

Soil Carbon Stocks and Radiocarbon Profiles in Three Agricultural Systems of California's Central Valley

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Abstract

Carbon stocks alone do not describe the age composition of soil carbon. We examined how soil carbon stocks and bulk radiocarbon varied with depth among fields with contrasting management histories in California's Central Valley. We compared monoculture and polyculture annual vegetable fields, 20- and 60-year-old peach [*Prunus persica* (L.) Batsch] orchards, and a bare field margin with 10- and 30-year-old hedgerows. We measured root dry mass, cumulative carbon (C) stock, and radiocarbon ($\Delta^{14}\text{C}$) to a target depth of 1 m, with orchard and hedgerow analyses restricted to 75 cm. The polyculture field had a higher observed mean C stock to 100 cm than the monoculture field, but radiocarbon differences between the fields were not supported. The C-stock comparison at 0–75 cm did not detect a difference between orchards. $\Delta^{14}\text{C}$ was higher in the 20-year-old orchard at 20–50 cm. Both hedgerows had higher observed mean C stocks than the bare margin to 20 cm, while radiocarbon differences among the field margins depended on depth. Each management category was represented by one field or field-margin location, so management effects cannot be separated from site differences. Examining C stocks alongside bulk $\Delta^{14}\text{C}$ across soil depths revealed differences among the sampled fields and field margins that overall stock comparisons alone did not capture.

Keywords: soil carbon, radiocarbon, Mediterranean agriculture, hedgerows, orchards, polyculture, land-use legacy

Plain Language Summary

We compared soil carbon in seven California fields and field margins, examining differences in crop diversity, orchard age, and hedgerow age within each system. Mean carbon stock in the top meter of soil was higher in the field growing multiple vegetable crops than in the single-crop field. Mean carbon stock to 20 cm was higher under the hedgerows than in the bare margin. Radiocarbon measurements give clues about carbon age. Radiocarbon differed between the orchards at 20–50 cm. The carbon-stock comparison to 75 cm did not detect a difference between orchards. The younger orchard followed a vineyard that likely received manure, a history that may help explain its carbon pattern. With one location representing each management type, the differences cannot be attributed to management alone. These findings show why soil depth and management history matter when comparing soil carbon.

Abbreviations

DOE, U.S. Department of Energy; IKON, annual monoculture field code; LAHE, annual polyculture field code; LDRD, Laboratory Directed Research and Development; LLNL, Lawrence Livermore National Laboratory; SOC, soil organic carbon; SOM, soil organic matter.

1. Introduction

Soils worldwide contain about 1,500 Pg of organic carbon (C) in the upper meter (Jobbágy & Jackson, 2000), and management can increase or decrease agricultural soil organic carbon (SOC) stocks (Paustian et al., 2016). In 2022, farms covered about 880 million acres in the United States, roughly 39% of the country's land area (U.S. Department of Agriculture, National Agricultural Statistics Service, 2024). Given this extent, even small per-acre changes in soil C can affect national soil C stocks (Pett-Ridge et al., 2023). California's Central Valley includes annual crop fields and perennial orchards within a diverse agricultural landscape (Smith et al., 2024). In California's Mediterranean croplands, changes in surface SOC may not reflect changes across the full soil profile (Tautges et al., 2019).

Plants move C from atmospheric CO₂ into soil through root exudation, root turnover, and litter inputs, but decomposition returns most of that C to the atmosphere as CO₂ (Jackson et al., 2017). A fraction enters soil organic matter (SOM) and cycles on decadal or longer timescales (Trumbore, 2009; Leuthold et al., 2025). Root-derived C can persist longer than shoot-derived C (Rasse et al., 2005), while SOM protected within aggregates or associated with minerals can be less accessible to microbes (Six et al., 2000; Schmidt et al., 2011). In annual systems, tillage and cover cropping can alter C cycling (Paustian et al., 2016; Jian et al., 2020), and residue management changes microbial contributions to SOM (Zhou et al., 2023). Converting annual crops to perennials can increase SOC, but responses vary with prior land use, depth, and time since conversion (Ledo et al., 2020; Siddique et al., 2023). Hedgerows store C in woody and root biomass (Axe et al., 2017) and can contain more SOC than adjacent cropland (Drexler et al., 2021). SOC responses to management vary among settings (Beillouin et al., 2023).

Agricultural management affects SOC by changing plant inputs and how long living plants cover the soil. The chemical makeup of plant residues affects how microbes process them, and microbial products can contribute to persistent SOM (Cotrufo et al., 2013; Kallenbach et al., 2016). In a long-term grassland experiment, greater plant diversity increased rhizosphere C inputs and microbial activity, and these changes were associated with more SOC (Lange et al., 2015). Later work from the same experiment found that the diversity effect extended into the subsoil (Lange et al., 2023). In croplands, cover crops replace bare fallow and generally increase SOC relative to systems without cover crops (Poeplau & Don, 2015).

C stocks describe how much C is present, while bulk $\Delta^{14}\text{C}$ provides information about its age composition. Combining these measurements across soil depths helps interpret differences among fields with contrasting management histories (Trumbore, 2009). Radiocarbon has been used to quantify soil organic matter pool sizes and dynamics in agricultural soils (Paul et al., 1997). Field comparisons have since combined deep C stocks and bulk $\Delta^{14}\text{C}$ to compare land uses or perennial cropping systems (Nagy et al., 2018; Quéro et al., 2022; Slessarev et al., 2020, 2026). Despite these applications, agricultural soils remain underrepresented in the International Soil Radiocarbon Database, while sampling across land uses is concentrated in surface mineral horizons (von Fromm et al., 2026).

We examined how soil C stocks and bulk $\Delta^{14}\text{C}$ varied with depth among fields with contrasting management histories. We selected three long-term farming settings in California's Central Valley for observational, within-system field comparisons: monoculture and polyculture vegetable fields, 20- and 60-year-old peach orchards, and a bare field margin with 10- and 30-year-old hedgerows (Figure 1). For annual vegetables, we expected the polyculture field to retain more SOC than the monoculture field because crop diversification generally increases bulk-soil

C (Li et al., 2024). For the orchards, we expected the 60-year field to hold more C than the 20-year field. For the hedgerows, we expected more soil C under hedgerows than in the bare margin and more under the 30-year than the 10-year hedgerow. Both predictions assume that soil C depends mainly on the duration of peach root and litter inputs in orchards and on cumulative plant C inputs under hedgerows. Within each perennial system, we also examined whether differences in soil C concentration were confined to surface soil or extended into the subsoil. Combining C stocks with bulk $\Delta^{14}\text{C}$ across depths reveals differences among the sampled fields that stock measurements alone do not capture.

2. Methods



Figure 1. Study locations in California's Central Valley for comparisons of soil carbon stocks and bulk-soil radiocarbon with depth. The Annual marker shows the general Fresno County location of the monoculture (IKON) and polyculture (LAHE) vegetable fields on separate farms. Peach denotes the approximately 20- and 60-year-old peach orchard fields at Masumoto Family Farm near Del Rey. Hedgerow denotes the Hardy property near Winters, Yolo County, where a bare field margin and 10- and 30-year-old hedgerows were compared.

2.1. Study sites

The study included three field comparisons, each within a farming system, in California's Central Valley (Figure 1). These comparisons examined how soil C stocks and bulk $\Delta^{14}\text{C}$ varied with depth among fields with contrasting management histories. Here, system refers to the annual vegetable, orchard, or hedgerow comparison, and management refers to the field or field-margin categories compared within each system: monoculture versus polyculture, 20- versus 60-year orchard, and bare margin versus 10- and 30-year hedgerow. The annual comparison included a monoculture field (IKON) and a polyculture field (LAHE) on separate farms in Fresno County, California. Both farms had been under their respective management for more than 30 years. The polyculture field rotated vegetables through the year. The orchard comparison included approximately 20- and 60-year-old peach orchards in separate fields on Masumoto Family Farm in Del Rey, California. The 20-year orchard followed a long-managed vineyard that likely received manure, whereas the 60-year orchard followed cotton (N. Masumoto, personal communication, March 2026). The hedgerow comparison included a bare field margin and 10- and 30-year-old hedgerows at separate field-margin locations on the Hardy property in Winters, California. These management comparisons were observational. Available records do not specify exact distances or soil matching.

Soil survey maps identify Hesperia soils in the approximate IKON and LAHE field areas, Hanford and Pollasky in the mapped orchard blocks, and Brentwood, Yolo, and Tehama across the hedgerow farm area (Soil Survey Staff, n.d.-b). Official series descriptions classify Hanford and Pollasky as Typic Xerorthents, Brentwood as Typic Haploxerepts, Yolo as Mollic Xerofluvents, and Tehama as Typic Haploxeralfs (Soil Survey Staff, n.d.-a). The local Eastern Fresno Area survey classifies the Hesperia components as Calcic Haploxerepts, whereas the official series description lists Xeric Torriorthents (Soil Survey Staff, n.d.-a, n.d.-b). These

descriptions refer to mapped field and farm areas, without assigning soil classes to individual cores.

2.2 Sampling design and soil collection

From each field or field margin, we analyzed three soil cores collected at 0, 50, and 100 m along a transect (Supplementary Figure S1). The 0-m sampling point was at least 10 m from the field edge. Additional cores were collected at 25-m intervals in the annual and orchard fields but were not used in these analyses. Soil cores were collected to a target depth of 1 m using an AMS gas-powered core collection kit. Core-length change during coring was recorded by comparing hole depth with recovered core length. An adjustment factor was calculated as recovered core length divided by hole depth and applied to each intended depth boundary during processing ($\text{cut position} = \text{intended in-situ depth} \times \text{recovered core length} \div \text{hole depth}$). The depth labels therefore represent estimated in-situ positions. Cores were transported to the Lawrence Livermore National Laboratory (LLNL) soil biogeochemistry facility and stored at 20 to 22 °C until processing. Each analyzed core contributed one observation per depth increment. Because sampling reached only 77 cm for two of the three 20-year orchard cores, and the 75 to 100 cm sample from one 60-year orchard core was unavailable for analysis, orchard analyses were restricted to 0 to 75 cm. Two 10-year hedgerow cores ended at 86 and 88 cm, whereas the other seven cores reached 100 cm. Primary hedgerow analyses were limited to 0 to 75 cm to compare the same four depth intervals across all nine cores. Measurements below 75 cm were retained in the Supplementary Data workbook.

2.3 Soil core processing

After collection, cores were extruded and cut into depth increments based on the farming system. Annual vegetable cores were cut into six increments: 0 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 50, and 50 to 100 cm. Orchard and hedgerow cores were cut into five increments: 0 to 10, 10 to

20, 20 to 50, 50 to 75, and 75 to 100 cm. Core segments were labeled and air-dried at room temperature. Gravimetric water content was determined by oven-drying subsamples at 105 °C for 24 hours (Gardner, 1986).

Dried soil was hand-homogenized to preserve aggregates, and visible roots were removed before sieving. Samples were then passed through a stainless-steel 2-mm sieve to separate fine earth from coarse mineral fragments. Aggregates retained on the sieve were broken up with a rubber-tipped pestle and re-sieved until the remaining soil passed. The <2 mm fraction was then inspected under a lighted magnifying lens, and remaining roots were removed with forceps before elemental and isotope analyses.

Roots recovered before sieving and from the <2 mm fraction after sieving were combined by depth increment and placed in preweighed paper envelopes. Envelopes were reweighed on a precision balance after oven drying to determine root dry mass per depth increment. No recovery test was conducted, so loss of fine roots during processing could not be quantified. Root dry mass was converted from g to mg and divided by the estimated in-situ soil volume of each increment to calculate recovered root density (mg cm^{-3} ; Freschet et al., 2021). Interval volume was calculated as $\pi \times (1.905 \text{ cm})^2 \times \text{the actual sampled interval thickness (cm)}$.

2.4 Total C, nitrogen, and bulk density

Approximately 15 g of 2-mm sieved soil per increment was placed in a 50 mL borosilicate jar with three stainless-steel grinding rods and milled on a rotary jar mill for 12 to 16 hours at room temperature. Ground soil was then weighed into tin capsules and analyzed for total C and N by dry combustion on an Elementar vario EL cube elemental analyzer (Langenselbold, Germany) at LLNL.

Bulk density was calculated as the oven-dry-equivalent soil mass in each increment divided by its cylindrical volume [$\pi \times (1.905 \text{ cm})^2 \times \text{actual sampled depth interval}$]. C stock per increment was calculated as C concentration (%) multiplied by bulk density (g cm^{-3}) and the actual sampled depth interval (cm), yielding t C ha^{-1} . Cumulative C stock was calculated as the running sum of the depth increment stocks from the soil surface at 0 cm to the bottom of the depth increment or core. Carbon stocks are presented on a fixed-depth basis, without an equivalent-soil-mass adjustment.

2.5 Radiocarbon

Radiocarbon analyses were conducted at the Center for Accelerator Mass Spectrometry at LLNL. Dried and ground soil was combusted to CO_2 in sealed quartz tubes with CuO and Ag at 900°C . The CO_2 was reduced to graphite on iron powder under H_2 at 570°C . Graphitization was based on Vogel et al. (1984). Accelerator mass spectrometry measurements had an average precision of 3.2‰. Values are reported as $\Delta^{14}\text{C}$ and corrected for isotopic fractionation, decay since 1950, and sampling year (Stuiver & Polach, 1977). $\delta^{13}\text{C}$ was measured separately by elemental analyzer–isotope ratio mass spectrometry (EA-IRMS) at the Center for Stable Isotope Biogeochemistry, University of California, Berkeley.

2.6 Statistical analysis

Models were fit separately for each system and response variable in R 4.6.0 and 4.6.1 (R Core Team, 2026) using glmmTMB (Brooks et al., 2017). Management, depth interval, and their interaction were included as categorical fixed effects. Replicate core was included as a random intercept because depth increments were repeated within cores. C concentration in all systems was modeled with a Gamma distribution and log link. $\Delta^{14}\text{C}$ and bulk density were modeled with Gaussian errors and identity links. Cumulative C stocks were compared with Welch t tests using

one value per core at 0–100 cm in annual fields, 0–75 cm in orchards, and 0–20 and 0–75 cm in hedgerows.

Root density was analyzed using generalized linear mixed models with a Gamma distribution and a log link. Samples with no recovered roots were retained in the analysis. A constant of 0.00017 g was added to every root dry-mass measurement before conversion to mg and division by sampled soil volume. Fixed effects were evaluated with asymptotic Wald χ^2 tests; non-root models used Type III tests (car; Fox & Weisberg, 2019). Non-root estimated marginal means and within-depth contrasts were obtained with emmeans (Lenth & Piaskowski, 2026). Model-based pairwise contrasts were unadjusted. Hedgerow C-stock p values were Holm-adjusted across all six endpoint contrasts. Residual diagnostics used DHARMA (Hartig, 2026); full statistical details accompany the scientific resources.

3. Results

Table 1. Statistical comparisons within each farming system.

A. Root density, C concentration and radiocarbon

Effect	Root density (mg cm ⁻³)	C (%)	Δ ¹⁴ C
Annual vegetables (monoculture vs. polyculture)			
Depth (df = 5)	183.59**** (<0.001)	73.81**** (<0.001)	79.21**** (<0.001)
Management (df = 1)	17.73**** (<0.001)	4.15* (0.042)	1.98 (0.160)
Depth × management (df = 5)	8.57 (0.127)	7.10 (0.213)	1.99 (0.850)
Peach orchards (20-year vs. 60-year)			
Depth (df = 3)	45.69**** (<0.001)	351.30**** (<0.001)	101.12**** (<0.001)
Management (df = 1)	2.48 (0.116)	7.28** (0.007)	9.71** (0.002)
Depth × management (df = 3)	1.48 (0.686)	10.60* (0.014)	10.46* (0.015)
Hedgerows (bare margin, 10-year, 30-year)			
Depth (df = 3)	19.13**** (<0.001)	648.34**** (<0.001)	296.12**** (<0.001)
Management (df = 2)	52.08**** (<0.001)	17.19**** (<0.001)	4.10 (0.129)
Depth × management (df = 6)	23.00**** (<0.001)	67.29**** (<0.001)	24.63**** (<0.001)

Note. Values are Wald χ^2 statistics, with p values in parentheses; degrees of freedom are in the row labels. Symbols: † 0.05 ≤ p < 0.10, * 0.01 ≤ p < 0.05, ** 0.001 ≤ p < 0.01, *** p < 0.001. For roots, the modeled response was 1000 × (root dry mass [g] + 0.00017 g) / sampled soil volume [cm³]. Root management and depth tests compare fitted log-density means with equal weighting across depth intervals and fields, respectively. Hedgerow profiles use 0–75 cm. Within-depth non-stock tests and contrasts are in Supplementary Table S1.

Table 1 continued. B. Cumulative C-stock comparisons at selected depths

Comparison	Observed stock mean $\pm$ SD	Difference [95% CI]	Welch t (df)	p value (Holm for hedgerows)
Annual vegetables, 0–100 cm				
Polyculture – Monoculture	Polyculture: 29.0 $\pm$ 5.6 Monoculture: 20.1 $\pm$ 3.5	8.8 [–2.6, 20.2]	2.33 (3.34)	0.094†
Peach orchards, 0–75 cm				
20 yr – 60 yr	20 yr: 26.4 $\pm$ 3.7 60 yr: 22.5 $\pm$ 5.6	3.9 [–7.6, 15.3]	1.00 (3.45)	0.381
Hedgerows, 0–20 cm				
10 yr – Bare margin	10 yr: 24.9 $\pm$ 3.3 Bare margin: 17.8 $\pm$ 0.3	7.0 [–1.0, 15.1]	3.68 (2.04)	0.386
30 yr – Bare margin	30 yr: 23.6 $\pm$ 3.0 Bare margin: 17.8 $\pm$ 0.3	5.8 [–1.6, 13.2]	3.29 (2.05)	0.393
30 yr – 10 yr	30 yr: 23.6 $\pm$ 3.0 10 yr: 24.9 $\pm$ 3.3	–1.2 [–8.4, 6.0]	–0.48 (3.97)	1.000
Hedgerows, 0–75 cm				
10 yr – Bare margin	10 yr: 56.5 $\pm$ 6.7 Bare margin: 52.0 $\pm$ 6.1	4.5 [–10.1, 19.1]	0.85 (3.96)	1.000
30 yr – Bare margin	30 yr: 50.3 $\pm$ 1.8 Bare margin: 52.0 $\pm$ 6.1	–1.8 [–15.5, 12.0]	–0.48 (2.34)	1.000
30 yr – 10 yr	30 yr: 50.3 $\pm$ 1.8 10 yr: 56.5 $\pm$ 6.7	–6.2 [–21.6, 9.1]	–1.56 (2.28)	0.979

Note. C stocks and differences are in t C ha^{–1}. Values are observed mean $\pm$ SD (n = 3 cores per field or margin). Differences are first group minus second group; confidence intervals are unadjusted 95% Welch intervals. Annual and orchard p values are unadjusted. Hedgerow p values were Holm-adjusted across all six contrasts at 0–20 and 0–75 cm. Symbols follow panel A.

3.1 Annual vegetables (monoculture vs. polyculture)

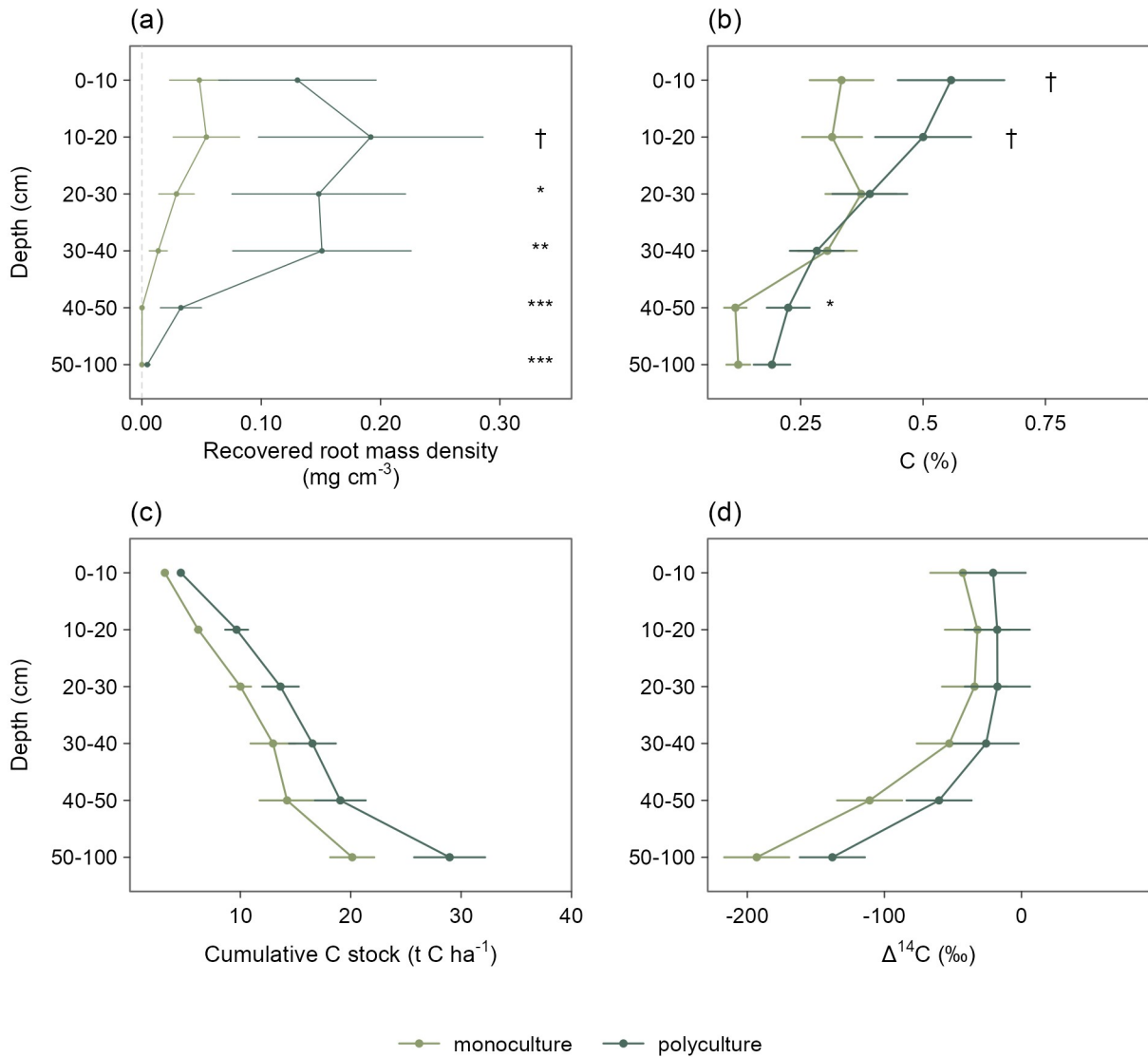


Figure 2. Monoculture (light) and polyculture (dark) annual vegetable fields in Fresno County, California, over 0–100 cm. Panels show (a) recovered root mass density, (b) total C concentration, (c) cumulative C stock, and (d) bulk-soil $\Delta^{14}\text{C}$. Panels (a), (b), and (d) show response-scale estimated marginal means ± 1 SE; panel (c) shows observed means ± 1 SE ($n = 3$ cores per field). The density equivalent of the 0.00017-g addition was subtracted from fitted root means for display. Symbols in (a), (b), and (d) mark unadjusted within-depth comparisons between fields: † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

In the annual vegetable fields, root density was estimated to be higher ($\chi^2 = 17.73$, $p < 0.001$) in the polyculture than monoculture field (Figure 2a). Root density varied with depth ($\chi^2 = 183.59$, $p < 0.001$; Table 1). Within-depth contrasts showed that root density was higher in the polyculture than monoculture field at 20–30, 30–40, 40–50, and 50–100 cm (unadjusted $p = 0.021$, 0.001 , <0.001 , and <0.001 , respectively; Supplementary Table S1). No roots were recovered from any of the three monoculture cores at 40–50 or 50–100 cm. The overall field comparison remained statistically significant across half to double the added mass, while the interaction test and estimated deep-layer ratios were sensitive to the addition.

Averaged across depths, the C concentration was higher in the polyculture than monoculture field ($\chi^2 = 4.15$, $p = 0.042$, Figure 2b). Carbon concentration also declined with depth ($\chi^2 = 73.81$, $p < 0.001$). Within-depth contrasts showed that C concentration was higher under polyculture than monoculture at 0–10 cm ($p = 0.063$), 10–20 cm ($p = 0.093$), and at 40–50 cm ($p = 0.018$).

Observed C stock to 100 cm averaged 29.0 ± 5.6 t C ha⁻¹ in the polyculture field and 20.1 ± 3.5 t C ha⁻¹ in the monoculture field (mean $\pm$ SD; $p = 0.094$; Figure 2c; Table 1B).

Soil $\Delta^{14}\text{C}$ varied with depth ($\chi^2 = 79.21$, $p < 0.001$), while neither management nor interaction terms were significant (Figure 2d). Mean $\Delta^{14}\text{C}$ was consistently higher in the polyculture field at every depth, and the observed core-level ranges did not overlap between fields in the upper three increments, but no unadjusted within-depth contrast reached $p < 0.10$.

3.2 Orchards (20-year vs. 60-year)

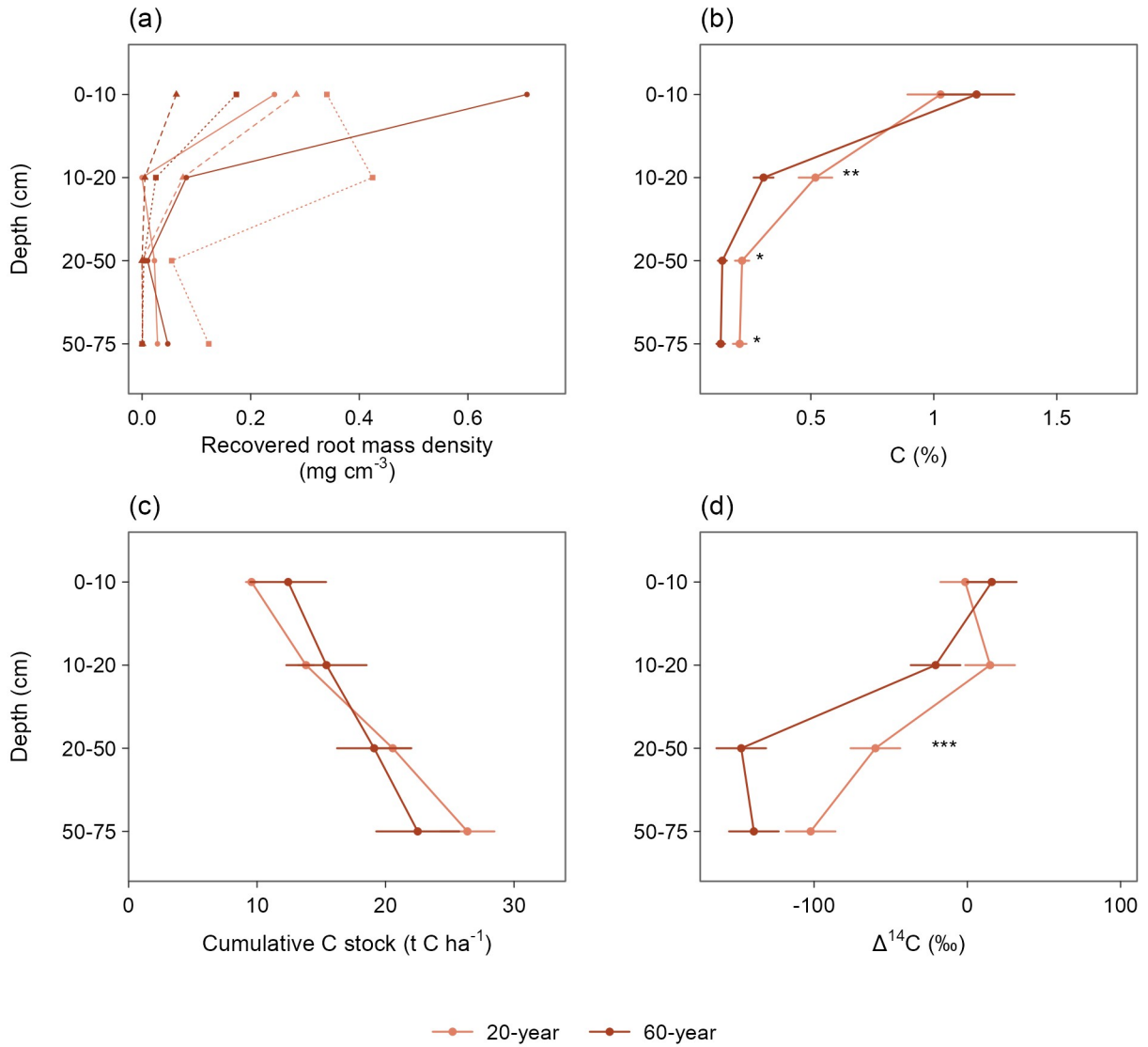


Figure 3. Approximately 20-year (light) and 60-year (dark) peach-orchard fields at Masumoto Family Farm in Del Rey, California, over 0–75 cm. Panels show (a) recovered root mass density, (b) total C concentration, (c) cumulative C stock, and (d) bulk-soil Δ¹⁴C. Panel (a) shows observed core profiles (n = 3 per field); panel (c) shows observed means ±1 SE, and panels (b) and (d) show response-scale estimated marginal means ±1 SE. Symbols in (b) and (d) mark unadjusted within-depth comparisons between fields: † p < 0.10, * p < 0.05, ** p < 0.01, *** p < 0.001.

In the 20- and 60-year-old orchards, root density varied with depth ($\chi^2 = 45.69$, $p < 0.001$), while the management ($\chi^2 = 2.48$, $p = 0.116$) and interaction ($\chi^2 = 1.48$, $p = 0.686$) terms were not statistically significant (Table 1 and Figure 3a). All within-depth 95% confidence intervals for the orchard contrast included 1.

Orchard C concentration had a statistically significant depth by management interaction ($\chi^2 = 10.60$, $p = 0.014$), as well as significant main effects for depth ($\chi^2 = 351.30$, $p < 0.001$) and management ($\chi^2 = 7.28$, $p = 0.007$, Figure 3b). The 20-year field had higher C concentration at 10–20, 20–50, and 50–75 cm (unadjusted $p = 0.005$, 0.015 , and 0.014).

Cumulative C stock to 75 cm averaged 26.4 ± 3.7 t C ha⁻¹ in the 20-year orchard and 22.5 ± 5.6 t C ha⁻¹ in the 60-year orchard (mean $\pm$ SD; $n = 3$ cores per field; Figure 3c). The 0–75 cm stock comparison did not detect a difference between orchards ($p = 0.381$; Table 1B).

Orchard $\Delta^{14}\text{C}$ had a statistically significant depth by management interaction ($\chi^2 = 10.46$, $p = 0.015$), as well as significant main effects for depth ($\chi^2 = 101.12$, $p < 0.001$) and management ($\chi^2 = 9.71$, $p = 0.002$, Figure 3d). At 20–50 cm, $\Delta^{14}\text{C}$ was 88‰ higher in the 20-year field than in the 60-year field (unadjusted $p < 0.001$). Other within-depth contrasts were not statistically significant.

3.3 Hedgerows (bare margin, 10-year, 30-year)

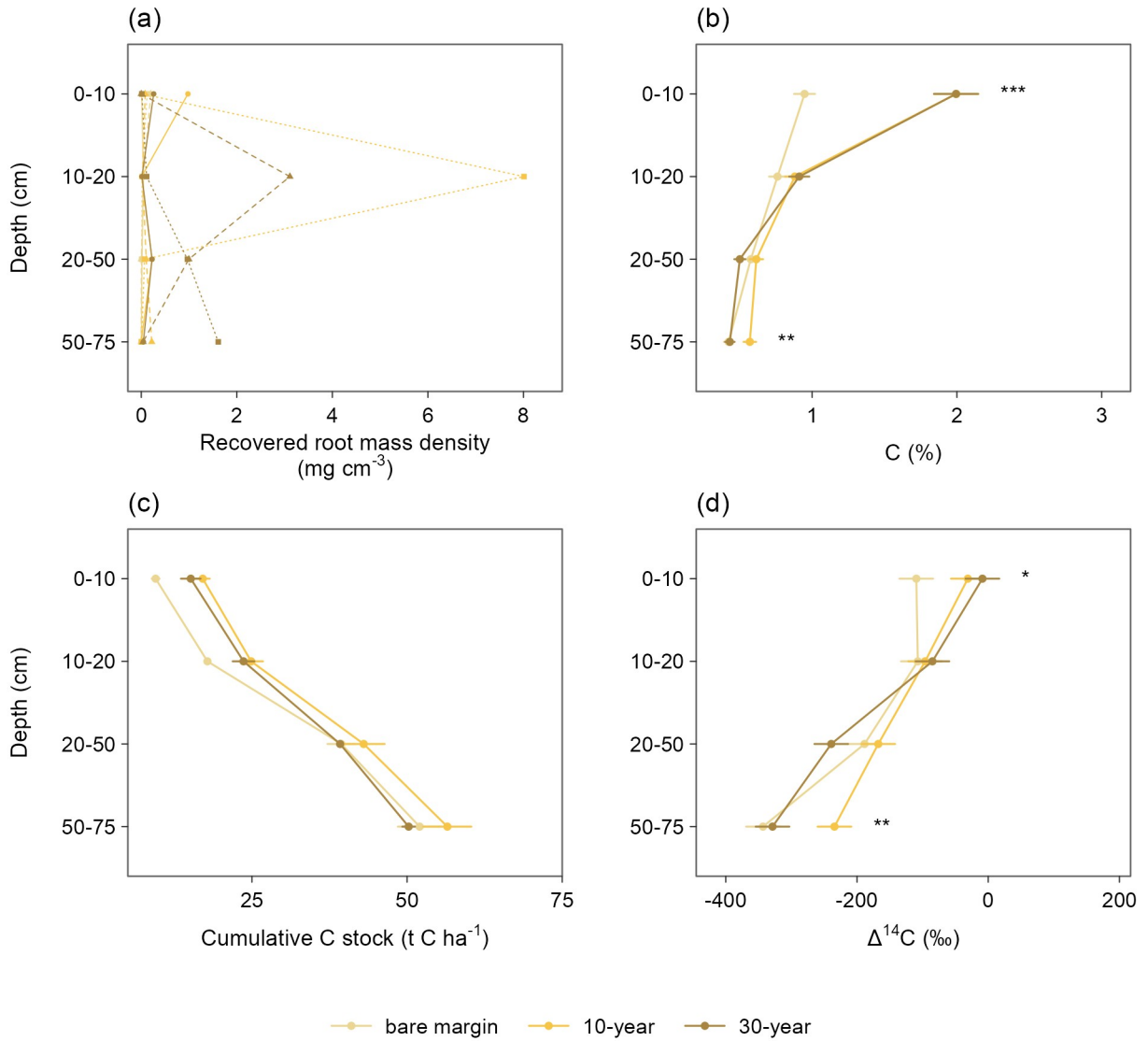


Figure 4. Bare margin (lightest), 10-year hedgerow, and 30-year hedgerow (darkest) at the Hardy property in Winters, California, over 0–75 cm. Panels show (a) recovered root mass density, (b) total C concentration, (c) cumulative C stock, and (d) bulk-soil $\Delta^{14}\text{C}$. Panel (a) shows observed core profiles ($n = 3$ per location); panel (c) shows observed means ± 1 SE, and panels (b) and (d) show response-scale estimated marginal means ± 1 SE. Symbols in (b) and (d) mark unadjusted joint management tests within each depth: † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

In the comparison of the bare margin and hedgerows over 0–75 cm, recovered root dry mass per unit soil volume (mg cm^{-3}) differed among fields in the Gamma interaction model ($\chi^2 = 52.08$, $p < 0.001$; Figure 4a). The depth ($\chi^2 = 19.13$, $p < 0.001$) and management $\times$ depth interaction ($\chi^2 = 23.00$, $p < 0.001$) terms were statistically significant. In contrasts averaged equally across depth intervals on the log scale, both the 10-year and 30-year hedgerows had higher root density than the bare margin (unadjusted $p < 0.001$ for both comparisons). The contrast between the planted hedgerows was not statistically significant (10-year/30-year ratio = 0.70; 95% CI, 0.25–1.97; unadjusted $p = 0.498$).

Carbon concentration also had a statistically significant depth by management interaction ($\chi^2 = 67.29$, $p < 0.001$), as well as significant main effects for depth ($\chi^2 = 648.34$, $p < 0.001$) and management ($\chi^2 = 17.19$, $p < 0.001$, Figure 4b). The unadjusted joint management test was supported at 0–10 and 50–75 cm. Both hedgerows had higher C concentration than the bare margin at 0–10 cm. At 50–75 cm, the 10-year hedgerow had higher C concentration than both the bare margin and the 30-year hedgerow.

Observed C stock to 20 cm averaged 24.9 ± 3.3 and $23.6 \pm 3.0 \text{ t C ha}^{-1}$ under the 10- and 30-year hedgerows, respectively, compared with $17.8 \pm 0.3 \text{ t C ha}^{-1}$ in the bare margin (mean $\pm$ SD; Figure 4c). The Holm-adjusted p values for the corresponding comparisons with the bare margin were 0.386 and 0.393. At 0–75 cm, all three pairwise comparisons had Holm-adjusted $p \geq 0.979$ (Table 1B).

In the bare margin and hedgerows, $\Delta^{14}\text{C}$ had a statistically significant depth by management interaction ($\chi^2 = 24.63$, $p < 0.001$) and a significant main effect for depth ($\chi^2 = 296.12$, $p < 0.001$, Figure 4d). At 0–10 cm, $\Delta^{14}\text{C}$ was higher under the 10- and 30-year hedgerows than in the bare margin (unadjusted $p = 0.031$ and 0.006 , respectively). At 50–75 cm, $\Delta^{14}\text{C}$ was higher under the

10-year hedgerow than in the bare margin ($p = 0.003$) and under the 30-year hedgerow ($p = 0.009$).

4. Discussion

4.1 Annual vegetables

Observed mean C stock to 100 cm was higher in the polyculture field than in the monoculture field. Root density was also higher in the polyculture field in the overall comparison. Mean $\Delta^{14}\text{C}$ was consistently less depleted in the polyculture field at every depth, although these differences were not statistically significant. Higher root density, C concentration, and observed mean C stock in the polyculture field are consistent with greater or more widely distributed C inputs than in the monoculture field. Root-derived carbon can support microbial polysaccharide production associated with aggregate stability (Sher et al., 2020). Crop rotations may alter the amount and chemical composition of residues returned to soil (Tiemann et al., 2015).

A global meta-analysis of cover cropping, crop rotations, and intercropping found 3.3% higher bulk-soil C content than in monocultures, with responses varying by site and management (Li et al., 2024).

4.2 Orchards

Our results did not confirm our hypothesis that the 60-year orchard would store more C than the 20-year orchard within 0–75 cm. The 20-year field had higher C concentration in depth increments between 10 and 75 cm and less depleted bulk-soil $\Delta^{14}\text{C}$ at 20–50 cm. Prior land use may influence these results: the 20-year orchard followed a long-managed vineyard that likely received manure, whereas the 60-year orchard followed cotton (N. Masumoto, personal communication, March 2026). Bulk-soil $\Delta^{14}\text{C}$ reflects the combined radiocarbon signatures of the carbon present. Our observation of less-depleted $\Delta^{14}\text{C}$ values at 20–50 cm depth in the 20-year than 60-year orchard is consistent with a greater contribution of recent C, but this

interpretation depends on input histories and the radiocarbon signatures of the contributing sources. Bulk soil ^{14}C values alone cannot distinguish greater recent inputs from greater loss of older, more depleted C (Trumbore, 2009). Finstad et al. (2020) interpreted lower soil $\Delta^{14}\text{C}$ under oil palm than under reference forests in Peru as a legacy of prior pasture use. Quéro et al. (2022) found radiocarbon evidence of C redistribution by deep plowing in a long-cultivated vineyard. Comparisons across several orchards of each age that account for prior land use and differences in the soil profile are needed to assess how orchard age relates to soil C stocks and bulk-soil $\Delta^{14}\text{C}$.

4.3 Hedgerows

Both the 10- and 30-year hedgerows had higher observed mean C stocks than the bare margin to 20 cm and higher C concentration at 0–10 cm. At 50–75 cm, C concentration was highest under the 10-year hedgerow. Root density was higher under the hedgerows than under the bare margin for depths between 10 and 75 cm. Both hedgerows had less depleted $\Delta^{14}\text{C}$ than the bare margin at 0–10 cm. At 50–75 cm, the 10-year hedgerow had less depleted $\Delta^{14}\text{C}$ than both the bare margin and the 30-year hedgerow. Fine-root turnover and rhizosphere inputs are possible pathways for root-derived SOC (Rasse et al., 2005). In Yolo County, SOC stocks through 1 m were 36% greater under hedgerows than in adjacent cropland (Chiartas et al., 2022). The observed stock means at the Hardy property showed a similar pattern to 20 cm.

4.4 Limitations

Each management category was represented by one field or field-margin location, with three soil cores analyzed per location. The design cannot separate management effects from other differences among locations or establish whether the same patterns occur elsewhere. Fertilizer inputs were not measured.

Bulk $\Delta^{14}\text{C}$ describes the radiocarbon composition of the measured C pool, but it does not identify the C source or cycling rate. Averaging over wider depth increments limits the resolution of vertical patterns in root density.

4.5 Conclusions

Observed mean C stock to 100 cm was higher in the polyculture field than in the monoculture field. Root density and C concentration were also higher in the polyculture field in the overall comparisons. The C-stock comparison to 75 cm did not detect a difference between orchards. C concentration and $\Delta^{14}\text{C}$ also differed between fields. Both hedgerows had higher observed mean C stock than the bare margin to 20 cm, while C concentration, root density, and $\Delta^{14}\text{C}$ differed at specific depths. In orchards, measurements that distinguish C sources by depth would help separate legacy C from C added under current management. Comparing several independent fields within each management system and documenting prior land use and soil conditions would test whether these patterns recur across locations. Cumulative C stocks and bulk-soil $\Delta^{14}\text{C}$ provided complementary information about soil C in the sampled fields. These comparisons show why surface measurements alone can miss differences deeper in the soil profile.

Supplemental Material. Supplemental Figure S1 shows the analyzed core layout and depth increments. The supplement reports bulk-density results and summarizes root-model checks; complete checks accompany the scientific resources. The Supplementary Data workbook contains Supplemental Tables S1 and S2, values used in Figures 2–4, and sample-level data.

Data Availability

The sample-level data and statistical results supporting this study are provided in the accompanying Supplementary Data workbook (Farming Carbon - Supplementary Data.xlsx).

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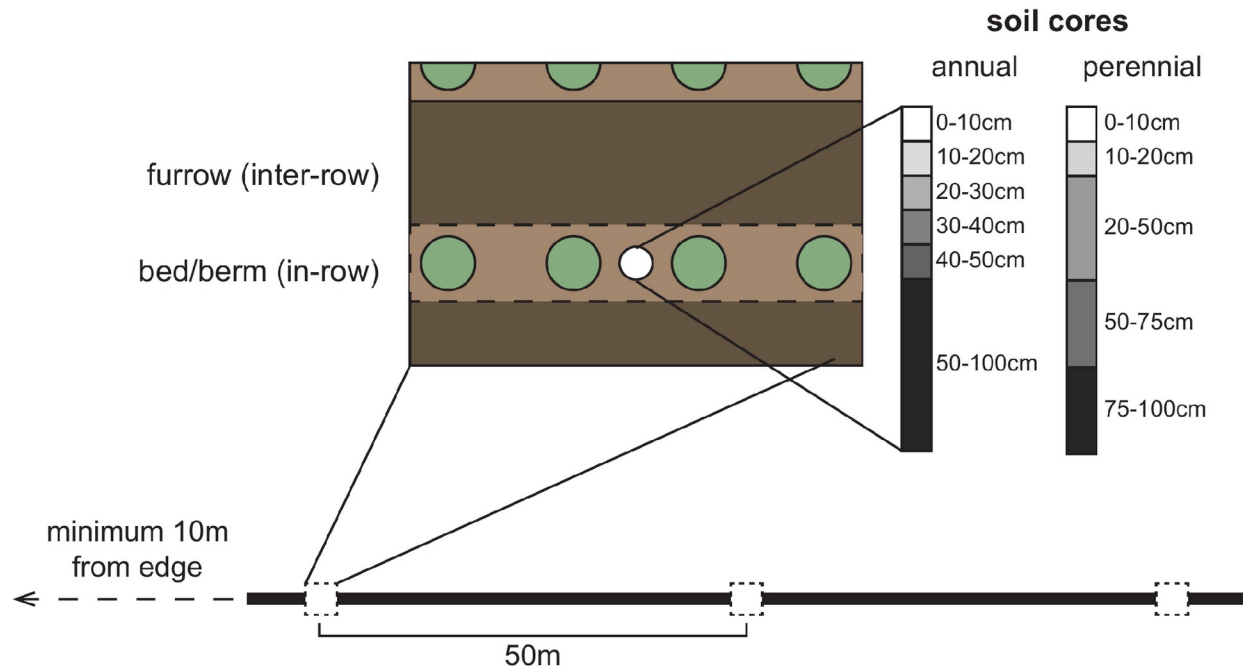
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Supplemental material

Figure S1 describes sampling. Tables S1–S2 are in the companion workbook. Bulk-density results and root-model checks are summarized below; complete checks accompany the scientific resources.

Sampling design



Supplemental Figure S1. Analyzed soil-core subset and intended depth segmentation. Samples were collected in 2024 from monoculture and polyculture vegetable fields, approximately 20- and 60-year-old peach orchards, and a bare margin and 10- and 30-year-old hedgerows in California’s Central Valley. Each management category was represented by one field or field-margin location. The diagram shows three analyzed cores per management category, one at each sampling point (0, 50, and 100 m along a transect). Other annual and orchard collection points are not shown. The first sampling point was at least 10 m from the field edge. The “annual” column refers to vegetable cores, and the “perennial” column to orchard and field-margin cores. Annual cores had intended depth increments of 0 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 50, and 50 to 100 cm. Orchard and field-margin cores had intended depth increments of 0 to 10, 10 to 20, 20 to 50, 50 to 75, and 75 to 100 cm. Depths are referenced to the mineral-soil surface after surface litter removal. Orchard analyses were restricted to 0–75 cm because deeper sample coverage was incomplete. Hedgerow analyses also used 0–75 cm to compare the same four depth intervals across all nine cores. Two 10-year hedgerow cores ended at 86 and 88 cm. Measurements below 75 cm remain in the Supplementary Data workbook.

Supporting data and statistical results

The companion workbook, Farming Carbon - Supplementary Data.xlsx, contains ten worksheets. Table S1 provides within-depth tests and contrasts for root density, C concentration and $\Delta^{14}\text{C}$; Table S2 provides Type III Wald tests for C concentration and bulk density. Endpoint Welch reports C-stock summaries and comparisons at the selected depths. Other worksheets contain sample data, figure values, variable definitions and source hashes.

Bulk density

No management differences in bulk density were detected between the sampled annual fields ($p = 0.899$) or orchards ($p = 0.929$). In the hedgerow system, bulk density differed among the sampled margins (management: $\chi^2 = 32.21$, $p < 0.001$), with higher estimated mean bulk density in the bare margin than in either hedgerow. The depth by management interaction was not significant ($p = 0.440$).

Root-model checks

Across half to double the added mass, the annual polyculture–monoculture root comparison remained statistically significant ($p < 0.001$), while the interaction test and deep-layer ratios changed with the addition. Holm adjustment across the six annual within-depth comparisons and omission of a single core changed support for some depth contrasts. Across 0.1–10 times the added mass, the orchard overall comparison remained nonsignificant, the hedgerow management and interaction tests remained significant, and the 10-year versus 30-year hedgerow contrast remained nonsignificant. Gamma simulations produced adjusted responses below the minimum set by the added mass and sampled volume, limiting interpretation of these estimates. The annual Gamma analysis is treated as exploratory support. Complete sensitivity results and diagnostic plots are provided with the scientific resources.