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Tree Species Identity Outweighs Provenance in Shaping Soil Organic Carbon Storage in an Arid Industrial Plantation, Northern Persian Gulf

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Research Article

Keywords: Soil organic carbon, Tree species identity, Provenance, Dryland agroforestry, Species selection, Variance partitioning

Posted Date: November 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11829839/v1

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Additional Declarations: The authors declare no competing interests.

Abstract

Soils beneath planted trees are a durable carbon sink, yet species-selection guidance for hyper-arid plantings rests on evidence from mesic forests and on the assumption that native species outperform introduced ones. In the hyper-arid South Pars industrial zone on the northern Persian Gulf coast, we sampled soils beneath three trees each of three native (*Phoenix dactylifera*, *Ziziphus spina-christi*, *Prosopis cineraria*) and three introduced species (*Eucalyptus camaldulensis*, *Callistemon viminalis*, *Conocarpus erectus*) at 0–10 and 10–30 cm, and partitioned variation in soil organic carbon between species identity and provenance with split-plot analysis of variance, multivariate variance partitioning, exact permutation tests and mixed models. Species identity explained 46% of multivariate soil dispersion and 77% of variance in log-transformed carbon, whereas provenance explained 12% and could not be separated from species-within-category variation. *Phoenix dactylifera* held 2.46% carbon versus 0.59% under *Conocarpus erectus*, a 4.2-fold range not sorted by provenance. Carbon declined 33% from 0–10 to 10–30 cm in 17 of 18 trees with parallel species profiles, and covaried negatively with clay, consistent with input rather than mineral limitation; indicative 0–30 cm stocks spanned 20.6–98.4 Mg carbon per hectare. Species-specific organic inputs, not provenance labels or mineralogical capacity, govern soil carbon in this input-limited system, extending the species-identity rule of mesic forests to the hyper-arid extreme. Plantation and agroforestry programmes in arid regions should therefore select at the species level, prioritising high-input taxa such as date palm and jujube, rather than applying native-versus-introduced rules.

1 Introduction

Soils store more carbon than the atmosphere and vegetation combined, and their management is central to climate mitigation in farming and forestry (Lal 2004; Jenkinson et al. 1991), while subsoil turnover remains poorly characterised (Jenkinson and Coleman 2008). Across the drylands, tree planting — on farms, in shelterbelts, around industry and towns — is promoted for dust suppression, amenity and carbon storage: trees add substantially to urban carbon stocks (Nowak and Crane 2002; Pouyat et al. 2006), management alters their biogeochemistry (Groffman et al. 2009), and dryland soils can gain carbon where inputs are sustained (Woomer et al. 2004). Yet in arid landscapes the choice of tree species for such plantings is still made on horticultural grounds — nursery availability, growth rate, dust capture — rather than on measured soil-carbon outcomes. No quantitative basis exists for deciding whether these plantings should be designed around native species, introduced ornamentals, or particular species regardless of origin.

Two research frontiers define the state of the art against which any such decision must now be judged. First, in mesic temperate and boreal forests, tree species identity has emerged as a first-order control on soil carbon: forest-floor and topsoil carbon differ substantially among species in common gardens and paired plots (Vesterdal et al. 2013; Andivia et al. 2016; Cha et al. 2019; Díaz-Pinés et al. 2011; Diers et al. 2021; Steffens et al. 2022a; Ureña-Lara et al. 2026; Waring et al. 2022), identity commonly outweighs species mixing or diversity as a driver of stocks and soil properties (Cremer et al. 2016; Dawud et al. 2016; Osei et al. 2021; Tang et al. 2024; Blaško et al. 2020), and global syntheses ascribe topsoil differences to functional type, mycorrhizal association and nitrogen-fixing ability (Hou et al. 2020; Peng et al. 2020). Mechanistic work attributes the signal to litter quantity and quality (Hüblová et al. 2026), root placement (Angst et al. 2019), microbial processing (Beugnon et al. 2023; Lorenz and Thiele-Bruhn 2019; Zheng et al. 2022; Wei et al. 2026),

mycorrhizal chemistry (Hicks Pries et al. 2023), nitrogen-fixer lipids (Ye et al. 2022, 2024) and mineral or aggregate stabilisation (Li et al. 2024; Liang et al. 2021; Staszel-Szlachta et al. 2025; Su et al. 2021). Second, a parallel literature asks whether provenance matters: a global meta-analysis found non-native forests hold more total carbon through aboveground biomass while natives hold more in soil (Lázaro-Lobo et al. 2025), and native mangroves and urban trees can outperform introduced counterparts in soil carbon (He et al. 2018, 2020; Jevon et al. 2025; Zhang et al. 2022). Because soil is the more durable pool, a native advantage in soil carbon, if general, would be the decisive argument for native-first planting policies.

Three gaps prevent this evidence from guiding plantings in arid regions. Almost all of it comes from mesic forests where organic inputs are large and mineral surfaces well supplied; in hyper-arid irrigated plantings, inputs are small, episodic and irrigation-dependent, and the input–protection balance that structures temperate soils may not hold — an untested extrapolation, even though tree effects on soil carbon strengthen under aridity (Yan et al. 2026), trait effects interact with site properties (Augusto and Boča 2022) and species rankings transfer poorly across climates (Razzaghi 2026). Persian Gulf evidence is sparse and restricted to single-genus native–invader contrasts in riparian forests (Moslehi Jouybari et al. 2022; Moslehi et al. 2025), which do not address the ornamental taxa that dominate regional plantings. And methodologically, plantation comparisons are usually observational, with species placed by planting decisions rather than random assignment, and with depths beneath few trees analysed as independent replicates, inflating precision (Hurlbert 1984); managed systems add a silvicultural signal difficult to separate from biology (Mayer et al. 2020). Finally, "native" is a provenance label, not a mechanism: functional traits vary more within than between provenance categories, so any category effect is an average of species effects rather than a causal property of origin.

The South Pars energy complex at Assaluyeh on Iran's northern Persian Gulf coast offers a demanding test. It is the country's largest industrial development, set on a hyper-arid coast (less than 200 mm winter rainfall, summer maxima above 45°C) on saline calcareous soils, where extensive amenity and shelterbelt planting runs along two traditions: locally native trees (*Phoenix dactylifera* L., *Ziziphus spina-christi* (L.) Desf., *Prosopis cineraria* (L.) Druce) and introduced ornamentals valued for rapid establishment (*Eucalyptus camaldulensis* Dehnh., *Callistemon viminalis* (Sol. ex Gaertn.) G. Don, *Conocarpus erectus* L.), the latter planted at massive scale across Gulf states over two decades. **Hypothesis** Because soil organic carbon in these hyper-arid plantings accumulates under small episodic inputs on coarse calcareous substrates whose mineral surfaces are far from saturated, we hypothesise that (H1) variation in soil organic carbon among stands is governed primarily by tree species identity — the traits controlling litter quantity, root turnover and input placement — and not by the native-versus-introduced dichotomy, so that species rankings will not sort by provenance and any provenance tendency will shrink once species-within-category variation and edaphic setting are accounted for; and (H2) carbon declines with depth under all species as a common response to surface-dominated inputs, giving parallel profiles in which surface carbon enrichment accompanies downward clay translocation, so that carbon covaries negatively with clay at these narrow clay contents and organic supply — not mineral protection capacity — is binding. As a secondary expectation, following the global belowground pattern (Lázaro-Lobo et al. 2025), we anticipate a positive but weak native tendency. **Objectives** (1) to partition soil carbon variation between species identity and provenance under a design treating the individual tree as the unit of replication; (2) to test whether any provenance effect survives adjustment for edaphic setting and the nested structure of the design; and (3) to characterise the vertical distribution of carbon —

concentrations, stratification and depth-weighted stocks — on a profile basis relevant to management. Resolving identity against provenance for the first time in a hyper-arid irrigated planting converts a global debate into an operational selection rule for dryland agroforestry and greening programmes.

2 Materials and methods

2.1 Study area

Fieldwork took place in the South Pars industrial zone at Assaluyeh, Bushehr Province, southern Iran (27°28' N, 52°36' E) on the northern Persian Gulf shore. The climate is hyper-arid, with mean annual temperature 25–35°C, summer maxima above 45°C, annual rainfall generally below 200 mm falling in winter, and high humidity year-round. Soils are shallow, calcareous and alkaline, developed on Quaternary alluvium over marine sediments, with elevated salinity near the coast. The plantings are supported by supplementary irrigation, without which none of the six examined species would persist.

2.2 Experimental design

We used a balanced split-plot (mixed-design) observational structure: six tree species × three replicate trees per species × two soil depths per tree = 36 composite samples. Stands of comparable age and management were selected within the zone so that species contrasts would not be confounded by establishment date, and three trees per species (18 in total) were chosen at random among eligible stands. This is the observational analogue of the common-garden approach used to isolate species effects on forest soils (Vesterdal et al. 2013; Waring et al. 2022), with the explicit caveat that assignment of species to planting positions was not under our control. The individual tree is the unit of replication; the two depths are repeated measures within each tree. Sampling was conducted in late winter (February 2016), at the end of the cool rainy season.

2.3 Treatments: tree species and soil depth

The primary treatment was tree species at six levels. The native group comprised *Phoenix dactylifera* (date palm; monocot with fibrous adventitious roots and coarse frond litter), *Ziziphus spina-christi* (jujube) and *Prosopis cineraria* (deep-rooted leguminous phreatophyte). The introduced group comprised *Eucalyptus camaldulensis*, *Callistemon viminalis* and *Conocarpus erectus*, all widely planted in the zone and across Gulf states. The secondary treatment was soil depth (0–10 cm surface; 10–30 cm subsoil), representing the rooted, irrigated solum. Provenance (native versus introduced) was treated as a grouping factor evaluated with species — not individual samples — as its replicates, because provenance is a species-level attribute.

2.4 Specific analyses: soil sampling and laboratory determinations

Soil was collected with an auger beneath each tree at 0–10 and 10–30 cm at a consistent position relative to the trunk; each sample was a composite of several cores bulked into sealed bags. Samples were air-dried, cleared of visible plant debris and passed through a 2 mm sieve. Organic carbon was determined by wet dichromate oxidation (Walkley and Black 1934): 1 g air-dry soil (< 0.5 mm) digested with 10 mL 1 N potassium dichromate and 20 mL concentrated sulphuric acid; after 30 min, 100 mL distilled water and 10 drops of ferroin indicator were added, and excess dichromate back-titrated against ammonium ferrous

sulphate; carbon (%) = M × (V_1 − V_2)/S with M the titrant normality and S the soil mass. Organic matter was obtained with the Van Bemmelen factor (1.724 × carbon) and is reported descriptively only, being a deterministic multiple of organic carbon. Texture was measured by the hydrometer method (Bouyoucos 1962): 50 g soil dispersed in 100 mL 4% sodium hexametaphosphate, made to 1 L, hydrometer readings at 40 s and 2 h under temperature correction, sand by difference. Fractions were closed to 100% and classes assigned with the USDA triangle (Soil Survey Division Staff 1993), recomputed from closed fractions (22 sandy loam, 14 loam). Analyses were performed by a certified consulting laboratory (Arazist Parsian Mehr Consulting Co.). Indicative stocks were computed as stock (Mg C ha⁻¹) = carbon (%) × bulk density (g cm⁻³) × thickness (cm) with a constant bulk density of 1.4 g cm⁻³, recomputed at 1.2 and 1.6 g cm⁻³ and with pedotransfer estimates as sensitivity checks (Table 5); stocks are indicative, not measured.

Table 5
Indicative soil organic carbon stocks by species and depth increment (Mg C ha⁻¹; means with SD of three trees at bulk density 1.4 g cm⁻³)

Species	Provenance	0–10 cm	10–30 cm	Total 0–30 cm	Total at Bd 1.2–1.6	Pedotransfer Bd
Phoenix dactylifera	Native	39.6 (13.0)	58.7 (19.5)	98.4 (32.5)	84.3–112.4	92.2
Ziziphus spina-christi	Native	21.2 (7.3)	32.8 (8.5)	54.0 (14.7)	46.2–61.7	55.7
Eucalyptus camaldulensis	Introduced	19.4 (14.1)	29.1 (13.1)	48.5 (8.0)	41.6–55.4	49.8
Prosopis cineraria	Native	17.4 (8.4)	20.6 (8.7)	38.0 (16.5)	32.6–43.4	40.2
Callistemon viminalis	Introduced	16.8 (3.7)	21.4 (7.0)	38.2 (10.2)	32.8–43.7	40.8
Conocarpus erectus	Introduced	12.4 (5.4)	8.2 (1.3)	20.6 (5.0)	17.7–23.5	22.6

Note Stock = carbon (%) × bulk density (g cm⁻³) × thickness (cm); bulk density was not measured, so stocks are indicative rather than measured. The ranking of extremes is invariant across bulk densities 1.2–1.6 g cm⁻³ and pedotransfer estimates. The 10–30 cm layer holds the larger stock in five of six species (28.5 vs 21.1 Mg C ha⁻¹ overall)

2.5 Statistical analysis

Organic carbon was right-skewed and natural-log transformed for parametric modelling, restoring normality of residuals (Shapiro–Wilk W = 0.979, p = 0.727) and homogeneity across species (Levene p = 0.406). The primary model was a balanced split-plot ANOVA on ln-carbon: species (between-tree, 5 df) tested against tree-within-species (error a, 12 df), depth (1 df) and the interaction (5 df) against depth × tree-within-species (error b, 12 df), Type II sums of squares, partial eta squared (ηp^2) as effect size; the model was fitted to raw carbon and to texture, with Aligned Rank Transform and tree-mean analyses (n = 18) as sensitivity checks. Species contrasts used Tukey's honestly significant difference on tree-level means as a compact letter display (Piepho 2004); depth effects used paired t tests (Cohen's dz) and Wilcoxon signed-rank tests within

trees. Provenance was tested at two levels: descriptively at the sample level (Welch's t, Mann–Whitney U, Hedges' g, bootstrap confidence intervals from 10,000 resamples, Benjamini and Hochberg 1995 false-discovery control), and inferentially with species as replicates (nested ANOVA, exact permutation over 20 allocations of species means, mixed model with species as random intercept, retrospective power). Multivariate structure was tested by permutational multivariate analysis of variance on Euclidean distances (9,999 permutations; Anderson 2001) and summarised by principal component analysis of z-standardised variables (loadings in Online Resource 1, Table S2); Pearson and Spearman correlations (Holm-adjusted) and partial correlations quantified relations. Analyses used Python 3.13 with fixed seeds; $\alpha = 0.05$. The sample-level record was audited against the laboratory report (Online Resource 1, Table S1): label irregularities resolved by the balanced design rule, three non-conforming particle-size sums closed to 100%, six laboratory texture labels corrected to USDA classes, and one inverted depth pair retained as recorded, with sensitivity analyses confirming no inference depends on these choices (Online Resource 1, Table S3). No outliers were present (maximum studentised residual 3.11).

3 Results

Organic carbon varied more than fivefold across the 36 samples (0.24–3.72%, mean 1.26%, CV 63%) whereas particle-size fractions were conservative (Table 1), and all samples fell in sandy loam or loam, so species were compared on broadly similar substrates. Species identity explained the dominant share of ln-carbon variance ($F(5, 12) = 8.01$, $p = 0.002$, $\eta p^2 = 0.77$; raw-scale $F = 6.12$, $p = 0.005$), with the interaction negligible ($p = 0.54$) and all sensitivity analyses concordant (Table 2). Species means ranked *P. dactylifera* (2.46%) > *Z. spina-christi* (1.34%) > *E. camaldulensis* (1.21%) > *P. cineraria* (0.99%) ≈ *C. viminalis* (0.98%) > *C. erectus* (0.59%) — a 4.2-fold range (Table 1, Fig. 1a). Tukey comparisons separated *P. dactylifera* (group a) from *C. erectus* ($p = 0.003$), *C. viminalis* ($p = 0.016$), *P. cineraria* ($p = 0.016$) and *E. camaldulensis* ($p = 0.046$), with *Z. spina-christi* intermediate (Table 1). The ranking did not sort by provenance: introduced *E. camaldulensis* ranked third, above two natives. Adjusting for silt, clay and depth did not remove the species signal ($F(5, 27) = 11.0$, $p < 0.001$).

Table 1

Descriptive statistics for soil organic carbon and particle-size fractions under the six tree species (36 composite samples; closed fractions), with Tukey groupings on tree-level means. Organic matter (1.724 × carbon) adds no independent information and is omitted

Species	Provenance	n trees	SOC mean (SD) %	SOC range %	SOC 0–10 cm %	SOC 10–30 cm %	Sand %	Silt %	Clay %	Tukey group
Phoenix dactylifera	Native	3	2.46 (0.84)	1.38–3.72	2.83	2.10	62.4	26.2	11.4	a
Ziziphus spina-christi	Native	3	1.34 (0.42)	0.89–1.87	1.51	1.17	43.3	43.0	13.7	ab
Eucalyptus camaldulensis	Introduced	3	1.21 (0.73)	0.43–2.43	1.38	1.04	63.3	26.4	10.2	b
Prosopis cineraria	Native	3	0.99 (0.51)	0.48–1.92	1.24	0.74	50.0	35.9	14.2	b
Callistemon viminalis	Introduced	3	0.98 (0.33)	0.49–1.43	1.20	0.77	57.1	28.6	14.3	b
Conocarpus erectus	Introduced	3	0.59 (0.41)	0.24–1.19	0.89	0.29	55.9	30.7	13.4	b
All samples	—	18	1.26 (0.79)	0.24–3.72	1.51	1.02	55.3	31.8	12.9	—

Note n = 3 trees per species (6 samples). Tukey honestly significant difference on tree-level means; species sharing a letter do not differ at α = 0.05 (*P. dactylifera* vs *C. erectus* p = 0.003, vs *C. viminalis* p = 0.016, vs *P. cineraria* p = 0.016, vs *E. camaldulensis* p = 0.046). All 36 samples are sandy loam (n = 22) or loam (n = 14) in the USDA classification. Kruskal–Wallis on tree means: H = 11.64, p = 0.040. SOC, soil organic carbon

Table 2

Split-plot (mixed-design) analysis of variance for soil properties. Species is tested against the tree-within-species mean square (error a, 12 df); depth and the interaction against the depth × tree-within-species mean square (error b, 12 df). Bold p values indicate significance at α = 0.05

Response	Source	SS	df	MS	F	p	ηp²
ln(SOC)	Species	7.89	5	1.58	8.01	**0.002**	0.77
	Tree(Species) [error a]	2.36	12	0.20	—	—	—
	Depth	1.78	1	1.78	9.60	**0.009**	0.44
	Species × Depth	0.79	5	0.16	0.86	0.537	0.26
	Depth × Tree(Species) [error b]	2.22	12	0.19	—	—	—
SOC (raw)	Species	12.35	5	2.47	6.12	**0.005**	0.72
	Tree(Species) [error a]	4.85	12	0.40	—	—	—
	Depth	2.18	1	2.18	10.34	**0.007**	0.46
	Species × Depth	0.17	5	0.03	0.16	0.971	0.06
	Depth × Tree(Species) [error b]	2.53	12	0.21	—	—	—
Sand (%)	Species	1741.36	5	348.27	9.30	**0.001**	0.79
	Depth	141.61	1	141.61	2.29	0.156	0.16
	Species × Depth	236.86	5	47.37	0.77	0.592	0.24
Silt (%)	Species	1285.42	5	257.08	10.63	**0.001**	0.82
	Depth	20.40	1	20.40	0.35	0.565	0.03
	Species × Depth	204.91	5	40.98	0.70	0.632	0.23
Clay (%)	Species	83.56	5	16.71	1.04	0.438	0.30
	Depth	47.61	1	47.61	17.13	**0.001**	0.59
	Species × Depth	4.34	5	0.87	0.31	0.896	0.12

Note Aligned Rank Transform sensitivity for SOC: species p = 0.005, depth p = 0.007, interaction p = 0.989; tree-mean analysis (n = 18): species F(5, 12) = 6.12, p = 0.005. Organic matter (1.724 × SOC) duplicates the SOC tests exactly and is not tabulated. SOC, soil organic carbon

Table 4

Provenance contrasts. a Sample-level descriptive contrasts (18 vs 18 samples; Welch t test; bootstrap 95% CI from 10,000 resamples; qBH, Benjamini–Hochberg adjusted p; g, Hedges' g). b Species-level inference with species as replicates of provenance (a)

Property	Native M (SD)	Introduced M (SD)	Diff [95% CI]	t	p	qBH	g
Organic carbon (%)	1.60 (0.87)	0.93 (0.55)	+ 0.67 [0.21, 1.14]	2.76	0.010	0.039	+ 0.90
Sand (%)	51.9 (9.2)	58.8 (9.3)	−6.9 [− 12.6, − 1.0]	−2.24	0.032	0.042	−0.73
Silt (%)	35.0 (8.5)	28.6 (7.3)	+ 6.5 [1.4, 11.3]	2.45	0.020	0.039	+ 0.80
Clay (%)	13.1 (3.1)	12.7 (3.4)	+ 0.4 [− 1.6, 2.6]	0.38	0.705	0.705	+ 0.12

(b)

Test (species as replicates)	Statistic	p
Nested ANOVA, provenance vs species(provenance)	$F(1, 4) = 2.51$	0.19
Exact permutation, 20 allocations of species means	Δ = 0.58 ln units	0.30
Mixed model, species as random intercept	+0.58 ln units (SE 0.37)	0.11
PERMANOVA provenance (whole-species permutation)	$R^2 = 0.12$	0.30
Retrospective power at observed effect	0.23	—
Minimum detectable effect (80% power)	1.38 ln units (≈ 4-fold)	—

Note Species(provenance) in the nested ANOVA: $F(4, 12) = 6.15$, $p = 0.006$. Sample-level contrasts are descriptive: individual samples are not independent replicates of a species-level attribute (intraclass correlation 0.44)

Carbon fell from 1.51% at 0–10 cm to 1.02% at 10–30 cm (− 33%; $t(17) = 3.70$, $p = 0.002$, $dz = 0.87$), with 17 of 18 trees declining (Fig. 2a); clay rose from 11.7% to 14.0% ($p < 0.001$) while sand and silt did not change (Table 3). The interaction was negligible on every scale: species rankings persisted at depth unchanged (Fig. 2b), and species separation was sharper in the subsoil ($F(5, 12) = 7.00$, $p = 0.003$) than at the surface ($p = 0.053$). Stratification ratios ranged from 1.29 (*Z. spina-christi*) to 3.15 (*C. erectus*); the high ratio of *C. erectus* stems from its carbon-poor subsoil (0.29%), not surface accrual (Fig. 2c).

Table 3
Paired within-tree comparison of soil properties between depth increments (n = 18 tree-level pairs)

Property	0–10 cm	10–30 cm	Δ (SD)	t(17)	p	p (Wilcoxon)	dz
Organic carbon (%)	1.51	1.02	+ 0.49 (0.56)	3.70	0.002	0.002	+ 0.87
Sand (%)	57.3	53.4	+ 3.9 (10.8)	1.52	0.146	0.163	+ 0.36
Silt (%)	31.0	32.6	−1.6 (10.3)	−0.64	0.528	0.832	−0.15
Clay (%)	11.7	14.0	−2.3 (2.1)	−4.64	0.001	0.002	−1.09

Note Positive differences indicate higher values in the upper increment. Organic carbon declined in 17 of 18 trees; the ln-scale paired test agrees (p = 0.006)

Native stands held 1.60% carbon versus 0.93% in introduced stands (difference + 0.67 points, bootstrap 95% CI 0.21–1.14; g = 0.90; qBH = 0.039; Table 4a, Fig. 1b), and occupied less sandy and more silty soils (clay did not differ). Tested with species as replicates, however, the provenance tendency was not separable from species-within-category variation (nested ANOVA p = 0.19; exact permutation p = 0.30; mixed model p = 0.11), with design power 0.23 at the observed effect and a four-fold minimum detectable effect (Table 4b). Multivariate partitioning agreed: species explained 46% of dispersion (p < 0.001), provenance 12% (whole-species permutation p = 0.30). Intraclass correlation was 0.44, so treating 36 samples as independent would understate standard errors.

All 36 samples fell in the sandy-loam (n = 22) and loam (n = 14) classes of the USDA textural triangle (Fig. 3). Carbon correlated negatively with clay (r = − 0.51, p = 0.001) but not with sand or silt (Fig. 4); controlling for species strengthened the association (partial r = − 0.57), and the strong sand–silt coupling (r = − 0.95) is a closed-compositional artefact. In the principal component analysis, the first two components captured 89% of variance: a texture axis (57%) and a carbon axis (33%) at near-orthogonal loadings (Fig. 5; Online Resource 1, Table S2), so the carbon signal is not a passive reflection of particle size. Finally, indicative 0–30 cm stocks ranged from 20.6 Mg C ha^{-1} under *C. erectus* to 98.4 under *P. dactylifera* (Table 5); although carbon was more concentrated near the surface, the 10–30 cm increment held the larger stock in five of six species and 14 of 18 trees (28.5 vs 21.1 Mg C ha^{-1}) because it is twice as thick. The ranking of extremes was invariant across bulk densities 1.2–1.6 g cm^{-3}. Dropping the label-ambiguous samples or trees left every inference unchanged (Online Resource 1, Table S3).

4 Discussion

The central result of this study is proportional: tree species identity accounted for 46% of multivariate soil dispersion and 77% of ln-carbon variance, whereas the native–introduced divide accounted for 12% and, tested where provenance is actually replicated, could not be distinguished from species-within-category variation. The ranking did not sort by provenance — introduced *E. camaldulensis* outranked two natives — and a fivefold range separated the best and worst species. Provenance is a historical label, not a functional trait: litter decomposability, rooting depth and turnover vary independently of it (Ontong et al. 2023), urban-forestry

species differ several-fold in sequestration because of growth form and litter rather than origin (Behera et al. 2022), and markedly different soil effects between congeneric *Prosopis* species (Moslehi et al. 2025) confirm that species-based guidance will outperform category-based guidance. The take-home message of this first variance partitioning in a hyper-arid plantation is therefore that the species, not the provenance category, is the unit of selection.

That the identity signal emerges here, in young irrigated stands on coarse calcareous material with small episodic inputs, extends a rule previously established only in mesic systems. Identity has outweighed mixing in European two-species mixtures (Osei et al. 2021), Mediterranean mountain forests (Ureña-Lara et al. 2026), subtropical *Pinus* stands (Tang et al. 2024), boreal mixtures (Blaško et al. 2020) and continental network data (Dawud et al. 2016; Cremer et al. 2016), and global syntheses attribute topsoil carbon to functional type and mycorrhizal strategy (Peng et al. 2020; Hou et al. 2020). These studies all concern forests receiving abundant litter; that the same hierarchy persists where inputs are irrigation-subsidised and rainfall negligible suggests identity effects do not depend on the temperate input–protection regime. The result is consistent with tree effects strengthening under aridity (Yan et al. 2026) and trait effects being amplified on poor sites (Augusto and Boča 2022), and it contrasts with urban and mangrove systems where natives lead (Jevon et al. 2025; He et al. 2018) — there, native status coincides with trait syndromes tuned to local stress; here it does not. The message extends beyond this industrial site: wherever dryland agroforestry, shelterbelt and greening programmes are expanding, species identity, not origin labels, is the transferable design variable.

The two extremes illustrate the mechanism. *Phoenix dactylifera* accumulated the most carbon at both depths while showing a modest stratification ratio (1.35), the signature of profile-distributed inputs rather than surface accumulation alone: coarse frond litter and pruning residues enter near the trunk while dense adventitious roots turn over through the upper profile (Angst et al. 2019; Hüblová et al. 2026). As a monocot with fibrous roots and no secondary thickening, date palm falls outside the broadleaf–conifer contrast that structures most trait models (Peng et al. 2020; Hicks Pries et al. 2023; Hou et al. 2020), and its performance is not explained by stature: soil and biomass carbon are decoupled across systems (Larsson et al. 2025; Lázaro-Lobo et al. 2025), and fast-growing *E. camaldulensis* did not translate growth into soil carbon. *Conocarpus erectus* sits at the opposite extreme, with the lowest concentrations at both depths and an impoverished subsoil; its high stratification ratio (3.15) arises from a carbon-poor denominator (0.29%), not surface accrual — a caution that an index conceived as a soil-quality indicator (Franzluebbers 2002) misleads in isolation. Given that *C. erectus* has been planted at enormous scale across the Gulf for dust control, this carbon cost deserves weighing against its establishment benefits; for any candidate, the functional view says the same: evaluate input traits per species, not membership in a planting tradition.

The negative carbon–clay relationship concentrates the mechanistic argument. Clay is the classical protector of organic matter, yet here carbon falls as clay rises ($r = -0.51$; -0.57 after controlling for species), and the ordination places carbon and texture on near-orthogonal axes. Three constraints explain the paradox. Depth contributes: clay translocates downward while carbon is deposited at the surface, so pooling increments builds in a negative association. Clay spans only 3–20%, below the range where mineral surfaces become limiting. And in hyper-arid plantings organic supply, not retention capacity, is the binding constraint: stabilisation requires both reactive surfaces and sufficient supply (Li et al. 2024; Su et al. 2021; Staszel-Szlachta et al. 2025), and microbial processing into mineral-associated forms is substrate-constrained

(Beugnon et al. 2023; Lorenz and Thiele-Bruhn 2019; Zheng et al. 2022; Wei et al. 2026), so at low inputs the protective capacity of clay is never approached. Input traits therefore dominate — which is precisely why species identity emerges as the leading factor. A caution for the literature: correlating six species means alone reverses the sign of the relationship, an aggregation artefact that disappears when all 36 observations are retained.

The vertical pattern completes the picture. Species scaled the whole profile without altering its shape: parallel declines of 33% under all six species, surface carbon enrichment set against downward clay translocation. This differs from mesic forests where identity governs vertical partitioning (Ahmed et al. 2016; Steffens et al. 2022b; Ma et al. 2024) or alters carbon quality without changing totals (Patrmanová et al. 2026); here identity changed magnitude, not distribution. For accounting, the consequence is concrete: because the 10–30 cm layer is twice as thick, most of the 0–30 cm stock lies below 10 cm in five of six species, so surface sampling understates storage and surface disturbance can release more carbon than concentration profiles suggest — deeper carbon is also generally more persistent (Jenkinson and Coleman 2008). Species that distribute inputs through the profile, like *P. dactylifera*, thereby build stocks where they are safest, and monitoring programmes should retain at least two depth increments and report depth-weighted stocks.

The provenance tendency itself — natives holding 1.7 times more carbon at the sample level — points in the same direction as the global belowground pattern, where natives exceed non-natives in soil carbon while non-natives carry more aboveground carbon (Lázaro-Lobo et al. 2025), and as native advantages in mangrove and urban systems (He et al. 2018, 2020; Jevon et al. 2025; Zhang et al. 2022). But three qualifications bound it. Natives occupied finer-textured soils that retain organic matter more effectively, so part of the contrast reflects planting position: natives tend to occupy older ground, while ornamentals such as *C. erectus* were placed on recently graded roadsides — without random assignment, tree and site effects cannot be fully separated (Mayer et al. 2020; Hurlbert 1984). Tested where provenance is replicated — across species — the effect is not statistically separable and the design could only detect contrasts of about four-fold. And texture adjustment and tree-level re-analysis both reduce its apparent strength. We therefore read the direction as consistent with the global pattern but its magnitude as an upper bound on the trees' causal contribution: provenance tendencies of this size cannot guide species choice, and a planted common garden with assigned positions would be needed to price origin itself.

The implications follow directly for the design of tree-based systems in drylands. Select species, not categories: six taxa span a 4.2-fold soil-carbon range unpredictable from native–introduced labels, so candidate lists for agroforestry, shelterbelt and greening programmes should carry measured soil-carbon performance per species, as is increasingly done for biomass (Culqui et al. 2025; Cha et al. 2019). Among those tested, *P. dactylifera* and *Z. spina-christi* combine high soil-carbon performance with drought and salinity tolerance and are priority candidates for the northern Persian Gulf littoral; the large-scale planting of *C. erectus* merits review on carbon grounds while weighing its genuine dust-suppression and establishment services. Mixed plantings remain an option — young mixtures can exceed monocultures (Warner et al. 2023) and native mixtures can stabilise carbon within decades (Cunningham et al. 2015) — but diversity effects emerge early in some systems and can be absent after ten years in others (Martin-Guay et al. 2022), acting through microbial efficiency and stabilisation pathways (Chen and Hu 2024; Duan et al. 2023, 2026a; Chen et al. 2023) that are themselves climate-dependent (Yan et al. 2026): mixtures should be chosen for

complementary input traits, not assumed diversity benefits. Management should measure bulk density and report equivalent-soil-mass stocks, sample below 30 cm where deep-rooted phreatophytes such as *P. cineraria* may hold missed carbon, and use fractionation to test whether high-carbon species also build persistent forms (Angst et al. 2019; Liang et al. 2021; Ye et al. 2022). A common-garden trial with assigned species positions would close the causal gap this observational design necessarily leaves open.

5 Conclusions

Under the applied conditions of hyper-arid, irrigated planting at Assaluyeh, soil organic carbon is governed by a mechanistic chain that begins and ends with tree species identity: species-specific functional traits determine the quantity, chemistry and placement of organic inputs; those inputs accumulate on coarse calcareous substrates whose clay fraction provides stabilisation capacity far in excess of the supply to be stabilised, which is why carbon covaries negatively with clay; and because supply rather than protective surfaces is limiting, variance in soil carbon is dominated by identity (46% of multivariate dispersion; partial η^2 = 0.77 on log-carbon) while the native–introduced divide accounts for 12% and cannot be separated from species-within-category variation. Our primary hypothesis is supported: species identity outweighs provenance, the ranking does not sort by provenance, and the provenance tendency surviving at the sample level is confounded with texture and planting position. Our second hypothesis is also supported: carbon declines 33% from 0–10 to 10–30 cm in 17 of 18 trees as a common, parallel response to surface-dominated inputs, accompanied by downward clay translocation, with the subsoil carrying the larger share of the profile stock in five of six species.

The novelty of this study is to resolve, for the first time and at a climatic extreme, the question posed for mesic forests: whether soil carbon under plantings should be managed through species identity or through the native-versus-introduced dichotomy. The answer — identity — extends the species-identity rule of temperate and boreal systems into the hyper-arid irrigated end of the aridity gradient and supplies its mechanistic basis: where input limitation binds, categories that only proxy traits cannot predict outcomes, and mineralogical indicators such as clay cease to predict carbon.

The implications are operational. Dryland agroforestry, shelterbelt and greening programmes — spanning the Persian Gulf, the Arabian Peninsula and other arid coasts where millions of trees are being planted — should select at the species level: in our system *Phoenix dactylifera* and *Ziziphus spina-christi* are the strongest soil-carbon candidates, and the extensive planting of *Conocarpus erectus* carries a measurable soil-carbon cost to be weighed against its other services. Subsoil deserves protection, because most of the 0–30 cm stock sits below 10 cm where it is also more persistent; bulk density should be measured so that management reports stocks rather than indicative estimates; and provenance labels should not drive policy — where native status is to be priced, it must be tested in assigned-position common gardens. Applied at species level, the levers identified here turn dryland tree planting from an amenity practice into a soil-carbon management tool.

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

This study involved soil and environmental sampling only. It did not involve human participants, identifiable human data, vertebrate animals or clinical material; ethics approval was not required.

Consent to participate

Not applicable (no human participants).

Consent to publish

Not applicable (no identifiable human data).

Funding

This research received no specific grant from any funding agency in the public, commercial or not-for-profit sectors.

Availability of data and materials

The sample-level dataset with data-audit notes is provided in Online Resource 1 and will be deposited in a public repository upon acceptance; no permissions restrict access.

Code availability

Analysis code (Python 3.13) is available from the corresponding author on reasonable request.

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Figures

Fig. 1

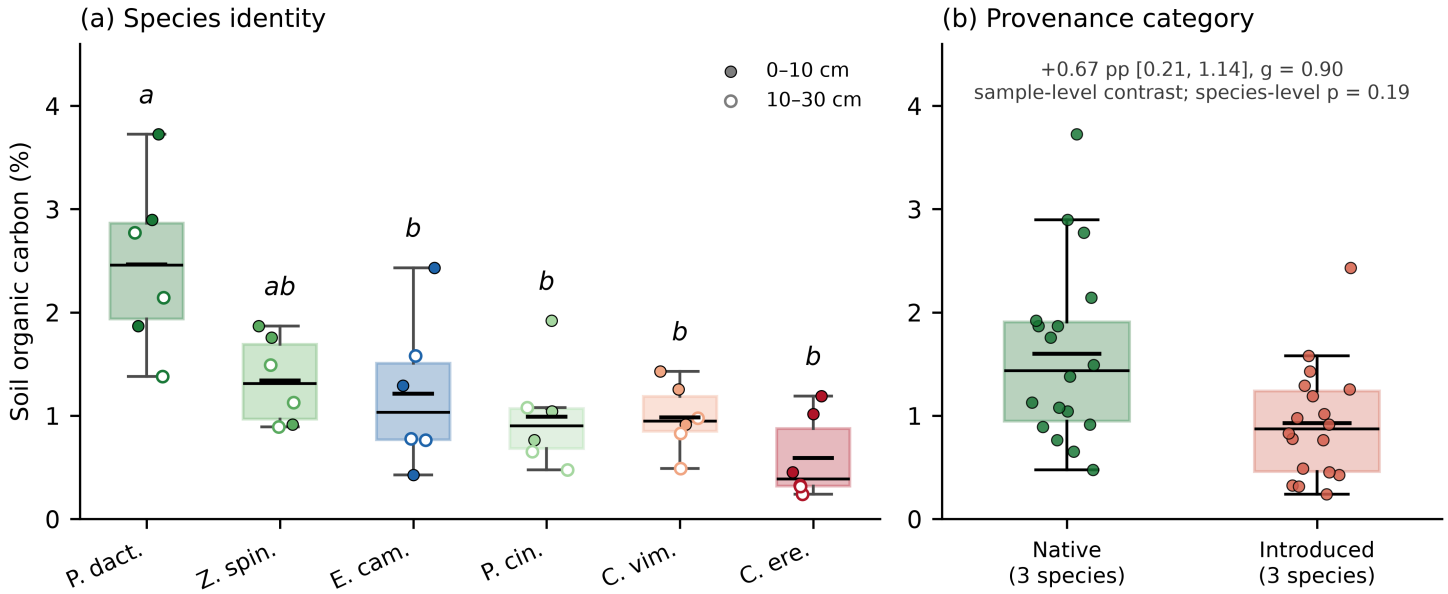


Figure 1

Soil organic carbon by species and provenance a Distribution of soil organic carbon concentration for each species; boxes span the interquartile range, whiskers the extremes, horizontal bars the means, and points are individual samples (filled, 0–10 cm; open, 10–30 cm); letters are Tukey compact-letter groupings from tree-level means (Table 1), species sharing a letter do not differ at α = 0.05 b Native and introduced stands pooled; the annotated contrast is the sample-level difference (Table 4a), the species-level test is not significant (Table 4b). SOC soil organic carbon

Fig. 2

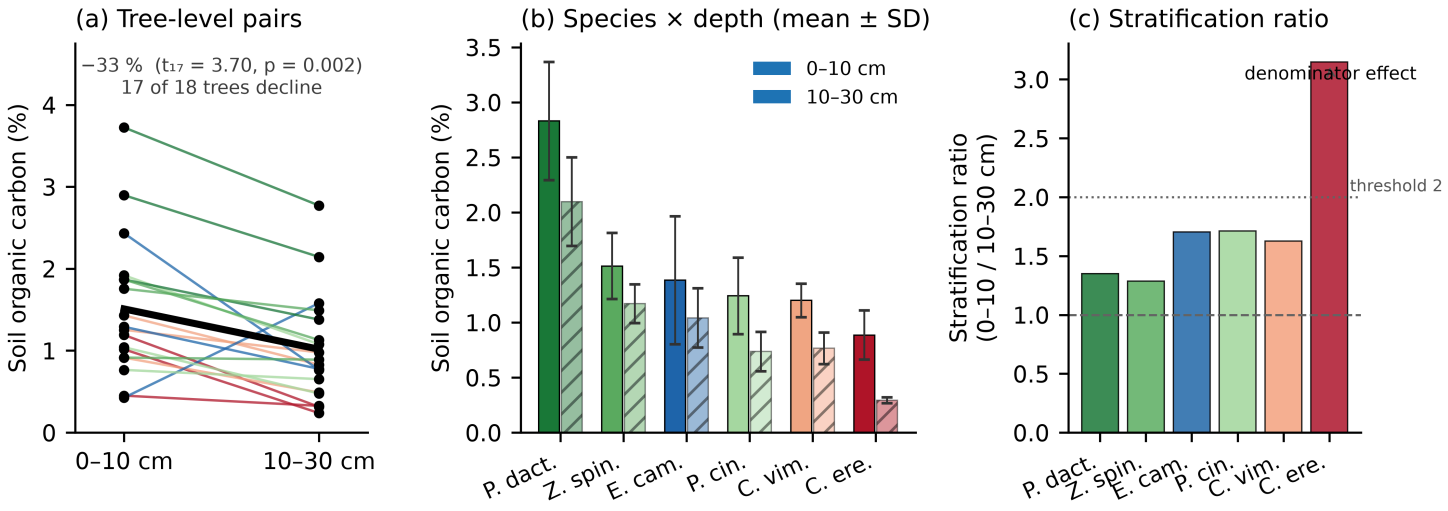


Figure 2

Vertical distribution of soil organic carbon a Paired values for the 0–10 and 10–30 cm increments of each of the 18 sampled trees, one line per tree coloured by species; bold line, overall means b Species × depth means

with SD; solid bars 0–10 cm, hatched bars 10–30 cm; parallel profiles reflect the non-significant interaction c Stratification ratio (0–10/10–30 cm concentration) by species; dashed line 1 (no stratification), dotted line 2 (conventional threshold); the high ratio of *Conocarpus erectus* is driven by its carbon-poor subsoil denominator

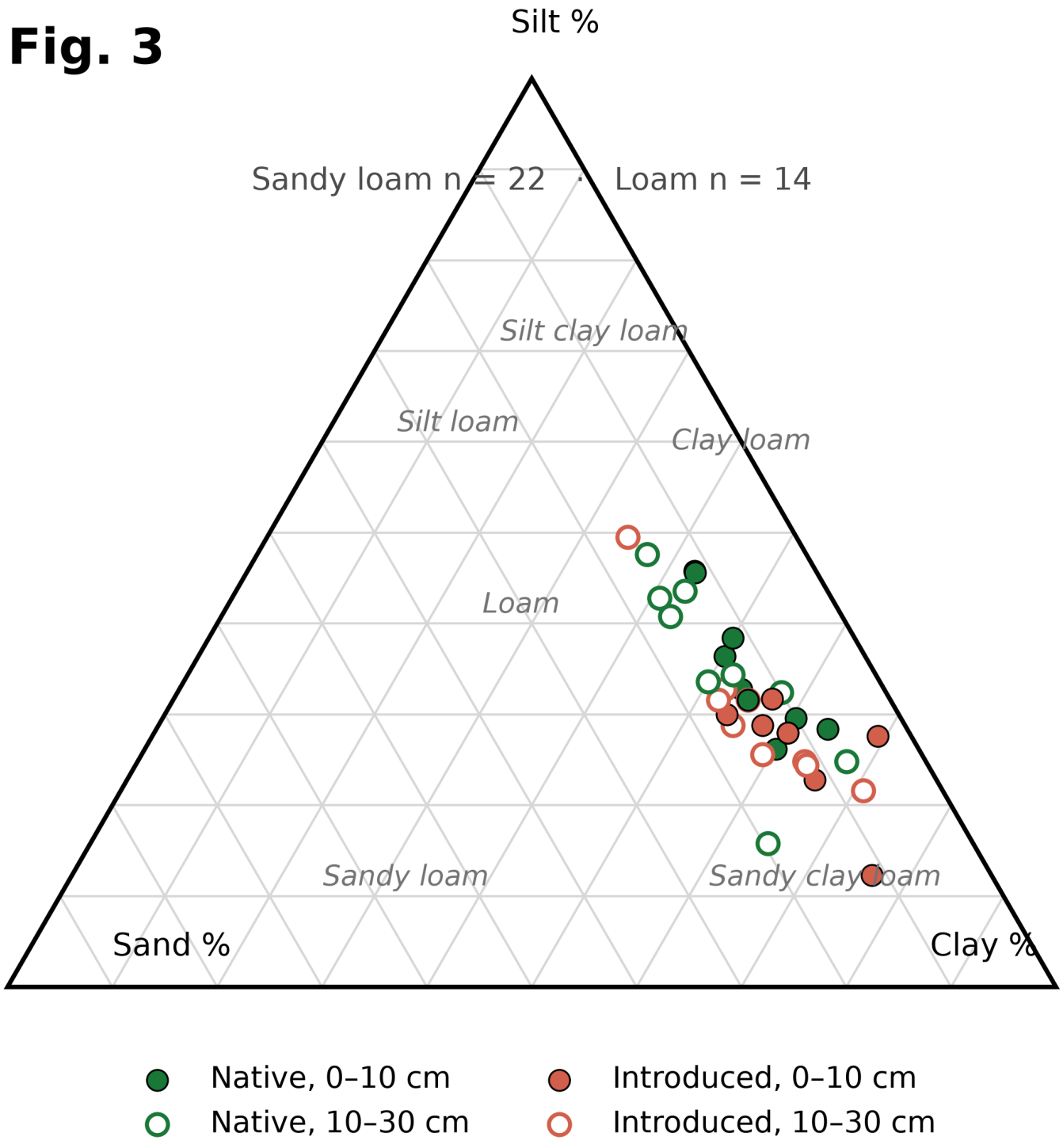


Figure 3

USDA textural classification of the 36 soil samples (closed fractions); boundaries follow the USDA textural triangle (Soil Survey Division Staff 1993); filled symbols 0–10 cm, open symbols 10–30 cm; green native, red introduced species; sandy loam n = 22, loam n = 14

Fig. 4

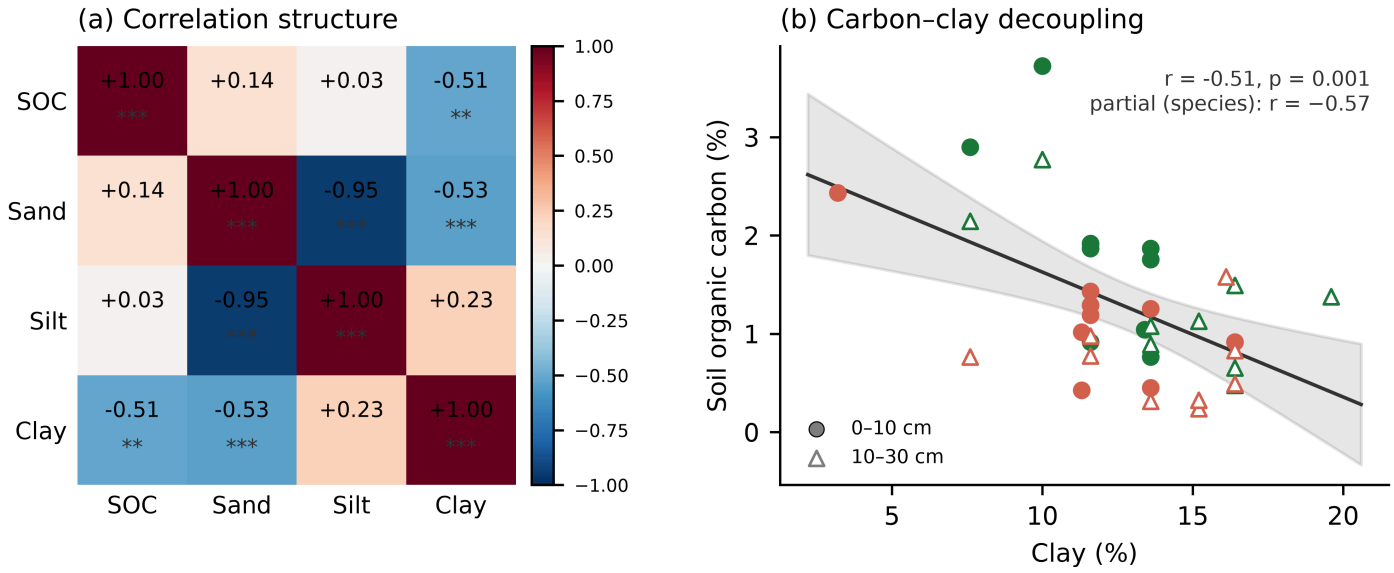


Figure 4

Correlation structure and the carbon–clay relationship a Pearson correlation matrix; *p < 0.05*, *p < 0.01*, **p < 0.001; organic matter excluded as a deterministic multiple of organic carbon b Soil organic carbon against clay with ordinary least-squares fit and 95% confidence band; circles 0–10 cm, triangles 10–30 cm; green native, red introduced; asterisks mark p < 0.05 (one), p < 0.01 (two) and p < 0.001 (three). SOC soil organic carbon

Fig. 5

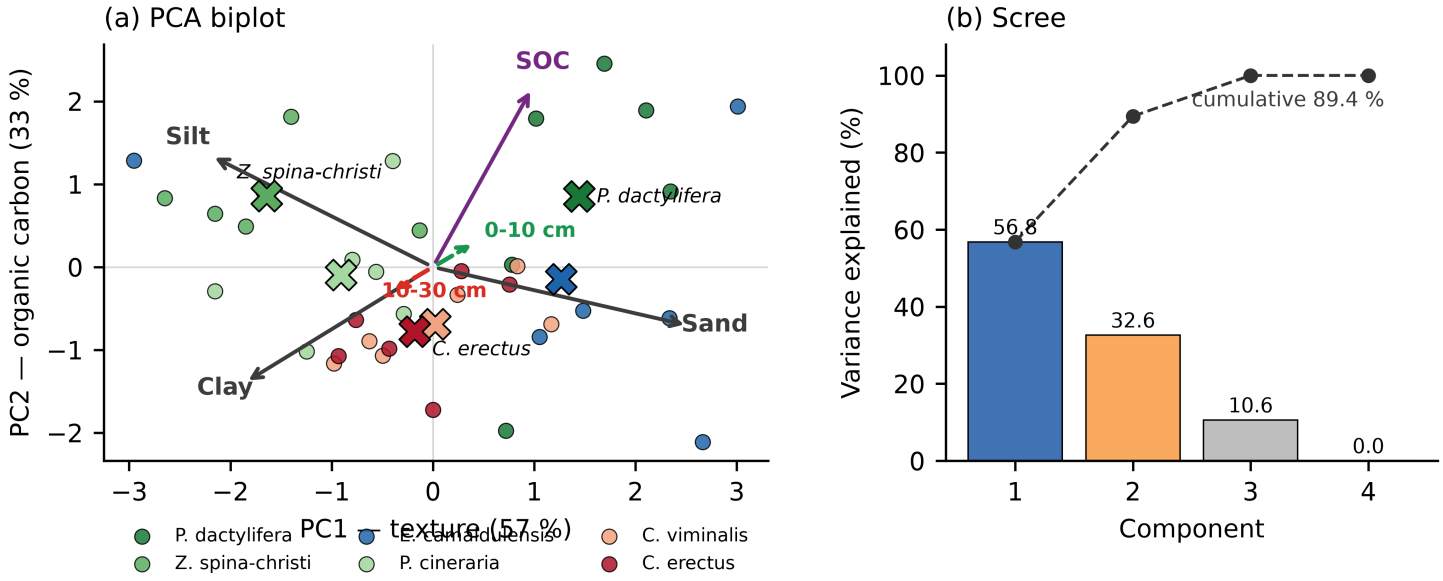


Figure 5

Principal component ordination of standardised soil properties a Sample scores on the first two components (89% of variance); arrows are variable loadings, crosses species centroids, dashed arrows depth centroids; loadings in Online Resource 1, Table S2 b Variance explained per component with cumulative percentages. PC principal component, SOC soil organic carbon