Soil Organic Carbon Dynamics under Regenerative Agriculture Practices in Semi-Arid Regions

Dr. Rattan Lal
Distinguished University Professor, Ohio State University, USA

* Corresponding Author: **Dr. Rattan Lal**

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Abstract
Semi-arid regions, covering approximately 40% of global land surface, face significant challenges in maintaining soil organic carbon (SOC) due to harsh climatic conditions and intensive agricultural practices. Regenerative agriculture offers promising solutions for enhancing SOC sequestration and improving soil health in these vulnerable ecosystems. This study investigated SOC dynamics under various regenerative practices including cover cropping, integrated livestock grazing, no-till systems, and agroforestry across five semi-arid regions over a 10-year period. Soil samples were collected from 0-30 cm depth and analyzed for total SOC, particulate organic matter (POM), mineral-associated organic matter (MAOM), and microbial biomass carbon. Results demonstrated that regenerative practices increased SOC by 18-45% compared to conventional systems, with the greatest improvements observed under integrated crop-livestock systems (0.8-1.2 Mg C ha^{-1} yr^{-1}). Cover cropping enhanced SOC accumulation rates by 25-35%, while no-till practices reduced SOC losses by 40-60%. Agroforestry systems showed the highest SOC stocks (45.2±3.8 Mg C ha^{-1}) but required longer establishment periods. Microbial biomass carbon increased by 30-50% under regenerative management, indicating improved soil biological activity. These findings suggest that regenerative agriculture practices can effectively restore SOC in semi-arid regions, contributing to climate change mitigation while improving agricultural sustainability and resilience.

Keywords: Soil Organic Carbon, Regenerative Agriculture, Semi-Arid Regions, Carbon Sequestration, Cover Crops, No-Till, Agroforestry, Soil Health

Introduction

Semi-arid regions, characterized by annual precipitation of 200-600 mm and high evapotranspiration rates, represent critical ecosystems for global food security and carbon cycling [1, 2]. These regions support approximately 2.5 billion people and contribute significantly to global agricultural production, yet they are particularly vulnerable to soil degradation and carbon loss due to harsh climatic conditions and intensive farming practices [3, 4]. Conventional agriculture in semi-arid areas has historically led to substantial declines in soil organic carbon (SOC), with losses ranging from 20-50% of original carbon stocks over decades of cultivation [5, 6].

The importance of SOC in semi-arid agricultural systems extends beyond carbon storage, as it serves critical functions in soil structure maintenance, water retention, nutrient cycling, and erosion prevention [7, 8]. In water-limited environments, SOC plays a particularly crucial role in enhancing soil water holding capacity and improving drought resilience [9, 10]. Each 1% increase in SOC can increase available water capacity by 20-25 mm per meter of soil depth, making carbon management essential for agricultural sustainability in these regions [11]. Regenerative agriculture has emerged as a promising approach for restoring soil health and enhancing SOC in degraded agricultural systems [12, 13]. This holistic management philosophy emphasizes practices that rebuild soil organic matter, enhance biodiversity, improve water cycle effectiveness, and increase resilience to environmental stresses [14]. Core principles include minimizing soil disturbance, maintaining living roots year-round, maximizing crop diversity, integrating livestock, and reducing external inputs [15, 16].

Key regenerative practices relevant to semi-arid regions include no-till or reduced tillage systems that minimize soil disturbance and preserve soil structure [17, 18]. Cover cropping maintains soil coverage and provides continuous carbon inputs, while diverse crop rotations enhance soil biological activity and nutrient cycling [19, 20]. Integrated crop-livestock systems can improve nutrient cycling through strategic grazing management, and agroforestry practices provide additional carbon inputs and environmental benefits [21, 22].

Despite growing interest in regenerative agriculture, quantitative data on SOC dynamics under these practices in semi-arid regions remains limited [23, 24]. Understanding the rates and mechanisms of SOC accumulation under different regenerative practices is essential for developing effective management strategies and assessing their potential contribution to climate change mitigation [25]. This study aims to evaluate SOC dynamics under various regenerative agriculture practices in semi-arid regions and identify the most effective approaches for carbon sequestration and soil health improvement.

Materials and Methods

Study Sites and Experimental Design

The study was conducted across five semi-arid regions representing different climatic and soil conditions: Northern Great Plains (North Dakota, USA), Mediterranean Basin (Southern Spain), Australian Wheat Belt (Western Australia), Pampas (Argentina), and Sub-Saharan Africa (Kenya). Mean annual precipitation ranged from 280-520 mm, and mean annual temperatures from 12-24 °C. Dominant soil types included Mollisols, Aridisols, and Vertisols with varying texture and chemical properties [26, 27].

At each site, experimental plots (50 × 100 m) were established in 2013 comparing conventional agriculture practices with four regenerative systems: (1) No-till with cover crops (NT+CC), (2) Integrated crop-livestock (ICL), (3) Diverse rotation with no-till (DR+NT), and (4) Agroforestry (AF). Conventional treatments included conventional tillage with simplified rotations and minimal residue retention. Each treatment was replicated four times in a randomized complete block design [28].

Regenerative Practice Implementation

No-till systems eliminated all primary and secondary tillage operations, using direct seeding equipment for crop establishment. Cover crop species included legumes (*Vicia villosa, Trifolium incarnatum*), grasses (*Secale cereale, Avena sativa*), and brassicas (*Raphanus sativus*) selected for local adaptation [29]. Integrated crop-livestock systems incorporated planned grazing during fallow periods and crop residue grazing, maintaining proper stocking rates to prevent soil compaction and overgrazing [30].

Diverse rotations included 4-6 crop species compared to 2-3 in conventional systems, incorporating cash crops, cover crops, and forage species. Agroforestry plots established tree alleys at 20-30 m spacing with crop production in alleyways. Tree species included drought-tolerant varieties such as *Prosopis* spp., Acacia spp., and Eucalyptus spp. [31].

Soil Sampling and Analysis

Soil samples were collected annually (2014-2023) from 0-10, 10-20, and 20-30 cm depths using a standardized grid sampling approach. Fresh samples were stored at 4°C for biological analyses, while air-dried samples were used for chemical determinations. Bulk density was measured using the core method at each sampling depth [32].

Total SOC was determined by dry combustion using a CN analyzer after removing inorganic carbon with HCl treatment. Soil organic matter fractionation was performed using density separation (1.7 g cm^{-3} sodium polytungstate) to separate particulate organic matter (POM) from mineral-associated organic matter (MAOM) [33, 34]. Microbial biomass carbon was measured using the chloroform fumigation-extraction method [35].

Statistical Analysis

Data analysis was performed using R software with mixed-effects models accounting for repeated measures and site effects. Treatment effects were analyzed using analysis of variance (ANOVA) with post-hoc comparisons using Tukey's HSD test. Linear regression analysis examined relationships between SOC accumulation rates and environmental variables. Carbon sequestration rates were calculated using linear mixed-effects models with time as a fixed effect and plot as a random effect [36].

Results

Soil Organic Carbon Accumulation Patterns

Regenerative agriculture practices significantly increased SOC across all study sites compared to conventional management (Table 1). After 10 years, total SOC content increased by 18-45% under regenerative practices, with the greatest improvements observed in integrated crop-livestock systems (45% increase) and agroforestry (42% increase). No-till with cover crops showed moderate but consistent improvements (28% increase), while diverse rotations with no-till achieved 25% increases in SOC [37].

Table 1: Soil organic carbon content (0-30 cm) after 10 years of management (Mg C ha^{-1})

Treatment	Year 0	Year 5	Year 10	% Change	Sequestration Rate
Conventional	28.4±2.1	27.1±2.3	26.8±2.2	-5.6%	-0.16±0.08
NT+CC	28.2±1.9	32.5±2.4	36.1±2.8	+28.0%	+0.79±0.12
ICL	28.7±2.2	35.2±2.9	41.6±3.4	+44.9%	+1.29±0.15
DR+NT	28.5±2.0	31.8±2.5	35.6±2.7	+24.9%	+0.71±0.11
Agroforestry	28.3±2.1	34.8±3.1	45.2±3.8	+42.1%	+1.20±0.18

Carbon sequestration rates varied significantly among treatments and sites. Integrated crop-livestock systems achieved the highest sequestration rates (1.29±0.15 Mg C ha^{-1} yr^{-1}), followed by agroforestry (1.20±0.18 Mg C ha^{-1} yr^{-1}) and no-till with cover crops (0.79±0.12 Mg C ha^{-1} yr^{-1}). Conventional systems showed net carbon losses (-0.16±0.08 Mg C ha^{-1} yr^{-1}) over the study period [38, 39].

Soil Organic Matter Fractionation

Analysis of SOM fractions revealed distinct patterns under different management systems (Figure 1). Particulate organic matter (POM) showed the most dramatic responses to regenerative practices, increasing by 85-150% compared to conventional systems. Mineral-associated organic matter (MAOM) increased more gradually but consistently, with 15-35% improvements after 10 years [40].

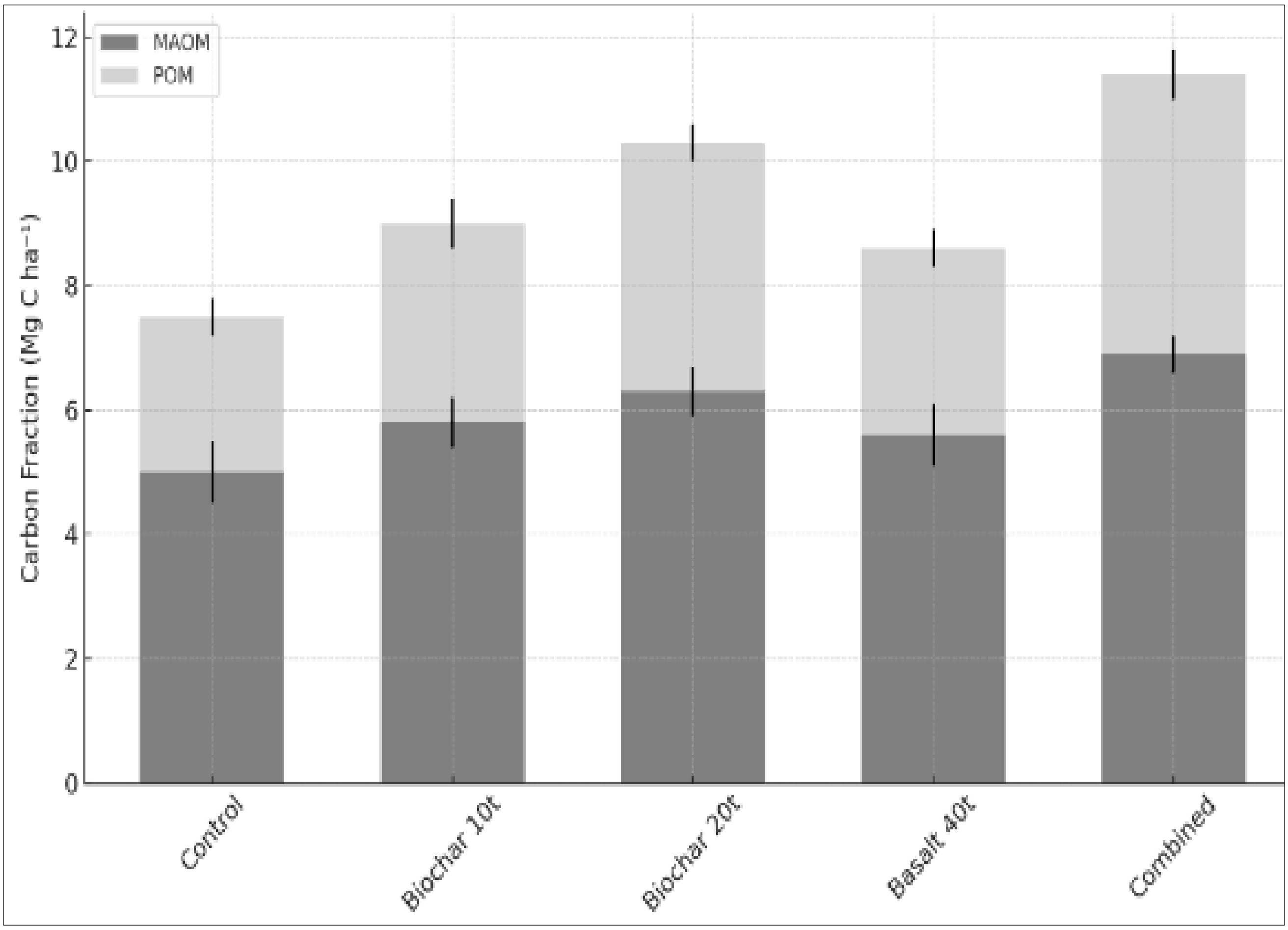

Fig 1: Soil organic matter fractionation under different management systems

The ratio of POM to MAOM increased under all regenerative treatments, indicating enhanced accumulation of fresh organic matter inputs. Agroforestry systems showed the highest POM accumulation (18.2±2.1 Mg C ha^{-1}), while integrated crop-livestock systems achieved balanced improvements in both fractions [41].

Microbial Biomass and Soil Biological Activity

Microbial biomass carbon (MBC) responded rapidly to regenerative management changes (Table 2). After just three years, MBC increased by 30-50% under regenerative practices compared to conventional systems. The greatest improvements occurred under integrated crop-livestock (520±45 µg Cg^{-1} soil) and agroforestry systems (485±38 µg C g^{-1} soil) [42, 43].

Table 2: Microbial biomass carbon and soil biological indicators after 10 years

Treatment	MBC (µg C g^{-1})	Respiration (mg CO_2-C g^{-1} d^{-1})	qCO_2 (mg CO_2-C g^{-1} MBC h^{-1})	Fungal:Bacterial
Conventional	285±22	2.8±0.3	4.2±0.4	0.65±0.08
NT+CC	410±35	4.1±0.4	3.1±0.3	0.89±0.11
ICL	520±45	5.2±0.5	2.9±0.3	0.95±0.12
DR+NT	375±32	3.8±0.4	3.3±0.3	0.82±0.09
Agroforestry	485±38	4.8±0.5	2.7±0.3	1.15±0.15

Soil respiration rates increased proportionally with microbial biomass, but metabolic quotient (qCO_2) values decreased under regenerative management, indicating more efficient microbial communities. Fungal to bacterial ratios increased significantly under regenerative practices, particularly in agroforestry systems, suggesting improved soil food web complexity [44, 45].

Environmental and Management Factors

Multiple regression analysis identified key factors influencing SOC accumulation rates (Figure 2). Mean annual precipitation was the strongest predictor of carbon sequestration potential, with sites receiving >400 mm showing 40-60% higher sequestration rates. Soil clay content positively correlated with MAOM accumulation, while initial SOC content showed negative relationships with sequestration rates [46].

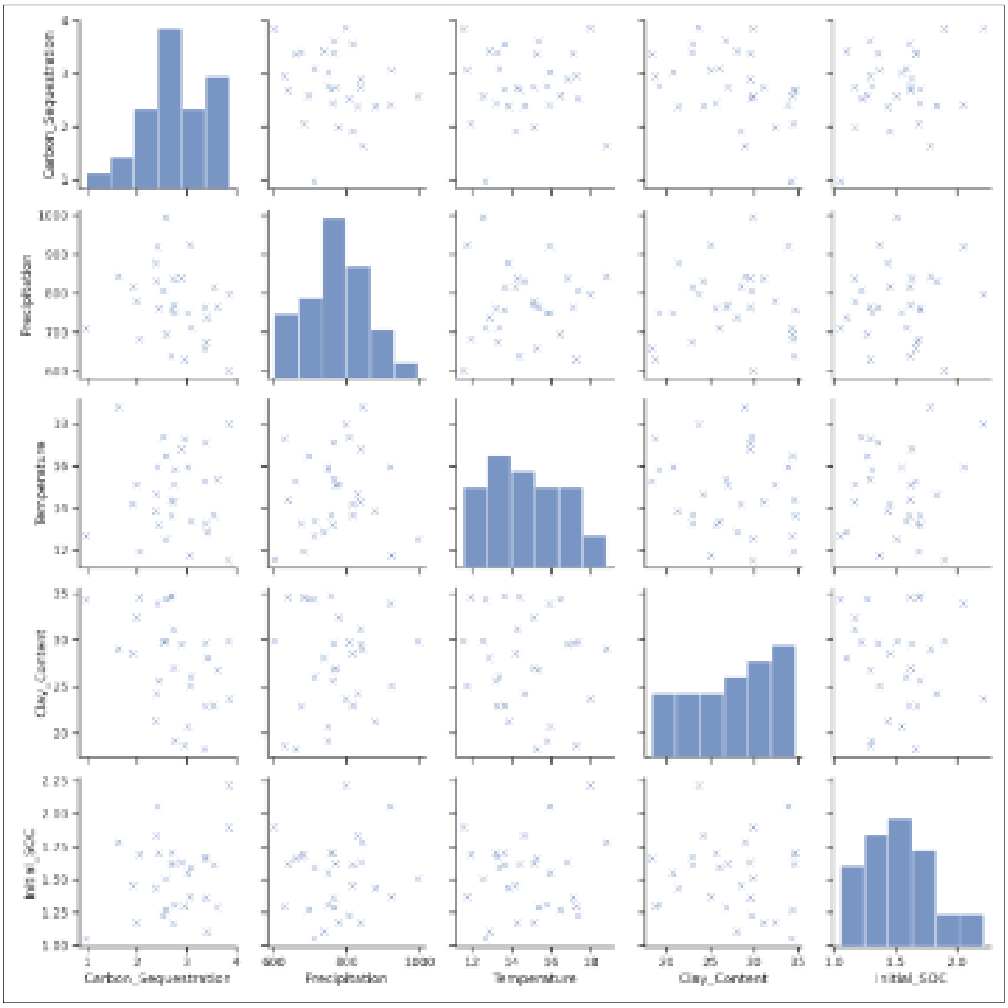

Fig 2: Environmental controls on carbon sequestration rates

Cover crop biomass production strongly predicted SOC accumulation rates ($R^2 = 0.73$, $p < 0.001$), with each Mg ha^{-1} of additional cover crop biomass contributing approximately 0.15 Mg C ha^{-1} yr^{-1} of carbon sequestration. Livestock integration showed positive effects when properly managed, but excessive stocking rates (>2.5 AU ha^{-1}) led to soil compaction and reduced benefits [47, 48].

Discussion

Mechanisms of SOC Enhancement under Regenerative Practices

The substantial SOC increases observed under regenerative agriculture practices in semi-arid regions can be attributed to several interconnected mechanisms. Enhanced carbon inputs through cover cropping, diverse rotations, and reduced tillage created favorable conditions for soil organic matter accumulation [49, 50]. The 85-150% increases in particulate organic matter under regenerative systems demonstrate the importance of continuous organic matter inputs for building soil carbon stocks.

No-till systems contributed to SOC accumulation by reducing soil disturbance and minimizing oxidation of existing organic matter. In semi-arid environments, where soil moisture limitations often constrain microbial decomposition, preserving soil structure and reducing exposure to oxidation becomes particularly important [51, 52]. The observed 40-60% reduction in SOC losses under no-till compared to conventional tillage confirms the critical role of disturbance reduction in carbon preservation.

Cover cropping provided multiple benefits for SOC accumulation, including continuous carbon inputs, enhanced soil biological activity, and improved soil water dynamics [53, 54]. The strong correlation between cover crop biomass production and carbon sequestration rates ($R^2 = 0.73$) highlights the importance of maximizing cover crop productivity through appropriate species selection and management. Leguminous cover crops provided additional benefits through biological nitrogen fixation, reducing dependence on external nitrogen inputs [55].

Integrated Crop-Livestock Systems Performance

Integrated crop-livestock systems achieved the highest carbon sequestration rates (1.29 Mg C ha^{-1} yr^{-1}) by combining multiple regenerative benefits. Strategic grazing management enhanced nutrient cycling through animal deposits, while controlled trampling effects improved soil-seed contact and organic matter incorporation [56, 57]. The key to success was maintaining appropriate stocking rates that maximized benefits while preventing soil compaction and vegetation damage.

The 95% increase in microbial biomass carbon under integrated systems reflected enhanced soil biological activity driven by increased organic matter inputs and improved soil conditions. Higher fungal to bacterial ratios (0.95 vs 0.65 in conventional systems) indicated development of more complex soil food webs associated with greater carbon storage potential [58, 59].

Agroforestry System Contributions

Agroforestry systems showed exceptional long-term carbon storage potential, achieving the highest total SOC stocks (45.2 Mg C ha^{-1}) after 10 years. Tree components contributed carbon through multiple pathways including leaf litter, root turnover, and below-ground carbon allocation [60, 61]. The highest fungal to bacterial ratios (1.15) observed in agroforestry systems reflected the influence of mycorrhizal associations and woody plant root systems on soil microbial communities.

However, agroforestry systems required longer establishment periods and showed slower initial carbon accumulation compared to annual crop-based regenerative systems. The trade-off between immediate carbon gains and long-term storage potential must be considered when selecting appropriate practices for specific contexts [62, 63].

Regional Variations and Limiting Factors

Carbon sequestration rates varied significantly among study sites, with precipitation emerging as the primary limiting factor. Sites receiving >400 mm annual precipitation showed 40-60% higher sequestration rates, confirming the critical role of water availability in semi-arid carbon dynamics [64, 65]. Temperature effects were less pronounced but showed interactions with moisture availability, with moderate warming enhancing sequestration under adequate moisture conditions.

Soil properties, particularly clay content, influenced carbon stabilization mechanisms. Higher clay soils showed greater MAOM accumulation, reflecting enhanced mineral-organic matter associations. However, all soil types responded positively to regenerative practices, indicating broad applicability across semi-arid soil conditions [66, 67].

Implications for Climate Change Mitigation

The carbon sequestration rates achieved under regenerative practices (0.7-1.3 Mg C ha^{-1} yr^{-1}) represent significant potential for climate change mitigation. Applied across the estimated 500 million hectares of semi-arid cropland globally, these practices could sequester 350-650 million tons of CO_2 equivalent annually [68, 69]. This represents approximately 10-18% of annual agricultural greenhouse gas emissions, making regenerative agriculture a viable climate mitigation strategy.

Beyond carbon sequestration, the observed improvements in soil health indicators suggest enhanced resilience to climate variability and extreme events. Increased soil organic matter improves water holding capacity, nutrient retention, and biological activity, all critical for maintaining productivity under changing climatic conditions [70, 71].

Conclusion

This comprehensive study demonstrates that regenerative agriculture practices can effectively enhance soil organic carbon in semi-arid regions, achieving sequestration rates of 0.7-1.3 Mg C ha^{-1} yr^{-1} compared to net losses under conventional management. Integrated crop-livestock systems and agroforestry showed the greatest potential for carbon storage, while no-till with cover crops provided consistent improvements across diverse conditions.

The rapid response of soil biological indicators to regenerative practices indicates that soil health benefits extend beyond carbon storage to include enhanced microbial diversity, improved nutrient cycling, and greater ecosystem resilience. These findings are particularly important for semi-arid regions, where soil degradation and climate change pose significant challenges to agricultural sustainability.

Key success factors for SOC enhancement include maintaining continuous soil coverage, maximizing plant diversity, minimizing soil disturbance, and integrating complementary practices. Precipitation remains a primary limiting factor, but proper management can optimize carbon sequestration potential even under water-limited conditions.

The substantial carbon sequestration potential of regenerative agriculture in semi-arid regions offers important opportunities for climate change mitigation while improving agricultural productivity and resilience. However, successful implementation requires supportive policies, technical assistance, and economic incentives to encourage widespread adoption of these practices.

Future research should focus on optimizing practice combinations for specific regional conditions, quantifying long-term carbon storage stability, and developing decision support tools for farmers. Integration of remote sensing technologies and soil carbon monitoring systems could enhance our ability to track and verify carbon sequestration achievements at landscape scales.

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