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Canopy-Induced Enrichment of Soil Organic Carbon and Nutrients under Six Tree Species in a Hot Arid Ecosystem of Western Rajasthan, India

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Abstract—*TIsolated trees in arid landscapes are widely believed to generate 'islands of fertility', yet quantitative evidence from planted stands of the Indian hot arid zone is limited. This study quantified the enrichment of soil organic carbon (SOC) and nutrients beneath the canopies of six tree species — Tecomella undulata, Ailanthus excelsa, Dalbergia sissoo, Prosopis cineraria, Acacia nilotica and Azadirachta indica — relative to paired open control plots in Sardarshahar tehsil, Churu district, Rajasthan, India. Soils were sampled at two depths (0–15 and 15–30 cm) across four seasons from November 2023 to October 2024 and analysed for pH, electrical conductivity, organic carbon, total and available nitrogen, available phosphorus and potassium, and DTPA-extractable micronutrients. Under-canopy soils contained 48.3% more organic carbon at 0–15 cm and 43.5% more at 15–30 cm than paired controls ($p < 0.001$). SOC stocks over 0–30 cm averaged 16.5 ± 1.1 Mg ha−1 under canopy against 12.3 ± 0.4 Mg ha−1 in the open, an increase of 34.1% (paired $t = 6.30$, $p = 0.001$) equivalent to a mean additional storage of 4.15 Mg C ha−1. Enrichment ratios varied from 1.19 in A. excelsa to 1.46 in A. nilotica and were closely predicted by canopy area (R2 = 0.805, $p = 0.015$) and stand age ($r = 0.949$, $p = 0.004$). Enrichment was strongest for organic carbon and total nitrogen (48% and 44%) and weakest for available potassium (21%), while under-canopy pH was 0.30 units lower than control. The results confirm that planted arid-zone trees generate measurable, species-dependent fertility islands, and identify A. nilotica and P. cineraria as the most effective species for combined soil restoration and carbon accrual in the Thar Desert margin.*

Keywords: *Arid zone; Enrichment ratio; Fertility island; Nutrient cycling; Soil organic carbon stock; Thar Desert; Tree–soil interaction*

I. INTRODUCTION

Soils store approximately three times more carbon than terrestrial vegetation and constitute the largest actively cycling terrestrial carbon reservoir (Batjes, 1996; Lal, 2004). In arid and semi-arid regions, which occupy 30–40% of the global land surface, soil organic carbon concentrations are inherently low because primary productivity is constrained by water availability rather than because decomposition is rapid. Precisely because the baseline is low, however, the relative gains achievable through vegetation restoration in drylands are proportionally large, and dryland soils have been identified as one of the more responsive targets for soil carbon sequestration (Lal, 2004).

A defining feature of arid landscapes is the pronounced spatial heterogeneity of soil resources. Since the pioneering observations of Zinke (1962) and Charley and West (1975), it has been recognised that individual woody plants concentrate organic matter and nutrients beneath their canopies, generating discrete patches of elevated fertility within an otherwise impoverished matrix. Garner and Steinberger (1989) formalised this as the 'fertile island' hypothesis, and Schlesinger et al. (1990, 1996) demonstrated that the redistribution of soil resources into such islands is a diagnostic signature of desertification, with the intervening interspaces becoming progressively depleted. The mechanisms are multiple and mutually reinforcing: litterfall and root turnover deliver organic matter directly beneath the crown; canopy shading lowers surface temperature and reduces evaporative loss; stemflow and canopy drip concentrate precipitation and dissolved nutrients near the bole; reduced wind speed promotes the deposition of fine, nutrient-rich aeolian particles; and the microclimate supports higher microbial and faunal activity (Rhoades, 1997).

The great majority of empirical work on fertility islands has been conducted in naturally occurring shrublands of North America, the Middle East and North Africa. Comparatively little quantitative information exists for planted stands of arid-zone trees in India, despite the fact that afforestation on degraded arid land is a central instrument of India's commitment under the Paris Agreement to create an additional carbon sink of 2.5–3.0 billion tonnes of CO2-equivalent by 2030. If the magnitude of canopy-induced enrichment differs systematically among candidate species, then species choice becomes a lever for maximising soil carbon accrual, and the effect size becomes a necessary input to any credible soil carbon accounting for afforestation projects.

The present study was therefore designed to (i) quantify the difference in soil organic carbon, macronutrients and micronutrients between under-canopy and paired open-control soils for six arid-zone tree species; (ii) express this difference as SOC stocks on an areal basis for the 0–30 cm profile; (iii) test whether the magnitude of enrichment differs among species and relate it to measurable canopy attributes; and (iv) evaluate the implications for species selection in restoration programmes on the Thar Desert margin.

2. MATERIALS AND METHODS

2.1 Study area

The investigation was conducted in Sardarshahar tehsil, Churu district, north-western Rajasthan, India (approximately 28°26′ N, 74°29′ E; 290 m above mean sea level), on the eastern margin of the Thar Desert. The region has a hot arid climate with a mean annual rainfall of about 300 mm, more than 80% of which falls during the south-west monsoon between July and September. Summer maximum temperatures exceed 45 °C and winter minima approach 2 °C. Soils are deep, sandy loam to loamy sand, calcareous, alkaline in reaction and low in organic matter. Six localities within the tehsil were selected for sampling, with the site at Bardasar serving as the reference locality.

2.2 Experimental design and soil sampling

A paired-plot design was employed. For each of the six species — Tecomella undulata (Sm.) Seem., Ailanthus excelsa Roxb., Dalbergia sissoo Roxb., Prosopis cineraria (L.) Druce, Acacia nilotica (L.) Delile and Azadirachta indica A. Juss. — ten mature trees of comparable age and canopy development were selected. Under-canopy samples were drawn at approximately half the canopy radius from the bole in four cardinal directions and composited. Control samples were collected from adjacent open areas at least twice the canopy radius from the nearest tree crown, on the same soil series and slope position, so that the pairs differed only in the presence of the tree. Samples were taken at two depths, 0–15 cm and 15–30 cm, in each of four seasons, winter (December), spring (March), summer (June) and rainy (September), between November 2023 and October 2024, giving a fully crossed species × location × depth × season design.

2.3 Laboratory analyses

Air-dried samples were passed through a 2 mm sieve prior to analysis. Soil pH and electrical conductivity were determined in a 1:2.5 soil–water suspension. Organic carbon was determined by the wet oxidation method of Walkley and Black (1934). Total nitrogen was estimated by the modified Kjeldahl procedure and available nitrogen by the alkaline potassium permanganate method of Subbiah and Asija (1956). Available phosphorus was extracted with 0.5 M sodium bicarbonate at pH 8.5 and determined colorimetrically following Olsen et al. (1954). Available potassium was extracted with neutral normal ammonium acetate and measured by flame photometry (Jackson, 1973). Micronutrient cations (Zn, Fe, Cu, Mn) were extracted with DTPA and determined by atomic absorption spectrophotometry following Lindsay and Norvell (1978). Bulk density was measured by the core method (Blake and Hartge, 1986) and particle-size distribution by the international pipette method.

2.4 Computation of SOC stocks and enrichment ratios

Soil organic carbon stocks were computed for each depth increment as:

SOC (Mg ha−1) = OC (%) × BD (g cm−3) × depth (cm) × 10

where OC is organic carbon concentration and BD is bulk density. Stocks for the two increments were summed to give the 0–30 cm profile stock. The enrichment ratio (ER) was defined as the ratio of the under-canopy value to the paired control value; ER > 1 indicates canopy-induced enrichment. Absolute gain was computed as the arithmetic difference between the paired values.

2.5 Statistical analysis

Under-canopy and control values were compared by paired t tests. The effects of species, season and depth on soil parameters were examined by three-way analysis of variance followed by Tukey's honestly significant difference test at $\alpha = 0.05$. Relationships between enrichment and tree morphometric attributes were examined by Pearson correlation and ordinary least-squares regression. Analyses were performed in SPSS; significance is reported at $p < 0.05$, $p < 0.01$ and $p < 0.001$.

3. Results

3.1 General soil reaction and salinity

Soils were alkaline throughout, but under-canopy soils were consistently less alkaline than paired controls, with a mean pH of 7.95 against 8.25 at 0–15 cm (−3.6%) and 8.10 against 8.35 at 15–30 cm (−3.0%); both differences were significant at $p < 0.05$. Electrical conductivity showed the opposite pattern, being 18.6% higher under canopy at 0–15 cm (0.51 against 0.43 dS m−1) and 18.4% higher at 15–30 cm, reflecting the greater concentration of soluble salts released during organic matter mineralisation. All values remained well below the salinity threshold of 4 dS m−1, so the increase carries no agronomic penalty in this system.

3.2 Organic carbon concentration and stocks

Organic carbon concentration averaged 0.43% under canopy against 0.29% in the open at 0–15 cm, an enrichment of 48.3%, and 0.33% against 0.23% at 15–30 cm, an enrichment of 43.5% (both $p < 0.001$). Organic carbon was the single most strongly enriched parameter measured. Three-way analysis of variance confirmed highly significant effects of species ($F = 6.73$, $p < 0.001$), depth ($F = 19.67$, $p < 0.001$) and season ($F = 4.63$, $p = 0.007$) on organic carbon concentration. The surface-to-subsurface ratio of organic carbon concentration averaged 1.29 (range 1.25–1.31), and the corresponding ratio of stocks was 1.33, indicating a pronounced but not extreme stratification of carbon in the upper profile.

Expressed as stocks, the 0–30 cm profile held 16.5 ± 1.1 Mg C ha−1 under canopy against 12.3 ± 0.4 Mg C ha−1 in the open, an increase of 34.1% (paired $t = 6.30$, df = 5, $p = 0.001$). The absolute gain averaged 4.15 Mg C ha−1 and ranged from 2.1 Mg C ha−1 under A. excelsa to 6.3 Mg C ha−1 under A. nilotica (Table 1). Enrichment ratios followed the sequence A. nilotica (1.46) > P. cineraria (1.42) > D. sissoo (1.36) > Az. indica (1.31) > T. undulata (1.24) > A. excelsa (1.19), with an overall mean of 1.33 ± 0.04. Enrichment was significant at both depths considered separately (0–15 cm: $t = 6.43$, $p = 0.001$; 15–30 cm: $t = 6.08$, $p = 0.002$).

3.3 Macronutrient enrichment

All macronutrients were significantly enriched beneath tree canopies, but the magnitude of enrichment differed systematically among elements. Total nitrogen showed the largest response after organic carbon, increasing by 43.8% at 0–15 cm and 44.0% at 15–30 cm. Available nitrogen increased by 29.7% and 29.2%, available phosphorus by 27.9% and 27.2%, and available potassium by 20.5% and 21.2% at the two depths respectively (Table 2). The gradient of enrichment — organic carbon ≈ total nitrogen > available nitrogen > available phosphorus > available potassium — mirrors the degree to which each element is bound to soil organic matter rather than to the mineral fraction.

3.4 Micronutrient enrichment

DTPA-extractable micronutrients were also significantly higher beneath canopies (Table 3). Zinc showed the greatest relative enrichment (0.76 against 0.55 ppm; +38.2%; $t = 8.66$, $p < 0.001$), followed by manganese (+32.1%), iron (+31.0%) and copper (+30.6%), all significant at $p < 0.01$. The enrichment of micronutrient cations is consistent with the lower pH and higher organic matter of under-canopy soils, both of which increase the solubility and chelation of these elements in calcareous substrates.

3.5 Canopy attributes as predictors of enrichment

The magnitude of enrichment was strongly related to tree size and age. Under-canopy SOC stock increased linearly with canopy area (SOC = 0.426 × canopy area + 5.31; $R2 = 0.815$, $p = 0.014$) and was closely correlated with stand age ($r = 0.969$, $p = 0.001$) and diameter at breast height ($r = 0.858$, $p = 0.029$). The enrichment ratio behaved similarly, increasing with canopy area ($R2 = 0.805$, $p = 0.015$), age ($r = 0.949$, $p = 0.004$) and DBH ($r = 0.851$, $p = 0.032$). Tree height was unrelated to either measure ($r = 0.252$ and 0.299, both $p > 0.5$), indicating that lateral crown development rather than vertical growth governs the spatial footprint of soil enrichment (Table 4).

Table 1. Soil organic carbon stocks (Mg ha−1) under canopy and in paired open controls, with enrichment ratios

and absolute gains.

Species	Under canopy 0–15	Under canopy 15–30	Under canopy 0–30	Control 0–30	Absolute gain	Enrichment ratio
Tecomella undulata	8.2	6.1	14.3	11.5	2.8	1.24
Ailanthus excelsa	7.5	5.6	13.1	11.0	2.1	1.19
Dalbergia sissoo	9.5	7.2	16.7	12.3	4.4	1.36
Prosopis cineraria	10.8	8.1	18.9	13.3	5.6	1.42
Acacia nilotica	11.5	8.6	20.1	13.8	6.3	1.46
Azadirachta indica	9.0	6.8	15.8	12.1	3.7	1.31
Mean ± SE	9.4 ± 0.6	7.1 ± 0.5	16.5 ± 1.1	12.3 ± 0.4	4.15	1.33 ± 0.04
Stocks computed as OC (%) × bulk density (g cm-3) × depth (cm) × 10. Paired t test on 0-30 cm stocks: t = 6.30, df = 5, p = 0.001. SE = standard error.						

Table 2. Comparison of soil chemical properties between under-canopy and paired control positions, pooled across all six species.

Parameter	Depth (cm)	Under canopy	Control	Change (%)	Sig.
pH	0–15	7.95	8.25	−3.6	*
	15–30	8.10	8.35	−3.0	*
EC (dS m−1)	0–15	0.51	0.43	+18.6	*
	15–30	0.45	0.38	+18.4	*
Organic carbon (%)	0–15	0.43	0.29	+48.3	***
	15–30	0.33	0.23	+43.5	***
SOC stock (Mg ha−1)	0–30	16.5	12.3	+34.1	***
Total N (%)	0–15	0.046	0.032	+43.8	***
	15–30	0.036	0.025	+44.0	***
Available N (kg ha−1)	0–15	188	145	+29.7	***
	15–30	155	120	+29.2	***
Available P (kg ha−1)	0–15	15.1	11.8	+27.9	**
	15–30	11.7	9.2	+27.2	**
Available K (kg ha−1)	0–15	235	195	+20.5	**
	15–30	200	165	+21.2	**
Values are means pooled across six species, four seasons and two locations. Significance by paired t test: * p < 0.05, ** p < 0.01, *** p < 0.001.					

Table 3. DTPA-extractable micronutrient concentrations (ppm) at 0–15 cm depth under canopy and in paired

controls.

Micronutrient	Under canopy	Control	Change (%)	Paired t	p
Zinc	0.76	0.55	+38.2	8.66	< 0.001
Iron	5.5	4.2	+31.0	7.77	< 0.001
Copper	0.47	0.36	+30.6	8.66	< 0.001
Manganese	3.7	2.8	+32.1	7.43	< 0.001
Means of four seasons x four replicates per species (n = 16 per species-location combination); paired t tests computed on species means (df = 5).					

Table 4. Pearson correlations between tree morphometric attributes and measures of canopy-induced soil enrichment.

Attribute	Mean value	r with SOC stock	r with enrichment ratio	Significance
Height (m)	8.2	0.252	0.299	ns
DBH (cm)	27.8	0.858	0.851	*
Canopy area (m^2)	26.2	0.903	0.897	*
Stand age (years)	15.8	0.969	0.949	**
n = 6 species means. ns = not significant, * p < 0.05, ** p < 0.01. Regression of under-canopy SOC stock on canopy area: R2 = 0.815, p = 0.014.				

4. DISCUSSION

4.1 Magnitude of the fertility island effect in planted arid stands

The enrichment recorded here — 48.3% for organic carbon at the surface and 34.1% for the 0–30 cm carbon stock — confirms that planted trees on the Thar Desert margin generate fertility islands of the kind first described for natural desert shrublands (Garner and Steinberger, 1989; Schlesinger et al., 1996). The effect size is nevertheless considerably smaller than that reported for long-established natural shrub islands, where under-canopy organic carbon may exceed interspace values by a factor of two to five (Charley and West, 1975; Schlesinger et al., 1996). Two considerations reconcile this difference. First, the stands examined here are 12–20 years old, whereas natural desert shrubs may have occupied the same microsite for many decades or centuries, and the strong correlation observed between stand age and enrichment ratio (r = 0.949) implies that the observed values represent an early stage of an ongoing accumulation process. Second, the control positions used here lie within the same managed landscape rather than in a fully degraded interspace, so the contrast reflects the tree effect alone rather than the combined tree effect and interspace depletion that characterises desertified systems.

4.2 Differential enrichment among nutrients

The ordering of enrichment — organic carbon (48%) ≈ total nitrogen (44%) > available nitrogen (30%) > available phosphorus (28%) > available potassium (21%) — carries mechanistic information. Carbon and total nitrogen reside almost entirely within the organic fraction and therefore track litter and root inputs directly. Available nitrogen, being the mineralised product of that organic pool, is enriched to a lesser degree because it is subject to plant uptake, leaching and gaseous loss. Phosphorus and potassium are held substantially in mineral form in these calcareous soils, so canopy inputs modify only the smaller organically cycled fraction of their total pools. The same logic explains why micronutrient cations are enriched by 31–38%: their availability in alkaline calcareous soils is governed jointly by pH and by organic chelation, and both were favourably altered beneath the canopies, where pH was 0.30 units lower and organic carbon nearly 50% higher than in the open.

4.3 Species differences and the role of canopy architecture

The threefold range in absolute carbon gain, from 2.1 Mg C ha−1 under A. excelsa to 6.3 Mg C ha−1 under A. nilotica, is the practically significant result of this study. The ranking is closely aligned with canopy area and stand age but not with tree height, which indicates that the horizontal extent of the crown — determining the area over which litter is deposited, shade is cast and wind speed is reduced — is the proximate control on soil enrichment. It is also notable that the three highest-ranking species (A. nilotica, P. cineraria, D. sissoo) are all nitrogen-fixing members of the Fabaceae. Symbiotic nitrogen fixation raises litter nitrogen concentration, narrows the litter C:N ratio and thereby accelerates the microbial processing that converts plant residues into mineral-associated organic matter, a pathway now understood to be the principal route to stable soil carbon (Cotrufo and Lavallee, 2022; Sokol and Bradford, 2019). P. cineraria in particular has long been valued in the traditional agroforestry of western Rajasthan for its beneficial effect on associated crops, and the present data provide a quantitative basis for that empirical knowledge.

Some caution is required in attributing the ranking wholly to species identity. Age and canopy area were confounded with species in this dataset, since the A. nilotica stands were also the oldest and largest. Disentangling an intrinsic species effect from a size-and-age effect would require either a chronosequence within each species or a common-garden design, and this is recommended as a priority for subsequent work.

4.4 Depth distribution and implications for carbon permanence

Enrichment was almost as strong at 15–30 cm (43.5%) as at 0–15 cm (48.3%), and the surface-to-subsurface ratio of 1.29 is modest by comparison with the steep stratification typical of mesic forest soils (Jobbágy and Jackson, 2000). This relatively even vertical distribution is consequential, because carbon located below the immediate surface layer is less exposed to erosion, temperature extremes and disturbance, and is more likely to be stabilised through association with mineral surfaces. The deep, exploratory root systems characteristic of arid-zone phreatophytes such as P. cineraria and A. nilotica deliver carbon directly into the subsurface through root turnover and rhizodeposition, a pathway with substantially higher conversion efficiency to stable mineral-associated organic carbon than aboveground litter (Sokol and Bradford, 2019). The relatively deep enrichment observed here therefore suggests that the carbon accrued beneath these species has a reasonable prospect of persistence.

4.5 Implications for restoration and carbon accounting

Scaled to a plantation, the mean gain of 4.15 Mg C ha^{-1} over 0–30 cm is equivalent to 15.2 Mg CO_2-e ha^{-1}, accumulated over roughly 16 years — an annual soil carbon accrual rate of the order of 0.26 Mg C ha^{-1} yr^{-1}. If A. nilotica is planted in preference to A. excelsa, the corresponding figure rises to 6.3 Mg C ha^{-1} (23.1 Mg CO_2-e ha^{-1}), a threefold difference attributable to species choice alone. These rates fall within the range of 0.1–0.3 Mg C ha^{-1} yr^{-1} that Lal (2004) considered attainable for dryland restoration, and they are additional to the carbon held in the woody biomass itself.

Two caveats attach to the accounting interpretation. First, the paired-plot design substitutes space for time; the difference between under-canopy and control positions is an inference about accumulation since planting rather than a direct measurement of change, and it assumes that the two positions were equivalent at establishment. Second, sampling was confined to the upper 30 cm, so carbon accrued below this depth by deep-rooted species is not captured and the values reported are conservative. Repeat sampling of the same positions at a defined interval, extended to at least 100 cm, would convert these space-for-time inferences into direct measurements of change.

5. CONCLUSION

Six tree species planted on the arid margin of the Thar Desert generated measurable fertility islands beneath their canopies. Under-canopy soils held 48.3% more organic carbon at 0–15 cm and 34.1% more carbon stock over 0–30 cm than paired open controls, together with 44% more total nitrogen, 20–30% more available macronutrients and 31–38% more DTPA-extractable micronutrients, while soil pH was reduced by 0.30 units. The magnitude of enrichment varied threefold among species and was predicted principally by canopy area and stand age rather than tree height. Acacia nilotica and Prosopis cineraria delivered the greatest soil carbon and nutrient benefits and are recommended as priority species for restoration and carbon-oriented afforestation in the hot arid zone of western Rajasthan. Because the enrichment extended almost undiminished to 30 cm, the carbon accrued is likely to be comparatively well protected, and the values reported here should be regarded as conservative estimates of the full profile response.

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