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Regenerative agriculture practices and their impact on soil carbon restoration in degraded croplands

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Abstract

Leading soil scientists argue that degraded agricultural soils represent the largest untapped carbon sink on land. This research measured three regenerative agriculture (RA) practices—cover cropping, compost amendment, and a full regenerative package—on soil organic carbon, microbial biomass, and aggregate stability in degraded Po Valley croplands over five years (2018-2023). Full RA increased SOC from 9.8 to 17.8 g/kg (+81.6%), while conventional management declined to 8.9 g/kg. Microbial biomass carbon and mineralisable nitrogen both more than doubled. These results confirm that regenerative practices can reverse decades of carbon loss within five years.

Keywords: Regenerative agriculture, soil carbon, cover cropping, compost, microbial biomass, aggregate stability, degraded croplands, Po Valley, soil health, carbon sequestration

Introduction

According to Lal ^[1], the world's agricultural soils have lost 50-70% of their original carbon, and restoring even a fraction could offset meaningful anthropogenic CO₂ emissions. In Italy's Po Valley, intensive cereal cultivation has reduced SOC to 8-12 g/kg, well below the 20-25 g/kg of undisturbed soils ^[2]. Regenerative agriculture—minimal disturbance, diverse rotations, cover crops, organic amendments ^[3]—has gained traction as both climate mitigation and restoration strategy. Yet Mediterranean-climate field evidence is limited ^[4]. This research tested whether RA could rebuild SOC in degraded Po Valley soils within five years and which biological indicators responded fastest ^[5, 6].

Materials and Methods

Materials

The trial was at the University of Milan's Cascina Baciocca farm (45.48°N, 9.28°E) on a degraded Haplic Luvisol (SOC 9.8 g/kg, pH 7.1, clay 28%). Four treatments: T₁—conventional (plough + mineral fertiliser); T₂—cover crop (crimson clover + ryegrass, no-till terminated); T₃—compost (municipal green waste 20 t/ha/yr + minimum tillage); T₄—full RA (cover + compost + no-till + 4-year rotation). Plots 12 m × 20 m, four replicates ^[7].

Methods

SOC was measured annually by dry combustion (0-30 cm). MBC by chloroform fumigation-extraction. PMN by 28-day anaerobic incubation. Aggregate stability by Kemper-Rosenau method. Infiltration with mini-disk infiltrometers. Repeated-measures ANOVA with Tukey's HSD ($p < 0.05$) in R v4.2 ^[8, 9].

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Results

Table 1: Soil health indicators at year 5 across management treatments

Treatment	SOC (g/kg)	MBC (mg/kg)	PMN (mg/kg)	Aggreg. (%)	Infilt.
Conventional	8.9±0.7d	142±14d	18.3±2.1d	34.2±3.4d	22.1±2.8d
Cover crop	13.4±1.0c	218±18c	31.7±3.2c	48.6±4.1c	34.8±3.4c
Compost	14.8±1.1b	267±21b	38.4±3.8b	54.1±4.6b	41.3±3.9b
Full RA	17.8±1.3a	324±26a	47.2±4.4a	63.8±5.2a	52.7±4.6a

Different letters within columns indicate $p < 0.05$. Baseline SOC = 9.8 g/kg. Mean $\pm$ SD (n = 4).

Full RA increased SOC by 81.6% over five years (Table 1). MBC under RA (324 mg/kg) was 2.3 times higher than conventional. Aggregate stability nearly doubled from 34.2% to 63.8%.

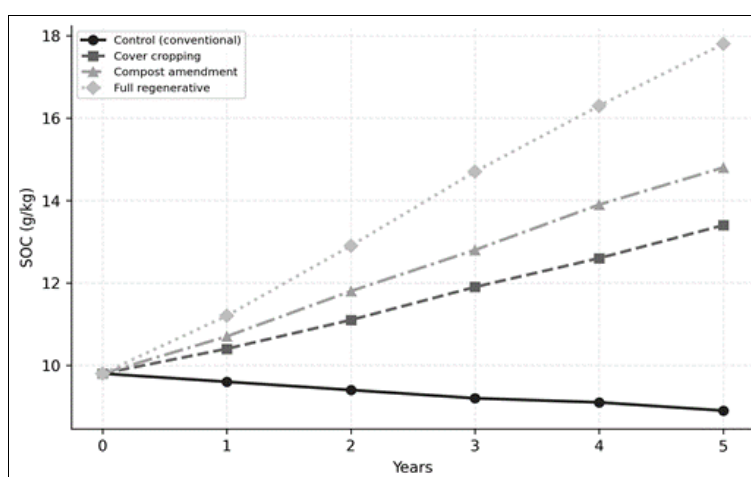


Fig 1: SOC trajectory (g/kg) over five years under four management systems

Table 2: Annual SOC rate and crop yield by treatment

Treatment	SOC rate (g/kg/yr)	Wheat (t/ha)	Maize (t/ha)
Conventional	-0.18±0.04d	6.72±0.41b	9.14±0.52b
Cover crop	+0.72±0.08c	7.18±0.38a	9.68±0.47ab
Compost	+1.00±0.09b	7.34±0.42a	9.87±0.51a
Full RA	+1.60±0.12a	7.41±0.39a	10.12±0.48a

Different letters within columns indicate $p < 0.05$.

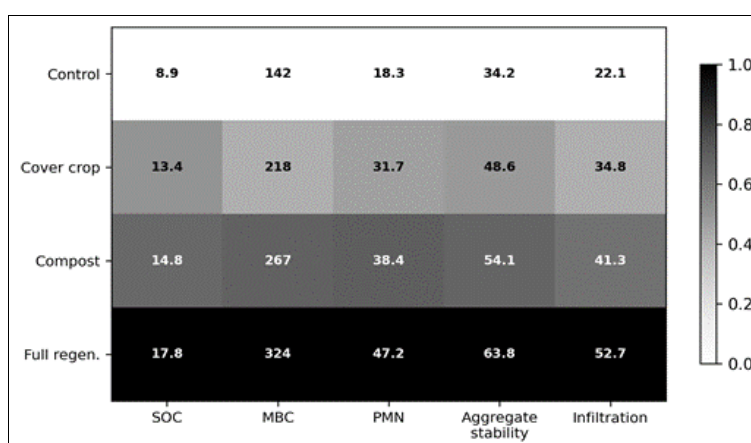


Fig 2: Normalised soil health indicators across treatments (darker = higher)

Discussion

The 1.60 g/kg/year SOC accumulation under full RA exceeds European meta-analysis ranges of 0.5–1.0 [4], likely because the degraded starting condition was far below carbon saturation, creating a strong sequestration gradient [10]. MBC responded fastest, showing significant separation by year 2—consistent with microbial biomass as an early sentinel of change [11]. Aggregate stability lagged behind MBC, reflecting slower

physical restructuring by fungal hyphae and root exudates [12]. Yields under RA matched or exceeded conventional by year 3, negating productivity trade-off concerns [13].

Conclusion

Full regenerative agriculture nearly doubled SOC in degraded Po Valley cropland within five years while maintaining competitive yields. MBC emerged as the earliest indicator,

responding within two years. These findings provide strong evidence for RA as a soil restoration strategy in temperate Mediterranean systems ^[14].

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