is already technically plausible. F. Liu et al. (2022) generated 90 m national soil information grids for China using representative soil profiles, high-resolution soil-forming covariates, and ensemble machine-learning methods. At the cropland scale, Xue et al. (2025) used multitemporal Sentinel-2 bare-soil reflectance and environmental covariates to map topsoil SOC across China at 10 m resolution. These studies do not provide POC and MAOC certification by themselves, but they show that dense covariates, machine learning, and uncertainty-aware mapping can support the infrastructure needed for more refined soil carbon accounting. SOC fraction-specific mapping provides the stronger scientific anchor. S. Zhang et al. (2024) compiled 356 studies across Chinese terrestrial ecosystems and used support vector machine and random forest models to estimate POC and MAOC density in the 0–30 cm layer. Their analysis showed that POC and MAOC have different spatial patterns and drivers: mean annual temperature was especially important for POC density, whereas clay content was important for MAOC density. High-precision accounting should therefore not map total SOC and then split it into POC and MAOC by a fixed ratio. It should build separate POC, MAOC, and uncertainty layers, and it should allow drivers to differ by fraction and region. Spectroscopy can help bridge the gap between costly fractionation and spatial prediction. S. Ding et al. (2026) reviewed infrared spectroscopy for predicting SOC fractions and found that spectroscopy combined with machine learning can provide a rapid and lower-cost approach for estimating POC and MAOC, while also emphasizing that model

transferability is constrained by soil context. Mid-infrared spectroscopy and partial least squares regression performed well in the reviewed studies, but prediction accuracy varied with texture, latitude, and interacting mineral factors. For China, this means that spectral libraries must be calibrated and independently validated across black soils, red and yellow soils, calcareous soils, eolian sandy soils, paddy soils, grasslands, and irrigated drylands. Global spectral models or bulk-SOC models should not be transferred into crediting systems without local validation.

A mature SOC fraction-DSM product should also move from stock mapping to potential and risk diagnosis. At minimum, a digital MRV system should report SOC, POC, MAOC, bulk density, depth, fraction change, and uncertainty intervals. Where mineralogical data are available, it should also estimate MAOC saturation deficit or mineral-associated carbon storage potential. Georgiou et al. (2022) showed that mineral-associated carbon capacity can be used to diagnose global MAOC deficits, although saturation concepts must be applied cautiously and locally. Viscarra Rossel et al. (2024) further demonstrated a methodological pathway for mapping MAOC stocks, deficits, sequestration potential, and uncertainty through soil-type grouping, frontier-line analysis, machine learning, and external-drift kriging. For China, this logic could support maps that identify where MAOC deficit is high and management access is feasible, where POC responds rapidly but reversal risk is large, and where mineral or water constraints limit stabilization efficiency. The central point is that AI-driven DSM should be a calibrated monitoring architecture, not an autonomous credit generator. Laboratory fractionation supplies mechanism and benchmark measurements; spectroscopy expands sample throughput; remote sensing and environmental covariates provide spatial structure; machine learning extends observations into continuous maps; and uncertainty propagation defines where model outputs are reliable enough for accounting. Only this combined architecture can transform POC and MAOC from laboratory indicators into spatially explicit, updateable, and auditable MRV products.

The strongest evidence currently supports spatial prediction, not direct detection of additional carbon over a crediting interval. A 10 m map describes output resolution; it does not imply 10 m independent measurement support or sufficient precision to detect small MAOC changes. Spatial cross-validation can also be optimistic where nearby observations share environmental information, and prediction outside the calibration domain remains uncertain (Wadoux et al., 2020). For fraction MRV, independent spatial and temporal validation, harmonized fraction definitions, and paired stock measurements are therefore more informative than grid size alone. A mapped MAOC deficit identifies a hypothesis for intervention; it is not evidence that management can fill that deficit within a project term.

4.2. Building an AI-Based MRV Framework for Fraction-Specific Soil Carbon Accounting

Digital mapping becomes useful for carbon governance only when its outputs are embedded in an MRV framework (Brummitt et al., 2024; Thornbush & Govind, 2025). Baseline assessment must describe the initial condition of the soil carbon pool. Monitoring must show that observed changes are attributable to eligible management actions rather than sampling noise, land-use change, erosion, or short-term organic inputs. Verification must then determine whether the change exceeds measurement and model uncertainty. For POC/MAOC accounting, AI-based MRV therefore has to answer three linked questions: where carbon changed, which fraction changed, and whether the change is large enough and traceable enough to support a credible claim (X. Dong et al., 2026; Dynarski et al., 2020; Kellner et al., 2025; Thornbush & Govind, 2025). Existing soil carbon MRV guidance already shows that creditable soil carbon depends on more than a measured stock increase. The World Bank SOC MRV Sourcebook (World Bank, 2021) emphasizes baselines, sampling design, monitoring intervals, uncertainty treatment, and conservative reporting for agricultural landscapes. Verra's VT0014 tool (Verra, 2025) indicates that DSM, geospatial data, model calibration, validation, and uncertainty assessment can be formalized within organic carbon stock estimation. Operational MRV evidence from agricultural soil carbon crediting also shows that scalable issuance requires farmer data intake, data-quality checks, hybrid soil sampling, modeling, uncertainty deduction, leakage treatment, and third-party verification (Brummitt et al., 2024). These examples do not constitute a Chinese POC/MAOC methodology, but they demonstrate that model-assisted soil carbon accounting can be institutionally organized when it remains conservative and auditable.

A SOC fraction-specific AI-MRV system should produce four types of outputs. The first is a baseline product: SOC, POC, MAOC, bulk density, equivalent soil mass or depth correction, management history, and sampling depth at project initiation. The second is a dynamic monitoring product: repeated estimates of POC stock, MAOC stock, MAOC/SOC ratio, and their spatial changes. The third is an attribution product: a documented connection between fraction changes and management records, such as straw return, cover crops, reduced tillage, manure application, grassland restoration, water management, or residue removal. The fourth is a verification product: a conservative accounting boundary that combines resampling, model extrapolation, uncertainty propagation, and third-party audit. Uncertainty should be treated as an entry condition for crediting,

not merely as a final deduction (Z. Lin et al., 2024a; L. Zhang et al., 2025). In POC/MAOC accounting, uncertainty arises from at least three sources: whether laboratory fractionation methods are comparable across time and regions, whether DSM models are valid for the target soil and management context, and whether management information is traceable within the monitoring period. Conventional accuracy metrics such as R^2, RMSE, and cross-validation summarize average predictive performance (Z. Lin et al., 2024a; W. Zhang et al., 2022), but they do not prove that a specific project boundary contains a verifiable carbon increment. Credit-oriented fraction mapping should therefore report independent validation, soil-type-specific error, management-specific error, spatial extrapolation limits, model versions, covariate time windows, and uncertainty-propagation methods. Repeated monitoring also requires careful treatment of physical soil change. Bulk-density shifts, soil compaction, unequal sampling depth, equivalent soil mass correction, erosion and deposition, and resampling-location error can all create apparent SOC or fraction changes (L. Chen et al., 2015; Z. Chen et al., 2023; Deumlich et al., 2018; H. Li et al., 2022a). These problems are especially important for POC because surface residues and recent organic inputs can change rapidly after management intervention (Bayer et al., 2006; Cotrufo et al., 2019, 2022). They are also important for MAOC because small apparent gains may be statistically indistinguishable from measurement and model uncertainty (Z. Lin et al., 2024a). For crediting, changes below uncertainty thresholds should be treated as early monitoring signals or soil-health indicators rather than immediately tradable removals.

Attribution requires a counterfactual as well as repeated measurements. A model's association between management covariates and carbon cannot by itself establish additionality. Pilots should compare project changes against a justified baseline trajectory and document uncertainty in both, alongside CH_4, N_2O, and material off-site effects (Brummitt et al., 2024; World Bank, 2021). Where net benefit is not distinguishable from uncertainty, the defensible outcome is continued monitoring or a non-offset performance payment, not automatic issuance after a nominal discount. Fraction gains must also reconcile with total SOC change: an internal transfer from POC to MAOC is not an additional atmospheric removal.

The practical design implication is that AI reduces neither the need for sampling nor the need for verification. It changes where sampling should be concentrated. Benchmark plots, regional calibration samples, independent validation sites, and risk-based resampling can constrain the model where the accounting risk is highest. AI supplies spatial continuity; laboratory fractionation supplies mechanistic anchoring; spectroscopy supplies throughput; and third-party verification supplies institutional credibility. In this form, AI-based MRV can convert soil fraction science into an accounting infrastructure while avoiding the weaker claim that models alone can create carbon assets.

4.3. Persistence Evidence and Limits to Permanence-Weighted Standards

The institutional value of fraction-specific MRV lies in its ability to introduce a stability dimension into soil carbon crediting. POC and MAOC differ in turnover, management responsiveness, and reversal risk. Zhou et al. (2024) estimated global MAOC and POC stocks of approximately 975 Pg C and 330 Pg C in the top meter, with mean turnover times of about 129 years and 23 years, respectively. These values should not be converted mechanically into legal permanence periods, because actual reversal risk depends on land use (Beillouin et al., 2022; Cheng et al., 2024; H. Li et al., 2015; Zhao et al., 2025), tillage (Bayer et al., 2006; H. Chen et al., 2009; S. Chen et al., 2026; Guo et al., 2020), erosion (Deumlich et al., 2018; Jakab et al., 2014; H. Li et al., 2022a), drying-wetting cycles (Kholodov, 2013; Najera et al., 2020), warming (Y. Chen et al., 2023; Z. Chen et al., 2024; Hou et al., 2023), and project governance (Baskaran & Byun, 2025; H. Duan et al., 2021; Sun et al., 2022; Zou et al., 2024). They nevertheless show why treating all SOC increments as homogeneous tonnes can obscure important differences in climate value.

Management evidence points in the same direction. Prairie et al. (2023) found that regenerative agricultural practices increased SOC, POC, and MAOC, with POC often responding more strongly to no-till and cropping-system intensification than MAOC. This pattern supports a balanced interpretation. POC should not be dismissed as low-quality carbon because it reflects recent carbon inputs, residue retention, root turnover, aggregate formation, and soil-health improvement. However, POC-dominated gains are more dependent on continued management and more exposed to disturbance. MAOC-dominated gains can provide stronger evidence for longer-term stabilization, but mineral-associated organic matter is heterogeneous and can include fast-cycling components (Jilling et al., 2025). Matus (2026) further cautions that mineral-associated carbon persistence arises from dynamic steady-state processes rather than from a universal fixed saturation threshold. Credit standards should therefore use fraction identity as a risk signal, not as a rigid permanence guarantee.

A conservative standard could classify soil carbon gains along a permanence-weighted gradient (Figure 3). Repeatedly observed MAOC stock gains may contribute evidence of persistence

when mineral context, equivalent-soil-mass accounting, net greenhouse-gas benefit, and uncertainty are jointly considered. POC gains may document useful management outcomes and potential longer-term storage, but require attention to disturbance and management continuity. Both fractions remain subject to reversal. Evidence-insufficient gains should not become tradable removals merely by applying a larger discount. The reviewed studies do not calibrate numerical permanence weights, buffer percentages, crediting periods, or financial premiums; these would require longitudinal validation and an authorized methodology. This classification should not be based on POC/MAOC ratios alone. Credit quality also depends on mineral capacity, management durability, depth distribution, hydrological setting, and disturbance exposure. Georgiou et al. (2022, 2025) and Pellegrini et al. (2026) show that storage potential, saturation concepts, management regime, and vulnerability to carbon loss must be evaluated together. For Chinese farmland, the same MAOC increase should not automatically receive the same credit quality in black soils, red soils, paddy soils, calcareous soils, and eolian sandy soils. Mineral protection, water constraints, erosion risk, management reversibility, and feasible monitoring intensity differ across these contexts. Standards should therefore write regional and soil-type stratification into methodology design rather than relying on one national SOC conversion coefficient.

Two disagreements limit a simple stability hierarchy. First, mineral capacity analyses identify apparent saturation deficits, whereas Begill et al. (2023) did not detect a universal upper limit in temperate agricultural soils; Six et al. (2024) emphasize that testing saturation depends on fractionation, units, mineralogy, and study design. Second, global mean turnover differences co-exist with fast-cycling MAOM and context-dependent destabilization (Jilling et al., 2025; Zhou et al., 2024). These findings support using fractions to formulate risk hypotheses, not assigning a project-level residence time from a global mean. Similarly, Prairie et al. (2023) found positive topsoil concentration responses without significant pooled subsoil responses, while X. Wang et al. (2023) reported depth-dependent SOC-stock responses to deep tillage. The outcomes differ in treatment, depth, and metric, so neither establishes a universally preferable practice. Long-term fraction gains, production effects, and net greenhouse-gas outcomes must be evaluated together.

Digital MRV provides the operational basis for this tiered approach (Brummitt et al., 2024; Thornbush & Govind, 2025; Tschakert et al., 2008; World Bank, 2021). Benchmark sampling and standardized fractionation define the measured fractions. Spectral prediction expands measurement throughput. DSM provides spatial layers of POC, MAOC, uncertainty, and potential. Versioned models and independent validation provide audit trails. Third-party verification converts these layers into conservative accounting parameters. Each credit unit should be traceable to project boundaries, sampling depths, fractionation methods, model versions, uncertainty deductions, resampling intervals, and reversal-response rules. Without these records, SOC fraction terminology would add scientific vocabulary but not institutional integrity.

4.4. Institutional Feasibility, Regional Pilots, and Remaining Gaps

In the Chinese context, fraction-sensitive soil carbon standards should begin with regional pilots rather than with a single national conversion factor. China spans large differences in soil type, climate, land use, farming systems, and management capacity (Cao et al., 2025; H. Li et al., 2022b; Z. Lin et al., 2024a; Tan et al., 2024; Wadoux et al., 2020). POC and MAOC responses to the same practice will not necessarily have the same magnitude or direction across regions. A premature national POC or MAOC coefficient would risk reducing scientific credibility. A more robust pathway is to standardize fractionation protocols, sample archiving, model-version registration, validation rules, uncertainty reporting, and third-party verification, and then gradually develop soil-type-specific, practice-specific, and credit-duration-specific technical rules (F. Liu et al., 2022; Lugato et al., 2021; Shi et al., 2026).

Pilot priorities should differ by region. In the Northeast black soil region and intensively cultivated North China, conservation tillage, straw return, cover crops, and deep-rooted crops should be evaluated for their ability to rebuild rapidly responsive POC while gradually increasing MAOC under suitable texture and moisture conditions (B. Huang et al., 2025; H. Li et al., 2022a; G. Ren et al., 2023; G. Yu et al., 2006). In southern red and yellow soils, standards should consider Fe/Al oxide protection, acidification, high-temperature and high-moisture acceleration of POC turnover, and the possibility that management changes also affect N_2O emissions (Q. Chen et al., 2025; Coward et al., 2017; Fang et al., 2021; Y. Li et al., 2025). In the Qinghai-Tibet Plateau, grasslands, and semi-arid irrigated regions, credit assessment should incorporate hydrothermal limitation, vegetation input, grazing intensity, salinization, irrigation management, and vegetation dynamics under climate and human disturbance (Q. Chen et al., 2019; Coonan et al., 2020; L. Dong et al., 2015; K. Huang et al., 2016; Peng et al., 2026; Shen et al., 2018). These regional examples should be read as pilot-design priorities, not as fixed national rules.

Implementation requires decisions that fraction science cannot resolve alone. For participating farms, project contracts would need to specify access for resampling, the duration of management

commitments, data use, benefit sharing, and responsibility after land-management changes. Aggregation through an eligible cooperative or service organization could spread sampling and verification costs, but would also require clear allocation of monitoring duties and reversal liability. Existing soil-carbon MRV experience supports examining these operational issues (Brummitt et al., 2024; World Bank, 2021); it does not establish the commercial viability of such arrangements in China. Pilots should report measurement and verification costs per hectare and per conservatively estimated tonne, alongside farmer participation, yield, water use, and management continuity.

A staged pathway follows from these constraints. Research pilots can first test fraction measurement, net greenhouse-gas accounting, and production safeguards without issuing offsets. Where performance and costs are acceptable, an eligible project proponent could prepare and seek evaluation of a methodology with defined baselines, additionality tests, uncertainty treatment, monitoring, and reversal obligations. Formal crediting would remain conditional on the applicable regulatory and registration requirements. Green lending and ecological compensation would require their own contracts and safeguards; the same removal must not be sold or claimed twice across programs. No national permanence coefficient, fixed price premium, or immediate scaling claim is supported by this review. Failure to demonstrate additional net benefit, sustained crop production, or affordable verification should prevent progression to crediting rather than be treated as a minor implementation detail.

5. Summary and Perspectives

This review shows that the governance value of agricultural soil carbon sequestration in China cannot be determined by total SOC or TOC gains alone. It should be evaluated through a combined framework of quantity, fraction identity, stability, uncertainty, and verifiability. The broader carbon-neutrality literature shows that China requires coordinated mitigation portfolios, negative-emission options, and market-governance mechanisms (H. Duan et al., 2021; Y. Liu et al., 2025; Z. Liu et al., 2022). Natural climate solution and cropland SOC studies further show that soil carbon can contribute to this transition, but its potential is constrained by biophysical conditions, management attainability, and regional heterogeneity (Bossio et al., 2020; Lu et al., 2022; Y. Wang et al., 2022; Zuo et al., 2023). The central conclusion of this review is therefore not that fraction carbon crediting is already institutionally mature. It is that POC/MAOC fraction supplies the mechanism-based path needed to move soil carbon sequestration from a general ecological benefit toward a higher-quality negative-emission asset.

From a scientific perspective, POC and MAOC represent different formation pathways, turnover characteristics, and management risks. POC often responds rapidly to straw return, conservation tillage, and land restoration, and it supports soil structure, nutrient cycling, and short-term SOC growth. Its disturbance sensitivity means that negative emission accounting should apply more frequent monitoring and more conservative risk treatment. MAOC is more closely associated with clay, silt, Fe/Al oxides, calcium interactions, and microbial necromass stabilization. It usually has stronger mineral protection and longer mean turnover, but recent work also shows that mineral-associated carbon is neither static nor risk-free (Cotrufo & Lavallee, 2022; Jilling et al., 2025; Lavallee et al., 2020; Matus, 2026; Zhou et al., 2024). This review therefore rejects the simple framing of POC as low-value carbon and MAOC as permanent carbon. The two fractions are better used as a coupled diagnostic framework for management design and risk classification.

For China, SOC fraction-informed soil carbon governance must also be regionalized. POC/MAOC map shows that the two fractions have different spatial patterns and dominant drivers, with POC more sensitive to climate and vegetation processes and MAOC more constrained by soil properties such as clay content (Lugato et al., 2021; S. Zhang et al., 2024). Mineral capacity, Fe/Al oxides, exchangeable Ca, pH, water availability, and fine-particle retention jointly shape MAOC formation opportunities and the interpretation of saturation deficits across soil regions (Georgiou et al., 2022, 2025; S. Ren et al., 2024; Rowley et al., 2018; Six et al., 2024). Management practices also cannot be evaluated by SOC gains alone. Straw return, tillage systems, manure-fertilizer combinations, and land restoration affect POC, MAOC, soil-depth distribution, and net greenhouse-gas effects in different ways (B.-J. Lin et al., 2023, 2024; Z. Lin et al., 2024a; Su et al., 2020; Zhao et al., 2025). Future farmland sequestration policy should therefore shift from asking whether a practice has been implemented to asking which fraction of new carbon enters, at which depth it is stored, and what reversal risk it faces.

Institutional feasibility remains conditional. Fraction indicators could strengthen baseline stratification, monitoring, and reversal-risk assessment, but evidence on ETS effects or green-finance outcomes does not establish farmland credit eligibility or lending terms. The next defensible step is regional pilot evaluation of additional net greenhouse gas benefit, production safeguards, monitoring costs, farmer contracts, and liability, followed where justified by methodology evaluation and the required registration and verification processes. Ecological compensation and soil-health payments can support management outcomes, provided they are not presented as unverified

offset removals. Digital technologies can provide the operational infrastructure for this transition, but they must remain evidence-constrained. S. Zhang et al. (2024) showed that POC and MAOC can be mapped at the China scale. F. Liu et al. (2022) and Xue et al. (2025) further show that high-resolution national soil grids and cropland SOC maps can be built from soil observations, environmental covariates, and machine learning. S. Ding et al. (2026) showed that infrared spectroscopy combined with machine learning can improve the throughput of fraction prediction, while Kellner et al. (2025), the World Bank (2021), and operational MRV studies (Brummitt et al., 2024; Thornbush & Govind, 2025) show that model-assisted soil carbon accounting requires calibration, validation, uncertainty treatment, and third-party verification. Digital soil mapping, spectroscopy, and AI models should therefore operate as part of an evidence chain that includes benchmark sampling, standardized fractionation, model validation, uncertainty deduction, and periodic verification.

Future work should first harmonize fraction measurements and test stock changes across major Chinese soil, depth, and management contexts. It should then evaluate these changes together with CH_4, N_2O, crop production, water use, and verification costs, particularly in paddy systems. Only pilots that demonstrate additional net benefit and workable responsibilities should progress toward methodology development. This review provides a critical synthesis and a source-reported effect table, not a newly pooled meta-analysis, validated zoning scheme, or tested financial standard. Its central implication is that fraction information improves diagnosis, while credible agricultural removals still depend on the joint evidence for quantity, persistence, net greenhouse gas balance, food production compatibility, and verifiability.

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Abbreviations

The following abbreviations are used in this manuscript:

SOC	soil organic carbon
TOC	total organic carbon
POC	particulate organic carbon
MAOC	mineral-associated organic carbon
CCER	China Certified Emission Reduction
POM	particulate organic matter
MAOM	mineral-associated organic matter
MRV	measurable, reportable, verifiable
ETS	emissions trading system
CDM	clean development mechanism
AI	artificial intelligence
UAVs	unmanned aerial vehicle system
CO_2	carbon dioxide
N_2O	nitrous oxide

CH_4 methane

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