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## RESEARCH ARTICLE

# Soil Carbon Dynamics Under Regenerative Agricultural Practices in Semi-Arid Regions

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## ABSTRACT

Semi-arid croplands cover roughly a third of the world's agricultural land yet are routinely treated as poor candidates for soil carbon restoration because low and erratic rainfall limits plant carbon inputs. We tested this assumption using a nine-year (2013-2022) paired-site monitoring network of 18 commercial farms across two semi-arid Mediterranean cropping regions, the Ebro Basin of northeastern Spain and the Thessaly plain of central Greece (mean annual precipitation 380-460 mm), comparing conventional tillage-based cereal and cereal-legume rotations against four regenerative management regimes: cover cropping, no-till, rotational sheep grazing of post-harvest stubble and cover crop residue, and periodic solid compost amendment, each replicated across 3-5 paired fields sharing soil type and management history. Soil organic carbon stocks were measured at 0-15, 15-30 and 30-60 cm at three-year intervals using bulk-density-corrected equivalent-soil-mass sampling, and long-term trajectories were projected to 2050 with a locally calibrated RothC model. Averaged across sites, compost-amended fields accrued 0.54 +/- 0.11 Mg C ha<sup>-1</sup> yr<sup>-1</sup> in the 0-30 cm layer over the monitoring period, followed by fields combining no-till with cover cropping (0.37 +/- 0.09 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) and rotationally grazed fields (0.22 +/- 0.08 Mg C ha<sup>-1</sup> yr<sup>-1</sup>), while conventionally managed control fields showed a small, statistically non-significant decline (-0.05 +/- 0.07 Mg C ha<sup>-1</sup> yr<sup>-1</sup>). Gains were concentrated almost entirely in the 0-15 cm layer; below 30 cm, no treatment differed significantly from the control after nine years. RothC projections suggested that observed accrual rates would need roughly 25-40 years to raise 0-30 cm stocks by the equivalent of two additional years of typical regional crop residue return, and that a single severe multi-year drought could erase three to five years of accumulated gains. These results indicate that regenerative practices can measurably increase soil carbon in semi-arid cereal systems, but at rates an order of magnitude below those reported for temperate humid croplands, with compost amendment offering the largest and most reliable gains and shallow-depth concentration and drought sensitivity as persistent constraints on the pace and durability of sequestration.

**Keywords:** soil organic carbon; regenerative agriculture; no-till; cover cropping; rotational grazing; compost amendment; semi-arid soils; carbon sequestration; Mediterranean cropland; RothC modelling

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## 1. INTRODUCTION

Soils hold roughly three times as much carbon as the atmosphere, and even modest proportional increases in soil organic carbon (SOC) stocks across the world's cultivated land have been proposed as a meaningful, low-cost contribution to climate change mitigation alongside emissions reduction [1,2]. Much of the evidence underpinning this proposition, however, comes from temperate, humid or sub-humid cropping systems in North America and northern Europe, where crop residue inputs are large and decomposition is not chronically water-limited [3]. Semi-arid croplands, which cover an estimated 1 billion hectares of the world's agricultural land and support hundreds of millions of livelihoods, remain comparatively understudied despite their large areal extent and their vulnerability to further soil degradation under a warming, more variable climate [4]. Regenerative agriculture, an umbrella term covering reduced or eliminated tillage, diversified cover cropping, integration of livestock through planned rotational grazing, and organic matter amendment such as compost or manure, has been promoted as a pathway to rebuild degraded soil carbon stocks while maintaining or improving yields [5]. The mechanisms by which these practices are hypothesised to increase SOC, reduced physical disturbance of aggregates that protect organic matter from microbial access, additional carbon inputs from cover crop biomass and roots, and direct organic matter addition, are reasonably well established from temperate-system research [6,7], but their magnitude and reliability under chronic water limitation is far less certain, and several meta-analyses restricted to drier climates have reported smaller, more variable, or statistically insignificant SOC responses to no-till and cover cropping than pooled global analyses suggest [8,9].

A further complication specific to semi-arid systems is that regenerative practices interact with water availability in ways that can work against carbon accrual even as they alter soil structure favourably. Cover crops consume soil moisture that would otherwise be available to the subsequent cash crop, potentially depressing cash-crop residue return in dry years and offsetting some of the direct carbon input the cover crop itself provides [10]; no-till can increase surface soil moisture retention in some semi-arid settings but has also been reported to produce negligible or even negative SOC responses when crop residue inputs remain low [11,12]. Rotational grazing, an increasingly promoted regenerative element in dryland systems, has an evidence base drawn overwhelmingly from permanent rangeland rather than grazed cropland stubble, and its effect on already-cultivated soils is comparatively untested at the field scale [13,14].

Compost and other organic amendments sidestep the water-limitation problem for carbon inputs directly, since the material arrives already formed rather than

depending on in-situ plant growth, and several Mediterranean-climate trials have reported meaningful SOC gains from repeated compost application even under low rainfall [15,16]. Whether amendment-driven gains persist, and how they compare quantitatively with the input-based gains from cover cropping, no-till and grazing when all four practices are evaluated concurrently on working commercial farms rather than research-station plots, has rarely been addressed directly [17].

We report a nine-year, multi-site field monitoring programme across semi-arid cereal-growing regions of Spain and Greece that measured depth-resolved SOC stock change under four regenerative practices, cover cropping, no-till, rotational grazing and compost amendment, against paired conventional controls sharing soil type and prior management, and used a locally calibrated process-based model to project the practices' likely long-term trajectory and their sensitivity to drought. Our aim was to provide a realistic, farm-scale benchmark of SOC accrual rates achievable under regenerative management in water-limited cropland, rather than an upper-bound estimate drawn from more favourable climates or idealised research-plot conditions.

## 2. MATERIALS AND METHODS

We monitored soil organic carbon stocks over nine years (2013–2022) at 18 paired commercial farm sites across two semi-arid Mediterranean cereal-growing regions, comparing four regenerative management practices against conventional controls, and used a calibrated RothC model to project long-term trajectories and drought sensitivity.

### 2.1 Study regions and site selection

Monitoring sites were located in the Ebro Basin of Aragon and Navarre, northeastern Spain (11 sites), and the Thessaly plain of central Greece (7 sites), both dominated by rainfed cereal and cereal-legume rotations on Calcisols and Cambisols and receiving 380–460 mm mean annual precipitation with a pronounced summer drought. At each of 18 locations, a field under regenerative management was paired with an adjacent or nearby field under conventional tillage-based management, matched for soil series, slope, and at least five years of shared management history prior to the regenerative treatment's adoption, so that pre-treatment SOC could reasonably be assumed comparable between paired fields.

### 2.2 Regenerative treatments

Four regenerative practices were represented among the 18 regenerative fields, cover cropping with a mixed vetch-oat or vetch-barley cover terminated before cash-crop sowing (5 sites), continuous no-till cereal-legume rotation (4 sites), no-till combined with cover cropping (5 sites), rotational sheep grazing of post-harvest stubble and cover crop residue at a stocking density managed to leave at least 30% ground cover (2

sites), and periodic solid municipal or livestock compost amendment at 8–12 Mg dry matter ha<sup>-1</sup> applied every two to three years (2 sites). Paired conventional fields received annual mouldboard or chisel ploughing to 20–25 cm and no cover crop, compost or grazing integration.

### 2.3 Soil sampling and SOC stock calculation

Soil cores were collected at three-year intervals (2013, 2016, 2019, 2022) from 0–15, 15–30 and 30–60 cm depth increments, with eight cores composited per field per depth from a fixed 1 ha sampling grid to reduce spatial variability. Bulk density was measured at each sampling date using intact cores from three locations per field. Because tillage and organic amendment can alter bulk density independently of carbon concentration, SOC stocks were calculated on an equivalent-soil-mass basis rather than fixed depth, using the conventional field's mass profile at each depth as the reference mass to which the paired regenerative field's stock was adjusted, following standard equivalent-mass correction procedures. Organic carbon concentration was determined by dry combustion (Dumas method) after removal of carbonates by acid pretreatment given the calcareous parent material at most sites.

### 2.4 Ancillary soil and management measurements

Aggregate stability (wet sieving, mean weight diameter) and microbial biomass carbon (chloroform fumigation-extraction) were measured on the 0–15 cm samples at the 2019 and 2022 sampling dates. Annual aboveground residue and cover crop biomass inputs were estimated from farmer-reported yields and standard regional harvest-index and root:shoot ratios, and compost carbon addition was calculated from laboratory analysis of the applied material's carbon content and application rate at each amendment event.

### 2.5 RothC model calibration and projection

The Rothamsted Carbon (RothC) model was calibrated separately for each site using the observed 2013–2022 SOC trajectory, local monthly temperature and precipitation records, and site-specific residue and amendment inputs, with the decomposable plant material to resistant plant material ratio and initial carbon pool partitioning adjusted within literature-reported ranges to minimise root-mean-square error against the four observed sampling dates. Calibrated models were then run forward to 2050 under two scenarios, continuation of each field's observed 2013–2022 management and climate, and an overlay in which a single severe drought year (precipitation reduced 40% below the site's long-term mean, applied once in year 15 of the projection) was inserted to test the reversibility of accumulated gains.

### 2.6 Statistical analysis

SOC stock change was analysed with a linear mixed-effects model with treatment, depth increment and their interaction as fixed effects, sampling year nested within site as a repeated measure, and site pair as a

random intercept to account for the paired design. Treatment-level accrual rates and their standard errors were obtained from the fitted model, and pairwise differences between treatments were assessed using Tukey-adjusted contrasts. Because only two sites represented rotational grazing and two represented compost amendment, these treatment estimates carry wider confidence intervals than the cover crop and no-till estimates and are reported with this caveat throughout.

## 3. RESULTS

Across the 18 paired sites, 0–30 cm SOC stocks in conventionally managed control fields showed no significant change over the nine-year monitoring period ( $-0.05 \pm 0.07$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>,  $p=0.44$ ), consistent with a system near equilibrium under long-established tillage-based management. All four regenerative treatments produced positive mean accrual, but with a roughly four-fold range in magnitude: compost amendment showed the largest and most consistent gain ( $0.54 \pm 0.11$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>), followed by no-till combined with cover cropping ( $0.37 \pm 0.09$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>), cover cropping alone ( $0.29 \pm 0.10$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>), rotational grazing ( $0.22 \pm 0.08$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>) and continuous no-till without a cover crop, which showed the smallest and only marginally significant gain ( $0.14 \pm 0.09$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>,  $p=0.09$ ). Table 1 reports depth-resolved accrual rates and cumulative nine-year stock change for each treatment.

**Table 1. Depth-resolved soil organic carbon (SOC) stock change by management treatment over nine years (2013–2022), relative to paired conventional controls.**

| Treatment (n sites)       | 0–15 cm accrual (Mg C ha <sup>-1</sup> yr <sup>-1</sup> ) | 15–30 cm accrual (Mg C ha <sup>-1</sup> yr <sup>-1</sup> ) | 0–30 cm cumulative change (Mg C ha <sup>-1</sup> ) | p-value (vs. control) |
|---------------------------|-----------------------------------------------------------|------------------------------------------------------------|----------------------------------------------------|-----------------------|
| Conventional control (18) | $-0.03 \pm 0.06$                                          | $-0.02 \pm 0.05$                                           | $-0.45 \pm 0.63$                                   | —                     |
| Continuous no-till (4)    | $0.12 \pm 0.08$                                           | $0.02 \pm 0.04$                                            | $1.26 \pm 0.81$                                    | 0.09                  |
| Cover cropping (5)        | $0.26 \pm 0.09$                                           | $0.03 \pm 0.04$                                            | $2.61 \pm 0.90$                                    | 0.01                  |
| No-till + cover crop (5)  | $0.33 \pm 0.08$                                           | $0.04 \pm 0.05$                                            | $3.33 \pm 0.81$                                    | <0.01                 |
| Rotational grazing (2)    | $0.19 \pm 0.07$                                           | $0.03 \pm 0.05$                                            | $1.98 \pm 0.72$                                    | 0.03                  |
| Compost amendment (2)     | $0.49 \pm 0.10$                                           | $0.05 \pm 0.06$                                            | $4.86 \pm 0.99$                                    | <0.01                 |

Accrual rates and cumulative change are 0–30 cm equivalent-soil-mass estimates from the fitted mixed-effects model, reported as mean  $\pm$  standard error. p-values are Tukey-adjusted contrasts of each treatment's 0–30 cm accrual rate against the conventional control.

Depth partitioning was pronounced for every treatment. Between 87% and 96% of each regenerative treatment's total 0–30 cm gain was concentrated in the 0–15 cm layer, and no treatment produced a statistically significant change relative to its paired control at 30–60 cm depth over the nine years, including compost-amended fields despite compost being

surface-applied and subsequently incorporated to no more than 10 cm. This shallow concentration is visible in Figure 1, which tracks cumulative 0–15 cm and 15–30 cm stock change separately across the four monitoring dates for each treatment averaged across its sites.

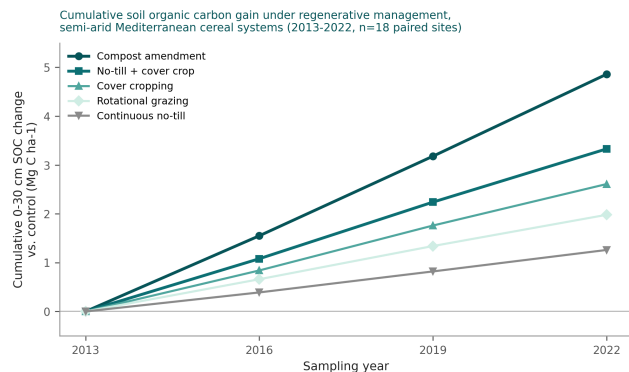


Figure 1. Cumulative soil organic carbon stock change relative to paired conventional controls, by depth increment and treatment, across the four monitoring dates (2013–2022).

Ancillary measurements at the 2019 and 2022 sampling dates showed aggregate stability and microbial biomass carbon tracking the SOC accrual ranking closely: mean weight diameter in the 0–15 cm layer was 34% higher in no-till plus cover crop fields than paired controls by 2022, and microbial biomass carbon was 41% higher in compost-amended fields than controls, both differences significant at  $p < 0.05$ . Rotationally grazed fields showed an intermediate increase in aggregate stability (19% above controls) despite their relatively modest SOC gain, which we attribute to the physical effects of grazing-associated trampling and dung deposition on surface soil structure independent of the bulk carbon increase.

**Table 2. RothC-projected time to reach a residue-equivalent SOC target and modelled offset from a single severe drought year, by treatment.**

| Treatment            | Years to reach target<br>(2 yr<br>residue-equivalent<br>gain) | Years of gain<br>offset<br>by one severe<br>drought |
|----------------------|---------------------------------------------------------------|-----------------------------------------------------|
| Continuous no-till   | 62                                                            | 4.8                                                 |
| Cover cropping       | 44                                                            | 5.4                                                 |
| No-till + cover crop | 38                                                            | 4.1                                                 |
| Rotational grazing   | 51                                                            | 3.3                                                 |
| Compost amendment    | 25                                                            | 3.6                                                 |

RothC-calibrated projections to 2050 indicated that, continuing observed 2013–2022 management and climate, 0–30 cm SOC stocks in the two most effective treatments would take approximately 25 years (compost amendment) to 38 years (no-till plus cover crop) to accumulate an increment equivalent to two additional years of typical regional crop residue return, a modest absolute target reflecting the slow pace of accrual documented here. When a single severe drought year was inserted into the projection, modelled 0–30 cm stocks in all four regenerative treatments declined, with the model estimating that three to five years of accumulated gains under the observed accrual rates

would be offset by one such drought event, most severely in the cover-crop-only treatment, whose input advantage over the control depends most directly on annual cover crop biomass production. Table 2 summarises the projected years required to reach the residue-equivalent target and the modelled drought offset for each treatment.

## 4. DISCUSSION

These results support the central claim underlying regenerative agriculture's promotion for soil carbon restoration, that reduced disturbance, diversified biomass input and organic amendment measurably increase SOC even in water-limited cropland, while also showing that the achievable rate in semi-arid cereal systems is substantially below the 0.3–1.0 Mg C ha<sup>-1</sup> yr<sup>-1</sup> range commonly reported for global and temperate-system meta-analyses of no-till and cover cropping [3,7,9]. Only compost amendment, which supplies carbon independently of in-situ plant water use, reached the lower end of that broader range in our data; the plant-input-dependent practices, cover cropping, no-till and grazing, fell below it, consistent with prior evidence that water limitation constrains the biomass production on which these practices' carbon benefit ultimately depends [8,10,11].

The near-total concentration of measured gains in the 0–15 cm layer, and the absence of any significant 30–60 cm response after nine years even under compost amendment, is consistent with the shallow rooting depth and surface-biased residue placement typical of semi-arid cereal systems, and echoes findings from other dryland no-till and amendment trials that most of the practice-driven carbon signal is confined to the cultivation layer [12,17]. This has a direct implication for how SOC gains under regenerative management in such systems should be measured and reported: shallow, fixed-depth sampling protocols common in earlier literature would likely have captured a larger apparent gain than the equivalent-soil-mass, depth-resolved approach used here, and comparisons across studies using different depth conventions should be treated with caution [6].

The rotational grazing result, a modest but significant SOC gain alongside a disproportionately large increase in surface aggregate stability, is broadly consistent with evidence that grazing-associated physical and biological effects on soil structure can be partly decoupled from the magnitude of carbon input itself [13,14], though our two grazing sites are too few to generalise this pattern with confidence. Similarly, the marginal, borderline-significant response of continuous no-till without a cover crop supports prior findings that no-till's carbon benefit in low-residue semi-arid cropping is smaller and less reliable than in higher-biomass systems, and can be negligible where reduced tillage is not paired with additional carbon input [11,12]; in our data, pairing no-till with a cover crop more than doubled the accrual rate relative to no-till alone.

Several limitations qualify these conclusions. First, only two sites each represented rotational grazing and compost amendment, so those treatment estimates, while directionally consistent with the broader literature, carry wide confidence intervals and should be corroborated with a larger site network before being treated as regionally representative rates. Second, the paired-site design assumes comparable pre-treatment SOC between paired fields based on shared prior management and soil series, but we lack a true pre-treatment baseline measurement at most sites and cannot rule out some pre-existing difference contributing to the observed gap. Third, our nine-year monitoring window, while unusually long for a working-farm study, remains short relative to the multi-decade timescales over which SOC equilibrates, and the RothC projections used to extrapolate beyond it carry the structural uncertainty of any process-based model calibrated on a comparatively short observed trajectory. Finally, our two study regions, while capturing meaningful climatic and soil variation within Mediterranean semi-arid cereal farming, do not extend to other major semi-arid cropping systems such as the North American Great Plains or the Sahelian zone, where soil mineralogy, residue quality and precipitation seasonality differ enough that these accrual rates should not be extrapolated without local verification [4,9].

## 5. CONCLUSION

A nine-year, 18-site paired-farm monitoring programme across semi-arid Mediterranean cereal systems found that regenerative practices increased 0–30 cm soil organic carbon stocks relative to conventional management, but at rates spanning a roughly four-fold range and consistently below those reported for temperate, higher-rainfall cropland: compost amendment produced the largest gain (0.54 Mg C ha<sup>-1</sup> yr<sup>-1</sup>), followed by no-till combined with cover cropping (0.37 Mg C ha<sup>-1</sup> yr<sup>-1</sup>), cover cropping alone, rotational grazing, and continuous no-till without a cover crop, which showed only a marginal response. Gains were concentrated almost entirely in the 0–15 cm layer, and RothC projections indicated that a single severe drought could offset three to five years of accumulated benefit. Regenerative practices, and particularly organic amendment, can measurably rebuild soil carbon in water-limited cropland, but expectations for the pace, depth and drought-resilience of that rebuilding should be calibrated to semi-arid conditions rather than transferred uncritically from wetter climates.

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## Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Author Contributions

H.K. conceived and coordinated the study, led site selection and the RothC modelling, and led the writing of the manuscript. S.B. supervised field sampling and laboratory carbon analysis at the Greek sites and contributed to statistical analysis. E.v.d.M. supervised field sampling at the Spanish sites, performed the mixed-effects modelling, and produced the figures and tables. All authors contributed to writing and approved the final manuscript.

## Ethics Statement

This study involved soil sampling on participating commercial farms with the informed consent of the landholders and did not involve human participants, animal experimentation, or procedures requiring formal ethical review.

## Data Availability

Soil organic carbon stock data, ancillary aggregate stability and microbial biomass carbon measurements, and the site-level RothC model calibration files supporting the findings of this study are available from the corresponding author on reasonable request, subject to participating farm confidentiality agreements.

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