



1 **Near-tree soil footprints show higher organic carbon and lower bulk density with no**
2 **detectable end-of-summer moisture penalty**

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7
8 **Abstract**

9 Scattered trees can create fine-scale surface soil enrichment, but it is unclear how far these
10 patterns extend through the mineral soil profile, translate into carbon stocks, and influence
11 moisture content. We quantified the soil functional footprint of 14 established trees from four
12 contrasting cohorts in an arboretum–grassland system under a Mediterranean climate in South
13 Australia. Soil was sampled at 1, 2, 4 and 8 m from each stem at depth intervals to 30 cm.
14 Directly measured surface bulk density was lower at 1, 2 and 4 m than at 8 m, while soil organic
15 carbon (SOC) concentration was 30% higher at 1 m and declined by 8% with each doubling of
16 distance. Total nitrogen, nitrate-N and Colwell-extractable P also varied with distance, whereas
17 gravimetric moisture did not decline towards the trees under the end-of-summer conditions
18 sampled. Distance × tree cohort interactions were not significant for these principal responses.
19 After accounting for depth and tree identity, distance explained 3% of joint soil property
20 variation whereas depth explained 39%. On an equivalent-soil-mass basis, SOC stock at 1 m
21 distance from the tree exceeded that at 8 m by 16.5 Mg C ha⁻¹, although the categorical fixed-
22 depth 0–30 cm SOC-stock test was not significant. Within the radially-weighted 0–8 m
23 footprint, we combined two carbon pools, model-assisted mineral-soil SOC and current
24 projected whole-tree carbon. Together these amounted to 67.4–123.2 Mg C ha⁻¹, with mineral-
25 soil SOC accounting for 59–89% of this combined soil tree total. These results identify a shared,
26 property-specific radial soil footprint characterised by lower bulk density and higher carbon
27 and nutrient concentrations without a detectable dry-season moisture penalty. They also
28 demonstrate why depth resolution, soil mass correction and radial area weighting are essential
29 when converting near-tree enrichment into spatially explicit carbon accounting and monitoring.
30 Because the near-tree zone retained higher carbon and nutrients without an end-of-summer
31 moisture penalty, established trees may support understorey forage production and its
32 resilience under increasing aridity rather than imposing a dry-season water cost.

33 **Key words:** Scattered trees, Soil organic carbon stocks, Soil functional footprint, Soil moisture
34 dynamics, Dry-season water cost, Radial area weighting.



35 1. Introduction

36

37 Soils are the largest terrestrial store of organic carbon, and their capacity to retain
38 carbon while supporting nutrient cycling, soil structure and water regulation underpins the
39 functioning of managed grasslands and agricultural landscapes worldwide (IPCC, 2019;
40 Paustian et al., 2016; Sanderman et al., 2017; Schmidt et al., 2011). Integrating trees into these
41 landscapes in silvopastoral, agroforestry and scattered-tree systems across temperate,
42 Mediterranean and dryland regions can add aboveground biomass carbon while modifying the
43 soil environment through litter deposition, root turnover, rhizodeposition, canopy-mediated
44 redistribution of water and nutrients, and changes in microclimate and biological activity
45 (Beillouin et al., 2023; Gan et al., 2021; Jose, 2009; Ma et al., 2020). These effects make
46 scattered trees potentially important components of climate-resilient land management, but
47 their soil influence cannot be assumed to be spatially uniform.

48 Individual trees commonly generate metre-scale heterogeneity in soil properties. The
49 resulting zones are often described as “fertility islands”, in which organic matter and nutrients
50 become concentrated around woody plants relative to locations farther from their stems
51 (Schlesinger et al., 1996; Waring et al., 2015). Radial enrichment of SOC and nutrients has
52 been reported in agroforestry, silvopastoral and woodland systems, frequently together with
53 lower bulk density or other changes in physical condition (Eldridge and Wong, 2005; Hoosbeek
54 et al., 2016; Pardon et al., 2017). However, the magnitude and spatial reach of these effects
55 vary with tree age and traits, climate, soil, land-use history and management (Mayer et al.,
56 2022; Mitrová et al., 2025; Peng et al., 2020). This fine-scale heterogeneity matters because
57 sampling only near stems can overstate a footprint-wide mean, whereas sampling only at wider
58 distances can miss locally important changes. Robust assessment therefore requires distance-
59 resolved measurements and an explicit method for aggregating them over the area represented
60 by each sampling position (Cardinael et al., 2017; Dean et al., 2020).

61 Vertical soil structure adds a second and often stronger source of variation. Tree-
62 associated SOC and nutrient enrichment is commonly greatest near the surface, where organic
63 inputs are concentrated, while deeper layers may respond differently or show weaker radial
64 separation (Steffens et al., 2022; Xu et al., 2021). Moreover, SOC concentration and SOC stock
65 answer different questions. A higher carbon concentration near a tree does not necessarily
66 produce an equivalent fixed-depth stock increase if bulk density and fine-earth mass also vary
67 with distance, and as a result, the total amount of SOC held in the soil may remain similar even
68 if concentrations vary. Fixed-depth comparisons quantify carbon within a common soil



69 volume, whereas equivalent-soil-mass comparisons reduce bias caused by differences in the
70 mass of soil being compared (Ellert and Bettany, 1995; Von Haden et al., 2020; Wendt and
71 Hauser, 2013). Spatial weighting and equivalent-soil-mass calculations have been applied in
72 agroforestry carbon assessments (Cardinael et al., 2017), but the broader individual-tree
73 literature still contains many more measurements of SOC concentration and soil chemistry than
74 integrated assessments of physical condition, water regulation and mass-corrected carbon
75 stocks (Rubeaud et al., 2026). This gap has a direct practical implication: where changes in
76 bulk density and soil mass are not carried through to stock estimation, the carbon significance
77 of scattered trees can be systematically misjudged; near-tree gains in SOC concentration may
78 be overstated as stock gains, or genuine gains missed, which weakens carbon accounting and
79 soil monitoring in tree-based land management (Cardinael et al., 2017). The unresolved issue
80 is therefore not whether individual trees can create fertility islands. Rather, it is whether a
81 coherent radial soil functional footprint remains detectable when distance and depth are
82 evaluated together, repeated observations are assigned to the correct tree-level experimental
83 unit, and changes in bulk density and soil mass are carried through to SOC-stock estimation.

84 Ryan et al. (2024) demonstrated radial variation in surface SOC concentration around
85 trees at the semi-arid Waite Arboretum (South Australia) site. Although it remains unknown
86 whether the surface concentration signal extended through the 0–30 cm mineral profile,
87 whether it represented a common response across contrasting tree groups, and whether higher
88 near-tree SOC translated into greater carbon stocks once bulk density and soil mass were
89 accounted for. Soil moisture is also particularly important to this integrated question in water-
90 limited, Mediterranean-climate environments. Trees can reduce evaporative demand through
91 shading and microclimatic buffering, but interception and root water uptake can also reduce
92 water availability to neighbouring herbaceous vegetation. The balance between facilitation and
93 competition depends on seasonal conditions, rooting depth, canopy structure and soil properties
94 and therefore cannot be inferred from SOC or nutrient enrichment alone (Butterfield et al.,
95 2016; Lee et al., 2021; Mitrová et al., 2025). An interesting and unresolved question is whether
96 there is a greater soil-water deficit in trees, or whether changes they induce to local soil
97 properties (e.g. improved structure and porosity) might offset this.

98 In this study, we characterised radial and vertical variation in soil properties around 14
99 established trees representing four contrasting cohorts within a common arboretum–grassland
100 environment in South Australia. We tested four linked hypotheses. First, there would be a
101 common radial footprint characterised by lower bulk density and higher SOC, TN and available
102 P closer to the tree stems, without a corresponding decline in end-of-summer gravimetric



moisture. Second, these radial effects are strongest in the surface mineral soil layers, and their magnitude would vary among tree cohorts. Third, that distance would explain a significant component of joint soil-property variation after accounting for the stronger vertical depth structure and repeated measurements within trees. Finally, higher near-tree SOC concentration would produce greater SOC stocks, particularly when expressed on an equivalent-soil-mass basis.

Together, the study connects the ecological concept of individual-tree fertility islands with the measurements required for spatially explicit soil assessment and carbon accounting.

2. Data and Methodology

2.1 Study area description

The study was conducted at the Waite Arboretum (35.0°S, 138.6°E) on Adelaide University's Waite Campus, South Australia (Fig. S1). The region has a Mediterranean-type climate characterised by hot, dry summers and cool, wet winters, with a long-term mean maximum annual temperature of 21.4 °C and mean annual rainfall of 618 mm (Gardner et al., 2017; Ryan et al., 2024). Established in 1928, the approximately 27-ha arboretum contains about 2,500 trees representing more than 800 species, grown under natural rainfall without routine supplementary irrigation after establishment (Gardner et al., 2017; Ryan et al., 2024). Soil profiles adjacent to the sampled trees were described in the field and classified as Red Chromosols according to the Australian Soil Classification (Isbell and the National Committee on Soil and Terrain, 2021), Supplementary Table S1. A nearby Waite reference soil pit was provisionally classified as a Vertic, Endostagnic, Hypocalcic, Rhodic Luvisol (Endoclayic, Colluvic; Cutanic) in the World Reference Base (R. Fitzpatrick personal communication, 2025).

2.2 Structural cohorts and tree attributes

Four structural tree cohorts (C1-C4, i.e. trees grouped by a similar growth form, canopy architecture and size (height and canopy area) rather than by similar age) were defined to represent contrasting tree architectures relevant to arid to semi-arid South Australian landscapes. Selection prioritised mature trees with established canopies and root systems that could have generated measurable litter accumulation and near-tree soil modification. All cohorts occurred within the same arboretum and therefore shared the same regional climate



and broadly similar soil-parent-material and management context, providing the common-site basis for the quasi-experimental comparison. Cohort C1 represented a dense, spatially defined mixed-canopy assemblage comprising two *Cupressus lusitanica*, one *Juniperus procera* and one *Quercus palustris*. The oak was retained within C1 because it occurred within the same sampling zone; consequently, C1 represents canopy structure and spatial context rather than a taxonomically pure treatment. Cohort C2 comprised two *Callitris gracilis* and one *Callitris rhomboidea*, representing upright conifer-form trees native to dry South Australian environments. Cohort C3 comprised one *Eucalyptus tereticornis* and two *Eucalyptus dealbata*, representing open-canopy eucalypts. Cohort C4 comprised two *Eucalyptus dumosa*, one *Eucalyptus pilbarensis* and one *Eucalyptus cooperiana*, representing the lower, multi-stemmed mallee growth form. Fourteen individual trees were sampled (C1 = 4, C2 = 3, C3 = 3 and C4 = 4). Per-tree attributes, including planting year, canopy area (m²), height (m), estimated carbon stored (kg C tree⁻¹) and estimated annual carbon sequestration (kg C tree⁻¹ yr⁻¹), were retrieved from the Waite Arboretum App (Friends of the Waite Arboretum, 2020). These values originated from the site-wide i-Tree Eco assessment conducted in 2016-2017 (Gardner et al., 2017) and were projected to 2025 as described below.

2.3 Field sampling

Sampling was conducted in March-April 2025, near the end of the summer dry season. At each tree, samples were collected along four radial transects oriented towards the north-east, south-east, south-west and north-west. These bearings were separated by 90° (azimuths 45°, 135°, 225° and 315°). Sampling positions were located 1, 2, 4 and 8 m from the tree stem along each transect. Field samples from the four transects were subsequently pooled within each Tree × Distance × Depth combination, retaining the individual tree as the experimental and repeated-sampling unit. Different soil properties were sampled at different depth intervals within the same profile (response-specific depth grids), because BD and soil chemistry each required a different sampling method. Undisturbed ring cores collected at 0-5 and 5-10 cm provided the primary surface bulk-density measurements (112 pooled Tree × Distance × Depth observations). Gravimetric moisture was represented at 0-5, 5-10, 10-20 and 20-30 cm (224 pooled observations). Chemical concentrations, including SOC, total N, C:N, mineral-N forms and Colwell-extractable P, were analysed only in the separately retained auger samples from 0-10, 10-20 and 20-30 cm (168 pooled observations). Fixed-depth SOC-stock calculations used the same three 10 cm stock layers, yielding 56 complete Tree × Distance profiles. The 0-5 and



169 5-10 cm ring-core chemistry values were not used for concentration inference because those
170 samples were oven-dried at 105 °C for physical measurements, whereas the auger samples used
171 for chemical analysis were dried below 40 °C. At each Transect × Distance position, one
172 undisturbed stainless-steel ring core was collected at 0-5 cm and one at 5-10 cm (5 cm height
173 × 5 cm internal diameter; approximately 98.2 cm³), giving a total of 448 samples. Rings were
174 pooled across transects within Tree × Distance × Depth to produce 112 bulk-density
175 composites. Intact cores were not collected below 10 cm because the hard, dry soil prevented
176 reliable insertion without disturbing soil structure. At the same 224 Tree × Transect × Distance
177 positions, soil was collected with a hand auger for the concentration and fixed-depth analytical
178 grids described above. Samples were sealed in labelled plastic bags immediately after
179 collection to retain field moisture and were transported to the laboratory under refrigeration.
180 Because a discrete organic (O) horizon is generally absent in these dryland soils, the loose
181 surface litter layer, best developed beneath tree canopies and sparse in the open area, was
182 collected at every Transect × Distance position from an approximately 30 × 20 cm area
183 delimited with a flat-bladed shovel. The four transect collections were pooled by Tree ×
184 Distance, producing 56 composite litter samples. A defined collection area was used, but total
185 dry litter mass per unit ground area was not available; litter was therefore analysed as carbon
186 concentration rather than as an aerial carbon stock.

187

188 **2.4 Laboratory analysis**

189

190 *Gravimetric and hygroscopic moisture*

191

192 Gravimetric soil moisture was determined from fresh subsamples by oven-drying at
193 105°C to constant mass and expressed as a percentage of oven-dry soil mass. SOC and total
194 nitrogen (N) concentrations were measured on material dried at 40 °C. For SOC stock
195 calculation only, SOC was placed on the same 105° C oven-dry basis as bulk density by
196 multiplying SOC₄₀ by (1 + θ_h), where $\theta_h = (M_{40} - M_{105})/M_{105}$. Depth specific hygroscopic
197 correction factors derived from the representative laboratory subset were 0.0120 for 0-10 cm,
198 0.0100 for 10-20 cm and 0.0085 for 20-30 cm. The correction was not applied to the SOC or
199 total-N concentration analyses.

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202



203 ***Bulk density and coarse fragment corrections***

204

205 Whole soil bulk density (ρ_b , total) including the >2 mm coarse fragment fraction, was
 206 calculated as oven-dry core mass divided by total ring volume. The volumetric coarse fragment
 207 fraction (CFv; v/v) was dominated by small gravel and computed by converting coarse
 208 fragment mass to volume using a particle density of 2.9 g cm^{-3} for lateritic/ironstone fragments
 209 and dividing by total core volume (Harbo et al., 2022). Coarse fragments were accounted for
 210 once in the SOC stock calculation through the term $(1 - \text{CFv})$, used with whole-soil bulk
 211 density; bulk density was not additionally converted to a fine-earth value (Poeplau et al., 2017).
 212 For the two layers with both measurements on the same intact core (0–5 and 5–10 cm),
 213 volumetric water content (VWC, $\text{cm}^3 \text{ cm}^{-3}$) was calculated as $\text{VWC} = \theta g \times \rho_b / \rho_w$, where θg is
 214 gravimetric water content (g g^{-1}), ρ_b is whole-soil bulk density (g cm^{-3}) and ρ_w is the density
 215 of water (1 g cm^{-3}); the volumetric coarse-fragment fraction was retained as a sensitivity check.

216

217 ***Soil and Litter Chemical Analyses***

218

219 Soil used for carbon and nitrogen analysis was dried below 40°C and ground to <1 mm.
 220 Total carbon and total nitrogen were determined by dry combustion using a LECO CN analyser
 221 (LECO Corporation, St. Joseph, MI, USA). Calibration and quality control followed
 222 manufacturer's soil protocol using LECO reference material 502-694 (certified values: C =
 223 $13.70 \pm 0.34\%$, N = $1.14 \pm 0.05\%$ and S = $0.201 \pm 0.007\%$). Samples showed no visible
 224 effervescence when screened with 10% HCl, indicating no detectable carbonate reaction;
 225 measured total carbon was therefore treated as SOC and reported as SOC g C kg^{-1} dry soil.
 226 Total N was reported as g N kg^{-1} dry soil, and C:N was calculated on a mass basis. Mineral N
 227 was extracted from fresh, <2 mm soil (5 g) with 10 mL of 1 M KCl by shaking for 1 h, followed
 228 by filtration and analysis using a SEAL AQ400 discrete analyser. Ammonium-N was
 229 determined by the salicylate-hypochlorite method at 660 nm (SEAL EPA-148-C). Nitrate plus
 230 nitrite-N was determined by cadmium reduction followed by Griess colour development at 520
 231 nm (SEAL EPA-127-A), while nitrite-N was determined on the same extract without cadmium
 232 reduction (SEAL EPA-115-A). Nitrate-N was calculated as $(\text{NO}_3^- + \text{NO}_2^-)\text{-N}$ minus $\text{NO}_2^- \text{-N}$.
 233 Concentrations were converted to mg N kg^{-1} dry soil using extract volume and gravimetric
 234 moisture. Colwell-extractable P was determined by shaking 2.5 g of air-dried soil with 25 mL
 235 of 0.5 M NaHCO_3 (pH 8.5) for 16 h at room temperature. After filtration, orthophosphate was
 236 quantified using the molybdenum-blue method at 880 nm (SEAL EPA-118-C) and reported as



237 mg P kg⁻¹ soil. Litter composites were dried at 40 °C to constant mass, milled to <1 mm and
238 analysed for total C by dry combustion using the LECO CN analyser. Calibration used LECO
239 Orchard Leaves reference material 502-931 (certified values: C = 48.62 ± 0.26%, N = 1.37 ±
240 0.03% and S = 0.118 ± 0.004%). Because total dry litter mass per sampled ground area was
241 unavailable, litter results were restricted to C concentration.

242

243 ***SOC stock layer specific bulk density gap filling***

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245 Layer-specific fixed-depth SOC stock was calculated as:

246

$$247 \text{ SOC stock (Mg C ha}^{-1}\text{)} = \text{SOC}_{40} \text{ (g kg}^{-1}\text{)} \times (1 + \theta_h) \times \text{layer thickness (cm)} \times \rho_{b,\text{total}} \text{ (Mg m}^{-3}\text{)} \times (1 - \text{CFv}) \times 0.1$$

248

249 where SOC₄₀ is the SOC concentration determined on material dried at <40 °C, θ_h is the depth-
250 specific hygroscopic moisture correction to an oven-dry basis, $\rho_{b,\text{total}}$ is whole-soil bulk
251 density, CFv is the volumetric coarse-fragment fraction, and 0.1 is a unit conversion factor.
252 Fixed-depth SOC stock to 30 cm was calculated as the sum of the 0–10, 10–20 and 20–30 cm
253 layer stocks. Bulk density and coarse-fragment mass were measured from intact cores at 0–5
254 and 5–10 cm. Coarse-fragment mass was converted to CFv, and the two surface layers were
255 combined as equal-thickness means for the 0–10 cm stock layer. Direct intact-core
256 measurements were unavailable below 10 cm. Missing deep-layer bulk density was therefore
257 estimated using an independent 1997 Waite Rotation Trial reference dataset (Arbor et al., 2023,
258 2024; Bishop et al., 1999; Malone et al., 2009; Sequeira et al., 2014)(Supplementary Table S9).
259 SOC stocks that incorporate these predicted 10–20 and 20–30 cm bulk-density values are
260 hereafter referred to as model-assisted, to distinguish them from the directly measured 0–10
261 cm stock layer.

262

263 **Projected whole-tree carbon and combined soil-tree carbon estimates**

264

265 Tree-level carbon storage and annual carbon sequestration were obtained from the
266 2016-2017 Waite Arboretum i-Tree Eco inventory. i-Tree Eco estimates whole-tree biomass
267 carbon from tree dimensions, species information and allometric relationships, including
268 above- and belowground living biomass (Gardner et al., 2017; Nowak et al., 2008; Nowak,
269 2024). Inventory carbon was projected to 2025 as:

270



$$C_{2025} = C_{2017} + (C_{seq} \times 8),$$

where C_{seq} is the annual carbon-sequestration estimate reported by the original inventory. This linear update assumes a constant annual increment over the eight-year interval and should be interpreted as a projection rather than a 2025 tree remeasurement. To match the soil sampling footprint, projected whole-tree carbon was expressed as a footprint-normalised per-hectare equivalent using the 0–8 m circular area around each tree ($A = \pi \times 8^2 = 201.06 \text{ m}^2$):

$$C \text{ density (Mg C ha}^{-1}\text{)} = [\text{tree C mass (kg)} \times (10,000/A)]/1,000.$$

Distance-specific 0–30 cm mineral soil SOC stocks were weighted by concentric-radially area within the same footprint. The primary midpoint boundaries were 0, 1.5, 3, 6 and 8 m for the 1, 2, 4 and 8 m sampling positions, respectively; equal weighting and annuli bounded at 0, 1, 2, 4 and 8 m were retained as spatial sensitivity analyses. This weighting assumes radial symmetry around each tree. The combined soil-tree carbon estimate was defined as area-weighted 0–30 cm mineral soil SOC plus projected whole-tree carbon within the sampled footprint. It was not described as total ecosystem carbon because litter carbon stock, deadwood and herbaceous biomass were not quantified. Footprint-normalised tree-carbon values represent the sampled tree-influence zone and should not be interpreted as a field-scale stocking density without an explicit tree-spacing scenario (IPCC, 2019; Paustian et al., 2016)

2.5 Data analysis

All analyses were conducted in Python 3.13.9 using Anaconda Navigator 2.7.0 and Jupyter Notebook 7.3.2, with pandas 2.2.3, NumPy 2.1.3, SciPy 1.15.3, statsmodels 0.14.4 (Seabold and Perktold, 2010) and Matplotlib 3.10.0.

Mineral soil responses were analysed with a tree-level split-plot (repeated-measures) ANOVA, equivalent to a linear mixed model with tree as a random effect. Cohort (C1–C4) was treated as a between-tree factor, while Distance (1, 2, 4 and 8 m) and Depth were repeated within-tree factors, with Depth evaluated on each response's validated grid (bulk density: 0–5 and 5–10 cm; gravimetric moisture: 0–5, 5–10, 10–20 and 20–30 cm; SOC, total N, C:N, mineral N and Colwell P: 0–10, 10–20 and 20–30 cm). Tree identity, defined by the unique Cohort $\times$ Tree combination, was the experimental unit, so repeated observations within a tree were not treated as independent replicates. Cohort was tested against variation among trees



305 within cohorts, and Distance, Depth and their interactions were tested against the
306 corresponding within-tree error strata. The models evaluated Cohort, Distance, Depth and all
307 their interactions. Litter C used the same structure, with Distance as the only within-tree factor.
308 Because cohorts were not randomised and all species were not replicated, cohort effects are
309 interpreted as cohort-level associations rather than causal species effects. Response scales were
310 selected from residual diagnostics: bulk density, NO_2^- -N and litter C were analysed on their
311 original scales; SOC, total N and C:N were natural-log transformed; gravimetric soil moisture
312 was square-root transformed; NH_4^+ -N, NO_3^- -N and Colwell-extractable P were transformed as
313 $\log_{10}(x)$. Untransformed tree-level means and standard errors ($\pm$ SE) are shown in figures and
314 descriptive summaries. Ordinary least-squares regressions of total N on SOC were used only
315 to describe their association and did not replace tree-structured split-plot inference.

316 Planned distance contrasts compared 1, 2 and 4 m with the 8 m reference, computed
317 from paired tree-level differences with cohorts weighted equally; the three contrasts formed
318 one Holm family per response (Holm, 1979). Depth and exploratory cohort-specific contrasts
319 were Holm-adjusted within their prespecified families. Significance was assessed at $\alpha = 0.05$.

320 For bulk density, SOC, litter C, soil moisture and SOC stocks, the distance conclusions
321 were checked with a Greenhouse-Geisser correction (Greenhouse and Geisser, 1959) and
322 Huynh-Feldt-Lecoutre correction (Lecoutre, 1991) sphericity corrections, 5,000-draw
323 parametric bootstrap tests, exact tree-level sign-flip tests continuous trends per doubling of
324 distance, leave-one-tree-out analyses and alternative response scales. Transformation-
325 sensitivity checks were also retained for mineral-N forms and Colwell P. These were treated
326 as sensitivity analyses rather than separate primary tests and are reported in the Supplementary
327 Tables S4a and S4b.

328 Fixed-depth and equivalent-soil-mass SOC stocks used the same tree-level split-plot
329 ANOVA (Cohort between-tree, Distance within-tree). Cohort differences in area-weighted
330 mineral-soil SOC, projected 2025 whole-tree carbon and their combined estimate were tested
331 with tree-level one-way ANOVA (F-tests), using 99,999-permutation Monte Carlo label tests
332 and stratified bootstrap confidence intervals as checks. For the stocks, calibration uncertainty,
333 profile-level bulk-density prediction error, alternative deep-layer gap-filling models and
334 alternative CFv propagation were evaluated separately, following established SOC-stock
335 uncertainty approaches (Goidts et al., 2009) (Supplementary Tables S2, S7 and S8).

336 Multivariate soil-property structure was assessed by partial redundancy analysis (partial
337 RDA) fitted by multivariate least squares. The response matrix (bulk density, gravimetric soil
338 moisture, SOC, total N, NH_4^+ -N, NO_2^- -N, NO_3^- -N and Colwell-extractable P) was aligned to a



common three-layer grid (0–10, 10–20 and 20–30 cm) across 14 trees $\times$ four distances ($n = 168$), analysed on the univariate response scales and standardised to zero mean and unit variance. Distance was tested conditioning on Depth and Tree ID (and vice versa), with interactions evaluated hierarchically using 9,999 Freedman-Lane permutations (Freedman and Lane, 1983) restricted within Tree ID to preserve repeated-measures structure.

3. Results

Bulk Density

Bulk density (BD; g cm^{-3}), measured directly at 0–5 and 5–10 cm, increased significantly with distance from the tree stem ($F(3, 30) = 14.00$, $p < 0.001$, Fig. 1). Relative to 8 m, BD was 0.129 g cm^{-3} lower at 1 m (pointwise 95% CI: -0.178 to -0.080 ; Holm-adjusted $p < 0.001$), 0.089 g cm^{-3} lower at 2 m (95% CI: -0.112 to -0.065 ; $p < 0.001$), and 0.061 g cm^{-3} lower at 4 m (95% CI: -0.102 to -0.021 ; $p = 0.007$), and it increased by 0.041 g cm^{-3} per doubling of distance from the tree stem (95% CI: 0.024 – 0.059 ; $t(10) = 5.28$, $p < 0.001$). This radial pattern was consistent across cohorts and between the two measured depths layers, with the Distance $\times$ Cohort, Distance $\times$ Depth and Distance $\times$ Depth $\times$ Cohort interactions all non-significant, and it remained supported under the sphericity-corrected and parametric-bootstrap analyses (Supplementary Table S4a).

Bulk density was significantly higher at 5–10 cm than at 0–5 cm (Depth: $F(1, 10) = 208.27$, $p < 0.001$), and this depth difference did not vary significantly among cohorts (Depth $\times$ Cohort: $F(3, 10) = 1.48$, $p = 0.279$). Mean BD, averaged across distances and the two measured depth layers, differed among cohorts ($F(3, 10) = 6.37$, $p = 0.011$).

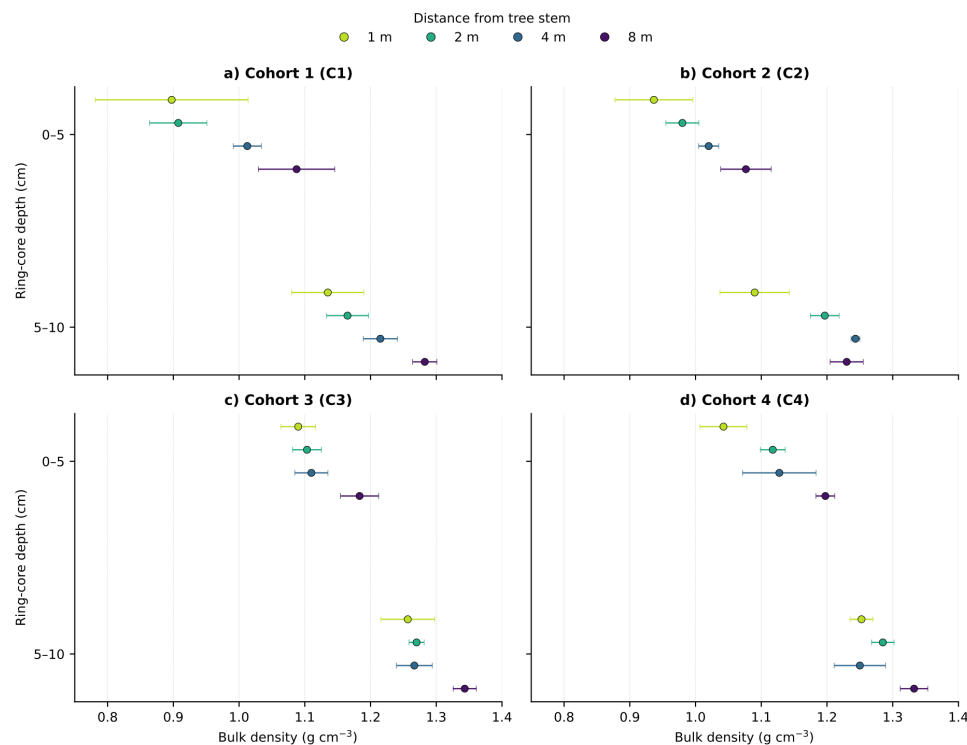


Figure 1. Observed bulk density across distance, depth and cohort. Points show tree-level means $\pm$ SE for bulk density measured directly from intact ring cores at 0–5 and 5–10 cm and at 1, 2, 4 and 8 m from the tree stem. Panels represent the four cohorts. Model-assisted bulk-density estimates for deeper soil layers are not included.

Soil Organic and Litter Carbon

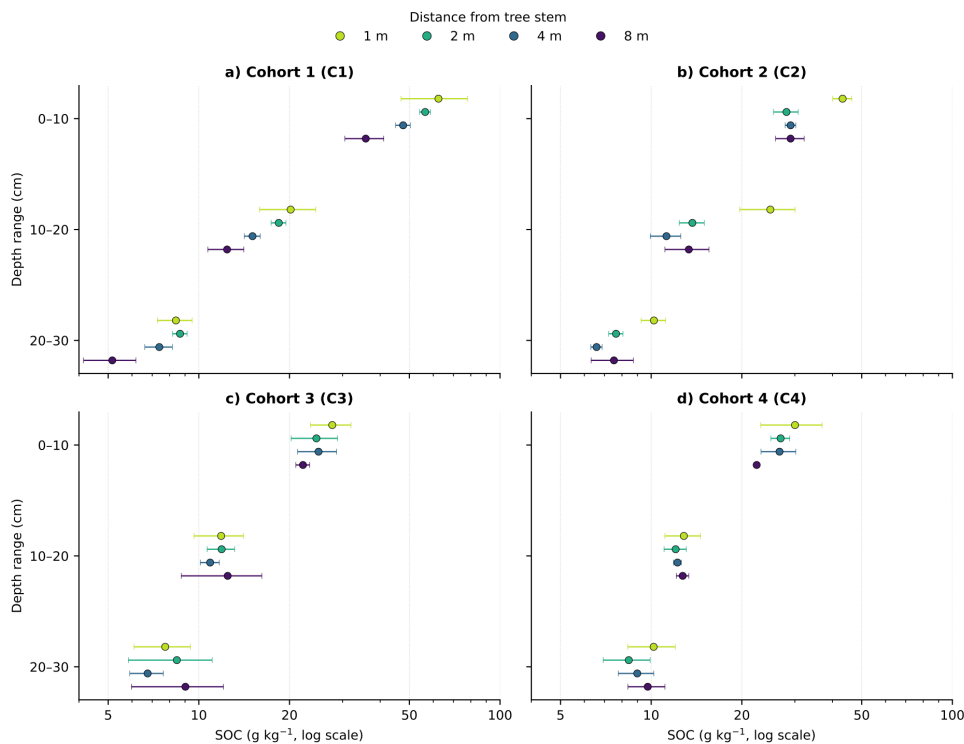
Soil organic carbon (SOC) concentration declined significantly with increasing distance from the tree stem ($F(3, 30) = 3.69$, $p = 0.023$). SOC at 1 m was 29.6% higher than at 8 m (ratio = 1.296; pointwise 95% CI: 1.071–1.568; Holm-adjusted $p = 0.038$; Fig. 2). SOC at 2 m was estimated to be 13% higher than at 8 m, but this contrast was not statistically significant after Holm adjustment (ratio = 1.134; pointwise 95% CI: 0.926–1.388; $p = 0.391$). SOC at 4 m also did not differ significantly from that at 8 m (ratio = 1.047; pointwise 95% CI: 0.854–1.283; $p = 0.628$). Consistent with these contrasts, SOC declined by an estimated 8.2% per doubling of distance from the tree stem (ratio = 0.918; 95% CI: 0.861–0.979; $t(10) = -2.97$, $p = 0.014$). This radial decline was consistent across cohorts and depth layers, with the Distance $\times$ Cohort: Distance $\times$ Depth and three-way interactions all non-significant, and it remained supported in the sphericity-corrected and parametric-bootstrap analyses (Supplementary Table S4a).



383 SOC concentration declined strongly with soil depth ($F(2, 20) = 574.14$, $p < 0.001$), although
384 the magnitude of vertical stratification differed among cohorts (Depth $\times$ Cohort: $F(6, 20) =$
385 11.69 , $p < 0.001$; Fig. 2). Relative to the 20–30 cm layer, SOC was 3.99 times higher at 0–10
386 cm and 1.72 times higher at 10–20 cm (Holm-adjusted $p < 0.001$ for both contrasts). All three
387 depth layers differed significantly within every cohort after Holm adjustment. Mean SOC,
388 averaged across distances and depths, did not differ significantly among cohorts ($F(3, 10) =$
389 3.65 , $p = 0.052$).

390 Litter C concentration differed among cohorts ($F(3, 10) = 5.41$, $p = 0.018$), being
391 highest in C3 and lowest in C1, but did not vary significantly with distance from the tree stem
392 ($F(3, 30) = 0.78$, $p = 0.515$). The full litter analyses (pairwise and continuous-trend results) and
393 the corresponding figure are provided in the Supplementary Material (Supplementary Table
394 S4b; Supplementary Fig. S3)

395



396
397 **Figure 2. Soil organic carbon concentration across distance, depth and cohort.** Points show observed tree-level means $\pm$
398 SE among trees for SOC concentration in the auger-sampled 0–10, 10–20 and 20–30 cm mineral soil layers at 1, 2, 4 and 8 m
399 from the tree stem. Panels represent the four cohorts, and colours represent distance. The x-axis is logarithmic for visualisation.
400 Statistical inference was based on the tree-level split-plot analysis of log-transformed SOC.
401
402



403 ***Total Nitrogen and C:N Stoichiometry***

404

405 Total nitrogen (TN) concentration varied significantly with distance from the tree stem
406 ($F(3,30) = 3.67$, $p = 0.02$; Supplementary Fig. S4), and although no planned contrast against 8
407 m survived Holm adjustment, the continuous analysis indicated an 8.8% decline per doubling
408 of distance ($t(10) = -2.43$, $p = 0.035$; exact $p = 0.023$). This radial pattern was consistent across
409 cohorts and depth layers, with the Distance $\times$ Cohort, Distance $\times$ Depth and three-way
410 interactions all non-significant. TN declined strongly with depth ($F(2, 20) = 199.35$, $p < 0.001$),
411 and neither mean TN nor its vertical pattern differed significantly among cohorts (Cohort: $F(3,$
412 $10) = 3.68$, $p = 0.051$; Depth $\times$ Cohort: $F(6, 20) = 2.19$, $p = 0.087$).

413 Across the 168 auger-sampled observations, TN was strongly positively associated with
414 SOC descriptive Ordinary Least Squares (OLS) $R^2 = 0.906$; slope = $0.0628 \text{ g TN g}^{-1} \text{ SOC}$),
415 with cohort-specific R^2 values ranging from 0.779 to 0.970; these regressions are descriptive
416 because observations from the same trees were repeated across distances and depths.

417 C:N ratios varied with depth ($F(2, 20) = 14.57$, $p < 0.001$) but not with distance ($F(3,$
418 $30) = 0.10$, $p = 0.958$), and no interaction or cohort effect was significant.

419

420 ***Mineral Nitrogen and Available Phosphorus***

421

422 Among the mineral nutrients, Colwell-extractable phosphorus showed the clearest
423 radial pattern (Fig. 3). Colwell P varied significantly with distance ($F(3,30) = 6.13$, $p = 0.002$),
424 with the 1 m versus 8 m contrast meeting the parametric Holm-adjusted threshold (15.1 vs 3.8
425 mg kg^{-1} ; adjusted $p = 0.046$) but marginally exceeding it in the exact sensitivity test ($p = 0.055$).
426 The 2 m and 4 m contrasts were not significant. Colwell P varied strongly with depth ($F(2,20)$
427 $= 85.61$, $p < 0.001$), and its vertical pattern differed among cohorts (Depth $\times$ Cohort: $F(6,20) =$
428 28.08 , $p < 0.001$). The Distance $\times$ Depth ($F(6, 60) = 2.80$, $p = 0.018$) and Distance $\times$ Depth $\times$
429 Cohort ($F(18, 60) = 1.81$, $p = 0.045$) interactions were also significant, so its radial response is
430 best interpreted hierarchically by depth and cohort; the Distance $\times$ Cohort interaction was not
431 significant.

432 Nitrate-N varied significantly with distance ($F(3,30) = 4.16$, $p = 0.014$), no planned
433 contrast survived Holm adjustment, but the continuous analysis indicated a decline with
434 distance ($t(10) = -2.39$, $p = 0.038$; exact $p = 0.020$). NO_3^- -N declined strongly with depth
435 ($F(2,20) = 122.16$, $p < 0.001$), with no significant interactions.



Ammonium-N and nitrite-N showed no significant radial effect ($\text{NH}_4^+\text{-N}$: $F(3, 30) = 2.79$, $p = 0.058$; $\text{NO}_2^-\text{-N}$: $F(3, 30) = 0.45$, $p = 0.722$) and no Distance $\times$ Cohort interaction. Both varied strongly with depth ($\text{NH}_4^+\text{-N}$: $F(2, 20) = 76.27$; $\text{NO}_2^-\text{-N}$: $F(2, 20) = 20.94$; both $p < 0.001$), each with a significant Depth $\times$ Cohort interaction ($\text{NH}_4^+\text{-N}$: $F(6, 20) = 5.23$, $p = 0.002$; $\text{NO}_2^-\text{-N}$: $F(6, 20) = 8.11$, $p < 0.001$). Mean $\text{NO}_2^-\text{-N}$ differed among cohorts ($F(3, 10) = 13.64$, $p < 0.001$).

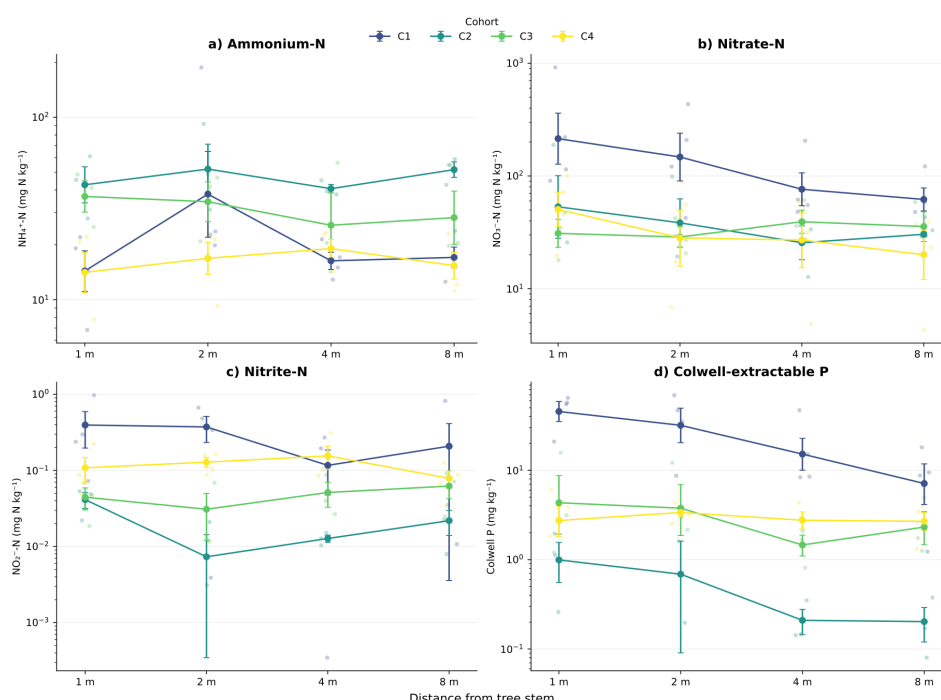


Figure 3. Distance distributions of mineral nitrogen and available phosphorus by cohort. Ammonium-N ($\text{NH}_4^+\text{-N}$), nitrite-N ($\text{NO}_2^-\text{-N}$), nitrate-N ($\text{NO}_3^-\text{-N}$) and Colwell-extractable P are shown at 1, 2, 4 and 8 m from the tree stem. For each tree, values were first averaged across the three auger-sampled depths; points show cohort means across independent trees and error bars show $\pm$ SE. Response axes use symmetrical-log scaling where required to retain zeros and small negative $\text{NO}_2^-\text{-N}$ values.

Soil Moisture

Gravimetric soil moisture did not decline towards the trees: it showed no significant distance effect ($F(3,30) = 1.71$, $p = 0.185$; supplementary Fig. S5), and no distance related interaction and no planned contrast against 8 m survived Holm adjustment. The estimated differences at 1, 2, 4 m were, if anything, slightly positive relative to 8 m. Moisture instead varied strongly with depth ($F(3, 30) = 48.58$, $p < 0.001$), and its vertical profiles differed among cohorts (Depth



457 $\times$ Cohort: $F(9, 30) = 24.75, p < 0.001$); mean moisture did not differ among cohorts ($F(3, 10)$
458 $= 1.83, p = 0.205$). Volumetric water content likewise showed no significant distance effect
459 ($F(3,30) = 1.31, p = 0.29$; near-tree [1–2 m] 0.038 vs 8 m $0.039 \text{ cm}^3 \text{ cm}^{-3}$; Fig. S8), because
460 the lower near-tree bulk density was offset by gravimetric moisture that did not decline toward
461 the stem. Accounting for the small volumetric gravel fraction (mean 1.2%) did not change this
462 result.

463

464 *Integrated radial and vertical soil property patterns*

465

466 The response-specific depth profiles showed lower measured surface BD and higher SOC and
467 TN closer to the tree stems, without a corresponding reduction in gravimetric soil moisture
468 (Fig. 4). Partial redundancy analysis supported this integrated pattern: across the transformed
469 and standardized three-depth matrix, soil properties varied significantly with distance after
470 accounting for depth and tree identity (pseudo- $F = 4.32$, unique $R^2 = 0.033, p < 0.001$; Fig. 5),
471 and this multivariate distance response did not differ among cohorts or depth Distance $\times$
472 Cohort, Distance $\times$ Depth and the three-way interaction all non-significant).

473 In the ordination, the SOC, total N, gravimetric moisture, nitrate-N, nitrite-N and
474 Colwell-extractable P vectors clustered together along the first axis, all pointing towards the
475 near-tree end of the distance gradient, whereas bulk density pointed in the opposite direction
476 (ammonium-N aligned mainly with the second axis); this shows visually that higher near-tree
477 carbon, nitrogen and phosphorus co-occurred with lower bulk density. Depth accounted for a
478 substantially larger component of the multivariate variation (pseudo- $F = 76.23$, unique $R^2 =$
479 $0.389, p < 0.001$), and vertical multivariate profiles differed among cohorts (Depth $\times$ Cohort:
480 pseudo- $F = 8.25$, unique $R^2 = 0.098, p < 0.001$).



Distance-resolved patterns in principal soil properties

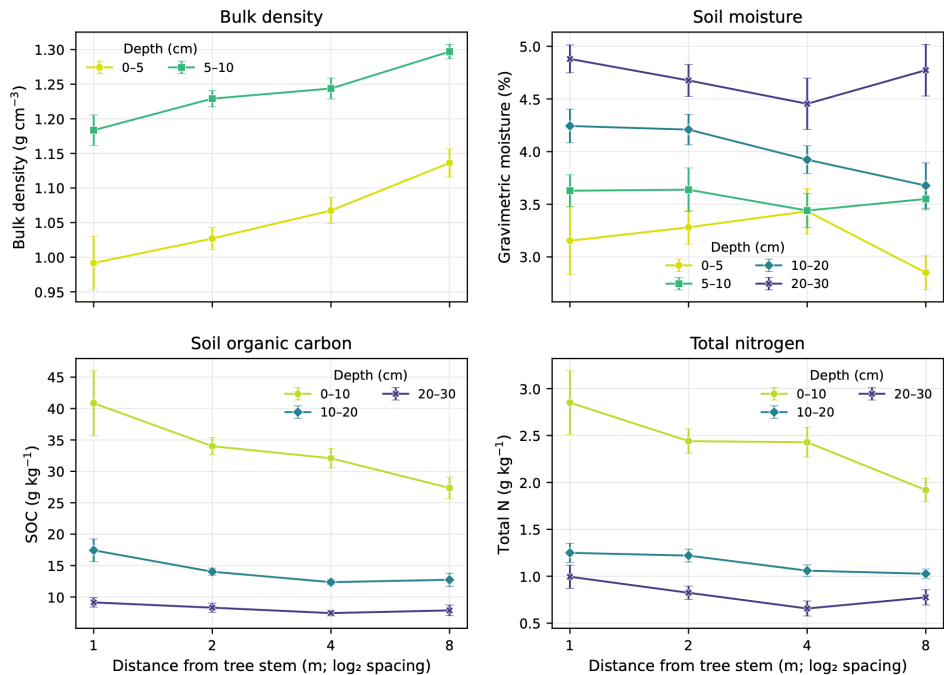
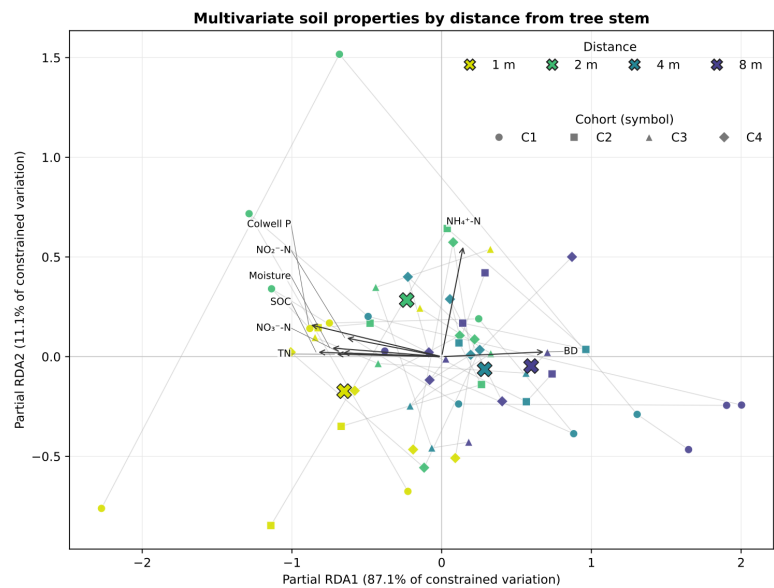


Figure 4. Distance-resolved patterns in four principal soil properties. Points show tree-level means $\pm$ SE for each response at 1, 2, 4 and 8 m from the tree stem ($\log_2$ spacing), plotted separately by depth layer. Bulk density is shown for the directly measured 0–5 and 5–10 cm ring cores; gravimetric moisture for four depth layers (0–5, 5–10, 10–20 and 20–30 cm); and SOC and total N for the auger-sampled 0–10, 10–20 and 20–30 cm layers. Distance was a significant predictor for bulk density ($F(3,30) = 14.00$, $p < 0.001$), SOC ($F(3,30) = 3.69$, $p = 0.023$) and total N ($F(3,30) = 3.67$, $p = 0.023$), but not for gravimetric moisture ($F(3,30) = 1.71$, $p = 0.185$). Statistical inference was based on the response-specific split-plot models with tree as the experimental unit.



Small symbols are tree-level partial scores, grey lines connect the four distances within each tree, X symbols are distance centroids, and arrows show response correlations.

Figure 5. Partial redundancy analysis of multivariate mineral-soil properties in relation to distance from the tree stem. The transformed and standardized response matrix comprised bulk density (BD), gravimetric moisture, SOC, total N (TN), $\text{NH}_4^+\text{-N}$, $\text{NO}_2^-\text{-N}$, $\text{NO}_3^-\text{-N}$ and Colwell-extractable P on the common 0–10, 10–20 and 20–30 cm grid. Soil depth and tree identity were conditioned before evaluating distance. Small circles show tree-level partial scores coloured by distance, X symbols show distance centroids, the line connects centroids from 1 to 8 m, and arrows indicate correlations of soil properties with the ordination axes. Distance alone explained 3.3% of the total standardized multivariate variance (pseudo- $F = 4.32$, $p < 0.001$; 9,999 permutations restricted within tree). The Distance $\times$ Cohort interaction was not significant (pseudo- $F = 1.45$, $p = 0.173$).

Estimated above and below ground carbon stocks

Fixed-depth 0–30 cm SOC stock did not differ significantly among the four categorical distances ($F(3,30) = 2.74$, $p = 0.061$), and there was no evidence that the radial pattern differed among cohorts (Distance $\times$ Cohort: $F(9,30) = 1.05$, $p = 0.425$). The estimated stock at 1 m was 14.9 Mg C ha⁻¹ higher than at 8 m, but the planned comparison did not remain significant after Holm adjustment (parametric $p = 0.056$; exact $p = 0.059$). The continuous-distance analysis nevertheless indicated a decline of 4.87 Mg C ha⁻¹ per doubling of distance ($t(10) = -2.81$, $p = 0.019$; exact $p = 0.019$).

When stocks were standardized to an equivalent soil mass, SOC stock varied significantly with distance ($F(3,30) = 3.71$, $p = 0.022$), while the Distance $\times$ Cohort interaction remained nonsignificant ($F(9,30) = 1.10$, $p = 0.391$). This difference was expected given the radial change in bulk density. Equivalent-mass SOC stock at 1 m was 16.5 Mg C ha⁻¹ higher than at 8 m (Holm-adjusted parametric $p = 0.019$; exact $p = 0.027$).



After weighting the four sampling distances by the areas of their corresponding concentric annuli, mean model-assisted 0–30 cm mineral-soil SOC stocks were 77.1, 60.3, 57.3 and 60.1 Mg C ha⁻¹ in C1, C2, C3 and C4, respectively. Projected 2025 whole-tree carbon densities were 46.2, 34.2, 40.0 and 7.3 Mg C ha⁻¹, giving combined soil-tree carbon estimates of 123.2, 94.5, 97.3 and 67.4 Mg C ha⁻¹, respectively (Fig. 6). Area-weighted mineral-soil SOC differed among cohorts ($F(3,10) = 13.79$, $p < 0.001$), as did projected whole-tree carbon ($F(3,10) = 6.76$, $p = 0.009$) and the combined soil tree-carbon estimate ($F(3,10) = 14.36$, $p < 0.001$). Whole-tree carbon represented approximately 37.5%, 36%, 41% and 11% of the combined soil-tree carbon estimate in C1–C4, respectively; mineral-soil SOC was therefore the larger component of this estimate in every cohort.

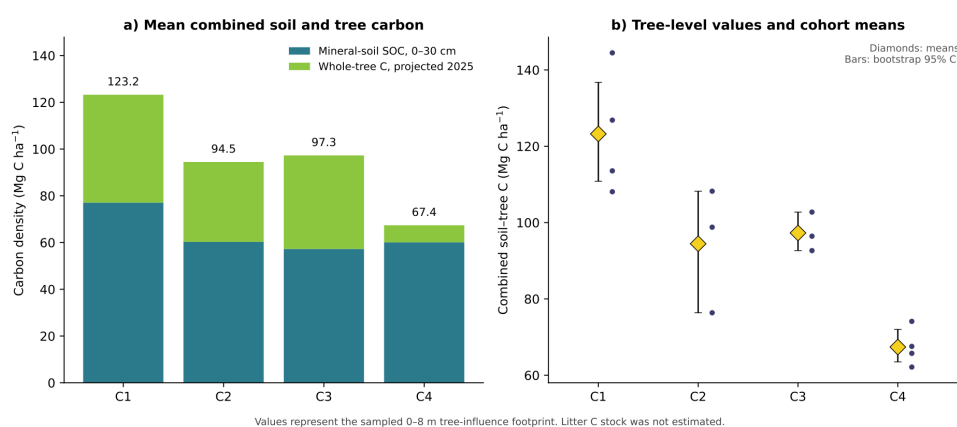


Figure 6. Soil-tree carbon estimates within the sampled 0–8 m tree-influence footprint across cohorts. (a) Stacked bars show cohort means of radially-area-weighted, model-assisted mineral soil SOC stock integrated to 0–30 cm and projected 2025 whole-tree carbon, expressed as footprint-normalised per-hectare equivalents (Mg C ha⁻¹). Values above the bars indicate the sum of the two carbon pools. (b) Blue circles show combined carbon pools for individual trees ($n = 3–4$ trees per cohort), yellow diamonds represent cohort means, and error bars show cohort-stratified bootstrap 95% confidence intervals. Whole-tree carbon includes above- and belowground living biomass represented in the i-Tree Eco inventory. These footprint-normalised values apply to the sampled circular footprint and do not represent a field-scale tree density. Litter carbon, deadwood and herbaceous biomass were not quantified; the combined values therefore represent soil-tree carbon estimates rather than total ecosystem carbon.

4. Discussion

4.1 A shared radial soil functional footprint around trees

The principal finding of this study was that proximity to tree stems structured a coherent but property-specific soil functional footprint across the four cohorts (Fig. 3). Directly measured bulk density was lower at 1, 2 and 4 m than at the 8 m reference position, whereas



SOC concentration was 29.6% higher at 1 m and declined by an estimated 8.2% with each doubling of distance. This finding supported Hypothesis 1, as did Total N, nitrate-N and Colwell-extractable P declining with distance, while soil moisture showed no significant radial decline. Distance $\times$ Cohort interactions were not significant for bulk density, SOC, total N or moisture, providing no evidence that their radial patterns differed among cohorts. The detectable extent of the tree footprint was soil property dependent: the bulk-density response remained evident at 4 m, whereas SOC enrichment was localised at 1 m and the nutrient responses were expressed more clearly as overall or continuous gradients than as uniformly significant reference contrasts. Together, these responses identify a near-tree zone characterised by lower surface bulk density and greater carbon and nutrient concentrations without a corresponding reduction in gravimetric soil moisture. The partial redundancy analysis supported this integrated interpretation (Fig. 4). After accounting for depth and the repeated observations within trees, distance explained a significant component of the joint soil-property matrix (unique $R^2 = 0.033$), supporting Hypothesis 3. The multivariate distance response did not differ significantly among cohorts, and consistent with the largely non-significant Distance $\times$ Depth interactions, the radial effects were not just concentrated in the surface layers, providing only partial support for Hypothesis 2. Depth accounted for a larger proportion of the multivariate variation (unique $R^2 = 0.389$), as expected for vertically stratified soil profiles, but distance retained a distinct explanatory contribution after accounting for vertical structure and tree identity. Tree proximity therefore introduced a lateral dimension of soil heterogeneity that was detectable across the three sampled mineral-soil depth layers (0-10, 10-20 and 20-30 cm).

These results are consistent with previous literature on tree “fertility-islands”, in which organic matter and nutrients become spatially concentrated around woody plants (Ding and Eldridge, 2021; Hoosbeek et al., 2016; Pardon et al., 2017; Waring et al., 2015). At the same arboretum, Ryan et al., (2024) demonstrated radial variation in surface SOC concentration around individual trees. The present study advances that evidence by resolving the 0–30 cm mineral-soil profile with response-specific sampling grids and integrating SOC concentration with directly measured surface bulk density, fixed-depth and equivalent-soil-mass SOC stocks, total and mineral N, available P, soil moisture and multivariate soil structure within the same 0–8 m footprint. It thus provides a depth-resolved characterisation of how multiple soil functions co-vary around individual trees in a semi-arid arboretum–grassland environment.

Several non-exclusive processes could generate the observed co-occurrence of higher SOC and total N with lower bulk density near trees. Litter deposition, fine-root turnover and



rhizodeposition can increase organic inputs, while microbial products, aggregation and pore development can connect carbon accumulation with changes in soil physical structure (Cotrufo et al., 2013; Gan et al., 2021; Lavalley et al., 2020; Six et al., 2002; Tisdall and Oades, 1982). The co-occurrence of lower bulk density with higher SOC and total N is therefore consistent with conceptual models in which organic inputs and biological soil structuring reinforce one another. The close association ($R^2 = 0.906$) between SOC and total N across the mineral soil samples, together with the absence of a significant distance response in C:N, indicates that C and N concentrations were tightly coupled across the radial footprint. This proportional response points to coordinated organic-matter and nitrogen accumulation near trees rather than enrichment of one element in isolation. The nutrient pools differed in their spatial expression. Colwell P and nitrate-N varied with distance, whereas ammonium-N and nitrite-N did not. For Colwell-extractable P, the near-tree enrichment was concentrated in the surface mineral soil (25.8 vs 1.4 mg kg⁻¹ near-far difference at 0–10 and 20–30 cm; significant Distance × Depth interaction), supporting the surface-focused element of Hypothesis 2. SOC, total N and extractable P can integrate spatially concentrated inputs and retention over longer periods, whereas mineral-N forms represent smaller and more rapidly cycling pools; the nitrate response therefore identifies a contemporaneous mineral-N gradient rather than a uniform response across all inorganic N forms. Overall, the combined univariate and multivariate evidence identify a shared radial soil functional footprint around trees. This footprint integrated improved surface physical condition, enhanced SOC and total N, spatial variation in nitrate-N and Colwell P, demonstrating that individual trees structured several dimensions of soil condition simultaneously within the surrounding grassland matrix.

4.2 No detectable near-tree moisture deficit under end-of-summer conditions

Gravimetric soil moisture did not decline significantly towards the trees during the end-of-summer sampling campaign. In fact, relative to the 8 m reference position, the measured moisture content was higher at all three nearer distances (+0.264% at 1 m, +0.238% at 2 m and +0.100% at 4 m) although this was not statistically significant. This absence of a radial decline was consistent across cohorts and depth layers (all distance-related interactions non-significant). Soil moisture was instead structured vertically, varying strongly with depth, and differed among cohorts, whereas distance did not alter this depth-dependent pattern. This absence of a near-tree moisture deficit supports the moisture component of Hypothesis 1, confirming that the improved near-tree soil condition was not accompanied by a water penalty



under the end-of-summer conditions sampled. Expressing soil water on a volumetric basis confirmed that this pattern was not an artefact of the radial bulk-density gradient. Because near-tree bulk density was lower, we recalculated soil water as volumetric water content ($VWC = \text{gravimetric moisture} \times \text{bulk density}$) for the directly measured 0–5 and 5–10 cm layers; VWC showed no significant radial trend (Fig. S8), as the lower near-tree bulk density was offset by gravimetric moisture that did not decline toward the stem. The absence of an end-of-summer moisture penalty near trees therefore holds on both a gravimetric and a volumetric basis. The lower bulk density and greater SOC concentrations observed in the near-tree zone likely support water retention by improving soil structure, porosity and infiltration (Bargués Tobella et al., 2014). These soil physical improvements could offset competition for water from the trees. Under increasing abiotic stress, facilitative effects associated with neighbouring plants can also become more important relative to competitive interactions (i.e. the Stress Gradient Hypothesis - (Bertness and Callaway, 1994; Butterfield et al., 2016)). In the present system, canopy shade and reduced exposure to solar radiation could lower surface temperatures and evaporative demand near trees, partially balancing water uptake by woody roots. Hydraulic redistribution, where deeply rooted woody plants redistribute water towards drier portions of the soil profile (Lee et al., 2021), could also contribute but were not tested here and are noted only as possibilities. Because hydrological responses to trees vary widely with climate, rooting, canopy structure and soil (Mitrová et al., 2025; Rubeaud et al., 2026), the present findings add a Mediterranean-climate example in which scattered trees did not generate the expected near-tree moisture deficit at the end of the summer dry season.

641

642 *4.3 Cohort differences occurred mainly in vertical structure and soil-tree carbon estimate* 643 *partitioning*

644

The principal radial responses were broadly shared among cohorts, whereas cohort differentiation was expressed selectively through soil property concentrations, vertical organisation and soil-tree carbon estimate partitioning. Vertical profiles differed among cohorts for SOC, gravimetric moisture, ammonium-N, nitrite-N and Colwell P, but not for directly measured surface BD, total N, C:N or nitrate-N. This separation reveals two complementary dimensions of tree influence: a lateral footprint extending away from the stem and cohort-associated differences in how particular soil properties were distributed through the mineral profile.



653 The organic litter provided an additional expression of cohort differentiation, with mean
654 litter C concentration highest in C3 and lowest in C1. Mean mineral-soil SOC and total N, by
655 contrast, were not significantly different among cohorts after the chemical layers were
656 restricted to the valid auger samples. Thus, cohort differences in the organic layer did not
657 translate into uniform differences in all mineral-soil C and N metrics. Cohort differentiation
658 became clearer when soil and tree carbon were considered together: area-weighted mineral-
659 soil SOC, projected 2025 whole-tree carbon and their combined soil-tree carbon estimate all
660 differed significantly among cohorts. The sampled cohorts were therefore associated not only
661 with different total carbon densities within the footprint but also with different partitioning
662 between mineral soil and living tree biomass. Replicated common-garden studies show that
663 tree identity, functional traits and productivity can influence bulk density, SOC, nutrient pools
664 and soil biological communities, while broader syntheses indicate that these effects are also
665 mediated by stand age and environmental context (Peng et al., 2020; Shi et al., 2025;
666 Stefanowicz et al., 2021; Waring et al., 2022). Here, cohort represents the combined ecological
667 context of tree size, age, canopy architecture, rooting and litter environments, and
668 establishment history rather than an isolated contrast of any one trait. Including cohort was
669 therefore analytically informative because it separated the radial pattern evident across the
670 sampled trees from group-associated differences in mean soil conditions, vertical structure and
671 soil-tree carbon estimate partitioning. The absence of Distance $\times$ Cohort interactions for the
672 principal responses provided no evidence that the direction of the radial footprint differed
673 among cohorts, whereas the cohort and Depth $\times$ Cohort results located much of the between-
674 group heterogeneity in mean levels and vertical organisation. By showing that the radial
675 footprint held consistently across four contrasting cohorts, the cohort analysis strengthens
676 support for the shared radial footprint predicted in Hypothesis 1, while the cohort and Depth $\times$
677 Cohort differences identify group-level patterns in vertical structure and carbon partitioning
678 that can guide hypotheses for future replicated, trait-based comparisons.

679

680 ***4.4 From SOC concentration to SOC stock and combined soil-tree carbon estimates***

681

682 Translating SOC concentration to SOC stock is central to interpreting the radial
683 response. Fixed-depth SOC stock integrated to 0–30 cm did not differ significantly among the
684 four categorical distances, although the continuous analysis indicated a decline of 4.87 Mg C
685 ha⁻¹ with each doubling of distance. When stocks were standardised to an equivalent soil mass,
686 the radial signal became clearer: distance was significant and SOC stock at 1 m exceeded that



687 at 8 m by 16.5 Mg C ha⁻¹ after Holm adjustment. These results support Hypothesis 4 and
688 represent complementary views of the same soil profile. Fixed-depth stocks quantify carbon
689 within a common soil volume, whereas equivalent soil mass stocks compare locations on a
690 common fine-earth mass basis. Because bulk density increased with distance from the trees,
691 accounting for differences in soil mass revealed carbon enrichment that was partly attenuated
692 in the fixed-volume comparison (Cardinael et al., 2017; Ellert and Bettany, 1995). Spatial
693 aggregation was equally important when moving from individual sampling positions to the
694 entire 0–8 m tree-influence footprint. After weighting each distance by the area of its
695 corresponding concentric radially, mean 0–30 cm mineral soil SOC ranged from 57.3 to 77.1
696 Mg C ha⁻¹ among cohorts. Projected 2025 whole-tree carbon contributed a further 7.3–46.2 Mg
697 C ha⁻¹, producing combined estimates of soil (below-ground) and tree (above and below
698 ground) carbon of 67.4–123.2 Mg C ha⁻¹. Mineral soil SOC was the larger component of this
699 estimate in every cohort, representing approximately 59–89% of the combined soil-tree carbon
700 estimate, while the contribution from standing tree biomass ranged from 11% in C4 to 41% in
701 C3.

702 Our spatially explicit approach has direct relevance for carbon monitoring and
703 accounting in landscapes containing scattered trees. Tree-associated soil properties changed
704 over distances of only a few metres, so the estimated mean depends on where samples are
705 collected and how those positions are aggregated. A transparent accounting workflow should
706 therefore combine depth-resolved SOC concentrations, bulk density, coarse-fragment
707 corrections and explicit radial weighting with measurements of tree biomass, density and
708 spatial arrangement. This is consistent with evidence that both soil and biomass make
709 substantial contributions to agroforestry carbon stocks and with calls for more explicit
710 representation of trees on farms in monitoring, reporting and verification systems (Cardinael
711 et al., 2017, 2025; Rosenstock et al., 2019). Spatial prediction and digital soil-mapping
712 approaches can subsequently extend such field-calibrated measurements across larger
713 management units while propagating uncertainty (Wadoux et al., 2026)

714 The same framework is relevant to tree management and revegetation planning. Tree
715 spacing and spatial arrangement determine the proportion of a plot that falls within near-tree
716 influence zones, while tree size and cohort characteristics affect the division of carbon between
717 soil and standing biomass. The observed 0–8 m gradients can therefore help inform where soil
718 monitoring should be concentrated and how tree-centred measurements can be translated into
719 field-scale scenarios with explicit tree densities. Rather than treating scattered trees as spatially
720 negligible elements, the results support their inclusion as structured components of soil-carbon



inventories and as potential management units for maintaining soil condition, nutrient retention and carbon storage (Pardon et al., 2017; Rosenstock et al., 2019).

4.5 Implications for monitoring, scope of inference and future directions

The study was designed as a quasi-experimental comparison of established trees in a shared arboretum–grassland environment. Cohorts were not randomly assigned, and the individual species represented within them were not replicated as species-level treatments. Cohort effects therefore describe associations among the sampled groups of trees rather than causal species effects. Similarly, the 8 m position provides a consistent far-distance reference within the sampled footprint but is not equivalent to a randomised treeless control. These design features define the scale at which the results are most directly applicable: radial and vertical soil variation around individual established trees within the common study environment. The measurements also identify clear opportunities for resolving the processes underlying this spatial footprint. Gravimetric moisture represented the end-of-summer conditions within the upper 30 cm when moisture stress would be expected to be most acute, while mineral-N concentrations represented pool sizes at the time of sampling rather than transformation rates. Litter C concentration was available without litter dry mass per unit ground area, and SOC was not separated into particulate and mineral-associated fractions. Root distributions, aggregate stability and microbial transformations were not measured. In the carbon assessment, deeper-layer bulk density was model-assisted, measured 0–10 cm CFv was carried through the deeper layers in the primary calculation, whole-tree carbon was projected from the earlier inventory, and the combined soil-tree carbon estimate excluded litter stock, deadwood and herbaceous biomass. These boundaries distinguish the combined soil-tree carbon estimate from total ecosystem carbon and define the measurements needed for a more complete mechanistic and whole-system assessment. Critically, the near-tree zone combined higher SOC, nitrogen and available phosphorus with no detectable end-of-summer moisture deficit, indicating that the fertility-island benefit is not offset by a dry-season water cost at the most water-limited time of year. In grazed grassland and silvopastoral systems this is relevant for forage supply, as scattered and paddock trees can raise understorey pasture biomass and improve soil condition (Addo-Danso et al., 2025) and can buffer the impact of a warming, drying climate on pasture production and quality (Hidalgo-Galvez et al., 2022). It would also be worthwhile to test the transferability of this radial framework to operational dryland cropping systems to assess the potential benefits of integrating trees. Repeated soil-moisture measurements extending to 1 m



depth, paired with spatially calibrated vegetation observations, would test whether the end-of-summer pattern persists across seasons and whether belowground water dynamics correspond to crop responses. More broadly, combining temporal soil-water profiles with high-resolution remote sensing and explicit tree-layout information would support the translation of tree-centred soil and carbon measurements to field-scale monitoring and management, addressing recognised needs for deeper, temporally resolved and spatially explicit evaluation of agroforestry systems (Mitrová et al., 2025; Terasaki Hart et al., 2023).

5. Conclusion

Across four contrasting tree cohorts, tree proximity structured a shared soil functional footprint characterised by lower directly measured surface bulk density, higher SOC and total N, radial variation in nitrate-N and Colwell-extractable P, and no detectable end-of-summer moisture deficit. This lateral structure remained significant in the multivariate soil property matrix after vertical depth variation and repeated observations within trees were accounted for. Cohort differences were expressed mainly through selected mean soil properties, vertical profiles and the partitioning of carbon between mineral soil and living tree biomass.

The comparison of SOC concentration, fixed-depth stock and equivalent-soil-mass stocks demonstrated why bulk density and soil mass must be incorporated when interpreting carbon enrichment around trees. Radially weighting area further showed how distance-resolved observations can be aggregated transparently within a defined tree-influence footprint. Together these results provide a transferable framework for monitoring scattered trees as structured components of grassland soil function and carbon storage. The findings also reinforce the need for spatially explicit soil sampling and combined accounting of soil and tree carbon when evaluating the contribution of individual trees to managed landscapes.

The absence of a dry-season moisture penalty alongside near-tree carbon and nutrient enrichment suggests that retaining scattered trees in grazed grasslands can reinforce soil function and forage resilience under a drying climate; a link that warrants direct measurement of understorey production in future work.



789 **Code, Data and Sampling availability**

790

791 The extensive analytical datasets, statistical tests, and detailed sampling methodologies are
792 fully available within the article's electronic supplement. The underlying raw dataset can be
793 provided by the corresponding author upon reasonable request.

794

795 **Authors contributions (CRediT)**

796

797 Ana Paula Ferreira de Brito: Conceptualization; Methodology; Investigation; Data curation;
798 Formal analysis; Visualization; Writing – original draft; Writing – review & editing; Project
799 administration; Software, Funding acquisition.

800

801 Luke Mosley: Conceptualization; Methodology; Investigation; Formal Analysis, Supervision;
802 Writing – review & editing; Resources; Software, Funding acquisition and Validation.

803

804 Mark Farrell: Conceptualization; Methodology; Investigation, Formal Analysis, Supervision;
805 Writing – review & editing; Funding acquisition, Software and Validation.

806

807 **Competing interests**

808

809 The authors declare no competing interests.

810

811 **Statement on inclusion in global research**

812

813 This study was conducted in South Australia by researchers based in Australia at the time of
814 the research; no international travel or samples from other countries were involved.

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816 **Disclaimer**

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839 **6. References**

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