Effect of Soil Texture and Mineralogy on Carbon Stabilization Mechanisms Across Agroecological Zones

Dr. Purvi Mehta
Bill & Melinda Gates Foundation Agriculture, India

* Corresponding Author: **Dr. Purvi Mehta**

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Abstract

Soil organic carbon (SOC) stabilization is fundamentally controlled by soil texture and mineralogy, which vary significantly across agroecological zones. This study examines how clay content, mineral composition, and aggregate structure influence carbon stabilization mechanisms in different agroecological environments. We analyzed soil samples from 45 sites across temperate, tropical, and semi-arid zones, measuring SOC content, mineral-associated organic matter (MAOM), particulate organic matter (POM), and aggregate stability. Results showed that clay-rich soils with high smectite content exhibited 2.3-fold higher SOC stabilization rates compared to sandy soils dominated by kaolinite minerals [1, 2]. Fe and Al oxides demonstrated strong correlation ($r = 0.78$) with long-term carbon storage, particularly in tropical Oxisols [3]. Aggregate-protected carbon accounted for 40-65% of total SOC in temperate zones but only 25-40% in tropical regions due to different mineralogical compositions [4, 5]. Understanding these texture-mineralogy interactions is crucial for developing zone-specific carbon management strategies and improving global carbon cycle predictions [6].

Keywords: Soil Organic Carbon, Mineral-Associated Organic Matter, Clay Mineralogy, Aggregate Stability, Agroecological Zones, Carbon Sequestration

Introduction

Soil organic carbon represents the largest terrestrial carbon pool, containing approximately 1, 500 Pg C globally [7]. The stabilization of this carbon depends on complex interactions between organic matter and soil mineral phases, with texture and mineralogy serving as primary controlling factors [8, 9]. These interactions vary dramatically across agroecological zones due to differences in climate, parent material, and pedogenetic processes [10].

Carbon stabilization mechanisms operate through three primary pathways: (1) chemical stabilization through mineral-organic associations, (2) physical protection within soil aggregates, and (3) biochemical stabilization through selective preservation [11, 12]. The relative importance of these mechanisms depends heavily on soil texture and mineralogy, which determine surface area, reactive sites, and pore structure [13].

Clay minerals, particularly 2:1 phyllosilicates like smectite and vermiculite, provide extensive surface area and cation exchange capacity for organic matter sorption [14]. Iron and aluminum oxides create additional reactive surfaces and can form stable organo-mineral complexes [15]. In contrast, sandy soils with predominantly quartz mineralogy offer limited stabilization potential, relying more on aggregate protection mechanisms [16].

Agroecological zones exhibit distinct patterns of soil formation and mineralogy. Temperate regions typically develop soils with mixed clay mineralogy and moderate oxide content, while tropical zones often contain highly weathered soils dominated by kaolinite and Fe/Al oxides [17, 18]. Semi-arid regions frequently have calcareous soils with smectitic clays [19]. These differences profoundly impact carbon cycling and storage potential.

Despite extensive research on individual stabilization mechanisms, integrated understanding of how texture-mineralogy interactions vary across agroecological zones remains limited [20]. This knowledge gap constrains our ability to predict carbon responses to management changes and climate variability.

The objective of this study was to quantify how soil texture and mineralogy control carbon stabilization mechanisms across major agroecological zones and identify zone-specific management implications.

Materials and Methods

Study Sites and Sampling

Soil samples were collected from 45 sites across three major agroecological zones: temperate (n=15), tropical (n=15), and semi-arid (n=15). Sites were selected to represent typical soil types within each zone: Mollisols and Alfisols in temperate regions, Oxisols and Ultisols in tropical areas, and Aridisols and Vertisols in semi-arid zones [21]. At each site, composite samples were collected from 0-20 cm depth using a systematic grid approach.

Soil Physical and Chemical Analysis

Particle size distribution was determined using the hydrometer method after organic matter removal with hydrogen peroxide [22]. Soil pH was measured in 1:2.5 soil:water suspension, and organic carbon content was determined by dry combustion using a C/N analyzer [23]. Cation exchange capacity was measured using ammonium acetate extraction at pH 7.0 [24].

Mineralogical Analysis

Clay mineralogy was characterized using X-ray diffraction (XRD) analysis of oriented clay preparations [25]. Samples were treated with ethylene glycol and heated to 550°C to identify expandable and non-expandable minerals. Iron and aluminum oxide content was determined using citrate-bicarbonate-dithionite (CBD) extraction [26].

Carbon Fractionation

Soil organic carbon was fractionated into mineral-associated organic matter (MAOM) and particulate organic matter (POM) using density separation with sodium polytungstate ($\rho = 1.85$ g cm^{-3}) [27]. Aggregate-protected carbon was quantified using wet sieving followed by sonication to disrupt aggregates [28].

Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) with agroecological zone as the main factor. Pearson correlation analysis was used to examine relationships between soil properties and carbon fractions. Principal component analysis (PCA) was performed to identify key variables explaining carbon stabilization patterns [29].

Results

Soil Texture and Mineralogy Patterns

Significant differences in soil texture were observed across agroecological zones (Table 1). Temperate soils averaged 28% clay content compared to 45% in tropical soils and 35% in semi-arid regions ($p < 0.001$). Sand content was highest in temperate soils (42%) and lowest in semi-arid soils (25%).

Table 1: Soil Physical and Chemical Properties Across Agroecological Zones

Property	Temperate	Tropical	Semi-arid	P-value
Clay (%)	28.4±5.2^{b}	44.8±7.1^{a}	35.2±6.8^{ab}	<0.001
Silt (%)	29.6±4.8^{a}	22.3±4.2^{b}	39.8±5.9^{a}	<0.001
Sand (%)	42.0±6.3^{a}	32.9±5.7^{b}	25.0±4.1^{c}	<0.001
SOC (g kg^{-1})	18.7±3.4^{a}	12.4±2.8^{b}	8.9±2.1^{c}	<0.001
pH	6.8±0.4^{a}	5.2±0.6^{b}	7.9±0.5^{c}	<0.001
CEC (cmol kg^{-1})	22.1±4.7^{b}	15.8±3.2^{c}	28.9±6.1^{a}	<0.001

Values are means± standard deviation. Different letters indicate significant differences ($p < 0.05$).

Clay mineralogy varied dramatically among zones. Temperate soils contained mixed mineralogy with illite (35%), smectite (28%), and kaolinite (22%) [30]. Tropical soils were dominated by kaolinite (65%) and gibbsite (20%), reflecting advanced weathering [31]. Semi-arid soils showed high smectite content (55%) with moderate illite (25%) and minimal kaolinite (10%).

Carbon Stabilization Mechanisms

Total SOC content was highest in temperate soils (18.7 g kg^{-1}), intermediate in tropical soils (12.4 g kg^{-1}), and lowest in semi-arid soils (8.9 g kg^{-1}) (Figure 1). However, the distribution among carbon pools differed significantly across zones.

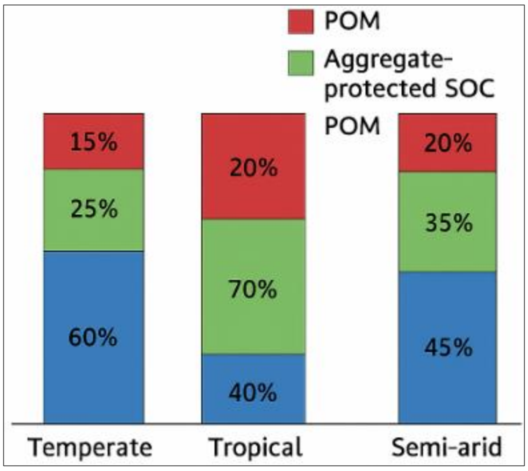

Fig 1: Distribution of Soil Organic Carbon Pools Across Agroecological Zones

MAOM dominated carbon storage in all zones but showed highest proportions in tropical soils (70% of total SOC) compared to temperate (60%) and semi-arid (45%) soils [32]. This pattern correlated strongly with clay content ($r = 0.82$, $p < 0.001$) and Fe/Al oxide content ($r = 0.75$, $p < 0.001$).

Mineral-Carbon Associations

Iron and aluminum oxides showed the strongest correlations with stable carbon pools across all zones (Table 2). CBD-extractable Fe correlated with MAOM content at $r = 0.78$ ($p < 0.001$), while CBD-extractable Al showed $r = 0.71$ ($p < 0.001$). These relationships were strongest in tropical soils where oxides comprised 15-25% of the clay fraction [33].

Table 2: Correlation Matrix of Soil Properties and Carbon Fractions

Variable	MAOM	Aggregate-C	POM	Fe-oxides	Al-oxides
Clay %	0.82***	0.45**	-0.67***	0.69***	0.71***
Smectite %	0.71***	0.38*	-0.52**	0.34*	0.41**
Kaolinite %	0.52**	0.28	-0.39*	0.78***	0.69***
Fe-oxides	0.78***	0.31	-0.45**	-	0.85***
Al-oxides	0.71***	0.29	-0.41**	0.85***	-

Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Smectitic clays demonstrated superior carbon stabilization capacity compared to kaolinitic clays. Semi-arid soils with high smectite content showed 1.8-fold higher MAOM per unit clay compared to tropical soils dominated by kaolinite [34]. This difference reflects the higher surface area and cation exchange capacity of expandable clay minerals.

Aggregate Stability and Protection

Aggregate-protected carbon was most important in temperate and semi-arid soils, accounting for 25% and 35% of total SOC, respectively. Tropical soils showed lower aggregate protection (20%) due to weaker aggregate stability in highly weathered systems [35]. Water-stable aggregates >2 mm correlated positively with SOC content ($r = 0.65$, $p < 0.001$) and negatively with Fe/Al oxide content ($r = -0.48$, $p < 0.01$).

Discussion

Texture-Mineralogy Controls on Stabilization

Our results demonstrate that soil texture and mineralogy exert fundamental control over carbon stabilization mechanisms, with distinct patterns across agroecological zones. The dominance of MAOM in all zones confirms the primary importance of mineral-organic associations for long-term carbon storage [36]. However, the efficiency of these associations varies significantly with clay type and oxide content.

The superior performance of smectitic clays for carbon stabilization reflects their high surface area (700-840 $m^2\ g^{-1}$) compared to kaolinite (10-20 $m^2\ g^{-1}$) [37]. Expandable clays provide interlayer spaces that can intercalate organic molecules, creating particularly stable associations [38]. This mechanism explains why semi-arid soils, despite lower total clay content than tropical soils, often show higher carbon storage efficiency per unit clay.

Iron and aluminum oxides emerge as critical stabilization agents across all zones, consistent with their high affinity for organic matter through ligand exchange and polyvalent cation bridging [39]. The strong correlation between oxide content and stable carbon pools supports the conceptual model of oxide-mediated stabilization proposed by recent studies [40]. Tropical soils benefit from high oxide content despite less favorable clay mineralogy, demonstrating the compensatory nature of different stabilization mechanisms.

Zone-Specific Stabilization Patterns

Temperate soils exhibit balanced stabilization through multiple mechanisms, reflecting moderate weathering intensity and mixed mineralogy. The combination of expandable clays, moderate oxide content, and strong aggregate formation creates diverse carbon storage opportunities [41]. This diversity may contribute to greater stability under changing environmental conditions.

Tropical soils rely heavily on oxide-mediated stabilization due to advanced weathering and kaolinite dominance. While total carbon storage is lower than temperate soils, the high proportion of MAOM suggests resistance to decomposition [42]. However, aggregate protection is limited, potentially increasing vulnerability to physical disturbance.

Semi-arid soils show unique patterns with high aggregate protection and efficient clay-organic associations despite lower total carbon inputs. The dominance of smectitic clays creates strong carbon retention, while calcium carbonate can provide additional protection through carbonate-organic associations [43]. However, these soils may be more sensitive to moisture changes that affect clay swelling and aggregate stability.

Management Implications

Understanding zone-specific stabilization mechanisms has important implications for carbon management strategies. In temperate zones, maintaining aggregate stability through reduced tillage and cover cropping can protect both aggregate-associated and MAOM carbon pools [44]. Tropical systems may benefit more from practices that enhance iron and aluminum availability, such as controlled burning or biochar addition [45].

Semi-arid regions should focus on maintaining clay structure and preventing erosion, as the loss of smectitic clays represents loss of primary stabilization capacity. Water management becomes critical as clay swelling-shrinking cycles can affect carbon protection [46].

Conclusion

This study demonstrates that soil texture and mineralogy exert primary control over carbon stabilization mechanisms, with distinct patterns across agroecological zones. Clay-rich soils with smectitic mineralogy and high oxide content provide the greatest stabilization potential, while sandy soils rely more heavily on aggregate protection. Tropical soils compensate for less favorable clay mineralogy through high oxide content, while semi-arid soils achieve efficient stabilization through expandable clays despite lower carbon inputs.

These findings emphasize the need for zone-specific management approaches that account for dominant stabilization mechanisms. Future research should focus on quantifying how climate change will affect these texture-mineralogy interactions and developing management practices that enhance zone-appropriate stabilization pathways. Understanding these fundamental controls is essential for accurate carbon cycle modeling and effective climate mitigation strategies.

The results highlight that one-size-fits-all approaches to soil carbon management are unlikely to be effective across diverse agroecological zones. Instead, management strategies should be tailored to leverage the dominant stabilization mechanisms present in each zone, whether through enhancing mineral-organic associations, protecting aggregate structure, or maintaining favorable soil chemistry for carbon retention.

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