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Review Article

SEASONAL AND DEPTH-WISE DYNAMICS OF SOIL CHEMICAL PROPERTIES UNDER ARID-ZONE TREE PLANTATIONS IN SARDARSHAHAR, RAJASTHAN (INDIA): IMPLICATIONS FOR SAMPLING DESIGN IN SOIL CARBON INVENTORIES

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Abstract

Soil carbon and nutrient inventories in dryland regions are commonly built on single-occasion sampling, an approach that implicitly assumes temporal stability of the measured properties. This study tested that assumption by monitoring seven soil chemical properties under six tree species — Tecomella undulata, Ailanthus excelsa, Dalbergia sissoo, Prosopis cineraria, Acacia nilotica and Azadirachta indica — across four seasons and two depths (0–15 and 15–30 cm) in Sardarshahar tehsil, Churu district, Rajasthan, India, from November 2023 to October 2024. All nutrient variables peaked in the rainy season and reached a minimum in summer, whereas pH and electrical conductivity followed the opposite phase. Organic carbon varied from 0.301% in summer to 0.420% in the rainy season, a seasonal amplitude of 33.3% of the annual mean, and was 39.6% higher in the rainy season than in summer ($t = 20.43$, $p < 0.001$). Corresponding rainy-to-summer increases were 36.6% for total nitrogen, 35.6% for available phosphorus, 26.4% for available nitrogen and 21.7% for available potassium, while electrical conductivity fell by 18.2% and pH by 4.8%. Seasonal means of every nutrient variable were almost perfectly correlated with those of organic carbon ($r \geq 0.998$), indicating a common moisture-mediated driver. Surface-to-subsurface ratios were statistically invariant across seasons (organic carbon 1.30–1.33), showing that season and depth acted additively rather than interactively. Partitioning of the explained sum of squares showed that species dominated variation in pH (75.6%) and electrical conductivity (61.5%), depth dominated available phosphorus (45.6%) and available nitrogen (38.8%), and season contributed a remarkably uniform 17.5–25.5% to every property. Estimated soil organic carbon stock for the 0–30 cm profile ranged from 13.5 Mg ha^{-1} if sampled in summer to 18.9 Mg ha^{-1} if sampled in the rainy season. Single-season sampling can therefore bias dryland soil carbon inventories by nearly 40%, and standardisation of sampling season is recommended as a prerequisite for comparability.

Keywords: Birch effect; Dryland soils; Sampling protocol; Seasonal variation; Soil organic carbon; Soil nutrient dynamics; Thar Desert

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1. Introduction

Estimates of soil organic carbon and nutrient status underpin land management decisions, national greenhouse gas inventories and the crediting of restoration projects. Almost universally these estimates rest on soil samples collected on a single occasion, and the resulting values are treated as fixed properties of the site. In humid and temperate systems, where soil moisture varies within a comparatively narrow band, this simplification is defensible. In arid systems it is far less obviously so, because the defining feature of dryland biogeochemistry is that biological activity is not continuous but pulsed, being switched on and off by discrete precipitation events (Austin et al., 2004; Huxman et al., 2004; Schimel, 2018).

The mechanistic basis for pulse-driven dynamics is well established. Birch (1958) first demonstrated that rewetting a dry soil produces a burst of mineralisation far exceeding that of a continuously moist soil, a phenomenon since confirmed across a wide range of systems and now known as the Birch effect (Fierer and Schimel, 2002; Borken and Matzner, 2009). Drying concentrates labile substrate through the disruption of aggregates and the accumulation of microbial osmolytes and necromass; rewetting makes this substrate abruptly available, and mineralisation, nutrient release and carbon dioxide efflux rise sharply within hours. In regions where more than 80% of annual precipitation is delivered in a three-month monsoon, the biogeochemical year is effectively compressed into a few weeks, and the soil sampled in June may be chemically quite unlike the same soil sampled in September.

Depth introduces a second and largely independent axis of variation. Organic inputs from litter are concentrated at the surface while root-derived inputs extend deeper, and the resulting vertical stratification of soil organic carbon is a general feature of terrestrial soils (Jobbágy and Jackson, 2000). Whether the vertical gradient is itself modified by season — that is, whether surface and subsurface layers respond to the monsoon pulse in the same proportion — has direct consequences for how deeply, as well as how often, soils should be sampled.

For the Indian hot arid zone these questions have been little examined, even though afforestation on arid land is a principal instrument of India's climate commitments and the soil carbon accrued is increasingly the subject of measurement and verification. The present study therefore set out to (i) quantify the seasonal course of seven soil chemical properties under six arid-zone tree species over a complete annual cycle; (ii) determine whether seasonal and depth effects operate additively or interactively; (iii) partition the variation in each property among species, season and depth; and (iv) evaluate the magnitude of the bias introduced into soil carbon estimates by the choice of sampling season.

2. Materials and Methods

2.1 Study area and design

The study 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 climate is hot arid, with mean annual rainfall of about 300 mm of which more than 80% falls between July and September, summer maxima above 45 °C and winter minima near 2 °C. Soils are deep, sandy loam to loamy sand, calcareous and alkaline.

Six tree species — Tecomella undulata (Sm.) Seem., Ailanthus excelsa Roxb., Dalbergia sissoo Roxb., Prosopis cineraria (L.) Druce, Acacia nilotica (L.) Delile and Azadirachta indica A. Juss. — were sampled in a fully crossed species × season × depth design. Soils were collected at two depths, 0–15 cm and 15–30 cm, in each of four seasons: winter (December), spring (March), summer (June) and rainy (September), spanning November 2023 to October 2024. Four replicate composite samples were drawn for each species × season × depth combination, giving 192 samples in total.

2.2 Laboratory analyses

Air-dried, 2 mm-sieved samples were analysed for pH and electrical conductivity in a 1:2.5 soil–water suspension; organic carbon by the wet oxidation procedure of Walkley and Black (1934); total nitrogen by the modified Kjeldahl method; available nitrogen by the alkaline potassium permanganate method of Subbiah and Asija (1956); available phosphorus by sodium bicarbonate extraction following Olsen et al. (1954); and available potassium by neutral normal ammonium acetate extraction with flame photometric determination (Jackson, 1973). Bulk density was determined by the core method (Blake and Hartge, 1986).

2.3 Derived quantities and statistical analysis

Soil organic carbon stock was computed as OC (%) × bulk density (g cm^{-3}) × depth (cm) × 10. Seasonal amplitude was expressed as the difference between the seasonal maximum and minimum divided by the annual mean, and the coefficient of variation across seasons was computed on the four seasonal means. The depth ratio was defined as the 0–15 cm value divided by the corresponding 15–30 cm value; constancy of this ratio across seasons was taken as evidence of additive rather than interactive season × depth effects.

Data were analysed by three-way analysis of variance with species, season and depth as fixed factors, followed by Tukey's honestly significant difference test at $\alpha = 0.05$. To compare the relative importance of the three factors across properties measured in different units, the sum of squares attributable to each factor was expressed as a percentage of the total sum of squares explained by the three main effects. Rainy-season and summer values were compared by paired t tests across the twelve species × depth units. Relationships among seasonal means were examined by Pearson correlation. Analyses were performed in Python 3 using the SciPy and statsmodels libraries.

3. Results

3.1 Soil reaction and salinity

Soil pH followed a clear seasonal course, rising from 7.88 in the rainy season to a maximum of 8.28 in summer, with intermediate values in winter (7.98) and spring (8.08). The seasonal amplitude of 5.0% of the annual mean was the smallest recorded for any property, but the pattern was highly consistent, occurring in every species and at both depths without exception. Electrical conductivity showed the same phase, peaking at 0.518 dS m^{-1} in summer and falling to 0.424 dS m^{-1} in the rainy season, an amplitude of 20.2%. The rainy-season decline relative to summer was 18.2% ($t = -24.87$, $p < 0.001$), consistent with the leaching of soluble salts from the upper profile during monsoon recharge and their capillary re-accumulation under high evaporative demand in summer.

3.2 Organic carbon and total nitrogen

Organic carbon showed the opposite phase and the largest relative variation of any property measured. Pooled across species and depths, it rose from a summer minimum of 0.301% to a rainy-season maximum of 0.420%, with winter (0.344%) and spring (0.365%) intermediate. The seasonal amplitude was 33.3% of the annual mean and the coefficient of variation across seasons 13.8%. The rainy-season value exceeded the summer value by 39.6% ($t = 20.43$, $p < 0.001$). Three-way analysis of variance confirmed significant effects of species ($F = 6.73$, $p < 0.001$), season ($F = 4.63$, $p = 0.007$) and depth ($F = 19.67$, $p < 0.001$). Total nitrogen tracked organic carbon closely, ranging from 0.0344% in summer to 0.0470% in the rainy season, an amplitude of 31.2% and a rainy-to-summer increase of 36.6% ($t = 17.41$, $p < 0.001$).

3.3 Available macronutrients

All three available macronutrients peaked in the rainy season and reached their minima in summer (Table 1). Available nitrogen ranged from 148.3 to 187.5 kg ha^{-1} (amplitude 23.4%; rainy versus summer +26.4%, $t = 32.50$, $p < 0.001$), available phosphorus from 10.88 to 14.75 kg ha^{-1} (amplitude 30.5%; +35.6%, $t = 22.09$, $p < 0.001$) and available potassium from 195.8 to 238.3 kg ha^{-1} (amplitude 19.6%;

+21.7%, t = 56.38, p < 0.001). Tukey's test separated the rainy season from all others and summer from all others for every nutrient, while winter and spring were statistically indistinguishable in each case (Table 1).

The seasonal means of every nutrient property were almost perfectly correlated with the seasonal means of organic carbon: total nitrogen r = 1.000, available phosphorus r = 1.000, available nitrogen r = 0.999 and available potassium r = 0.998. Both pH and electrical conductivity were inversely related to organic carbon across seasons (r = −0.887 and −0.890 respectively). The nutrient properties thus behave as a single coherent bundle driven by a common seasonal forcing, from which soil reaction and salinity are decoupled in the opposite direction.

3.4 Depth stratification and its constancy across seasons

Every property except pH was higher in the 0–15 cm layer than at 15–30 cm. Depth ratios pooled over the year were 1.31 for organic carbon, 1.31 for available phosphorus, 1.28 for total nitrogen, 1.22 for available nitrogen, 1.17 for available potassium and 1.12 for electrical conductivity; for pH the ratio was 0.975, the subsurface being slightly more alkaline.

Critically, these ratios were essentially invariant across seasons (Table 2). For organic carbon the depth ratio was 1.307 in winter, 1.305 in spring, 1.329 in summer and 1.301 in the rainy season, a total range of 0.028 or 2.1% of the mean ratio. Comparable constancy was observed for every other property. Surface and subsurface layers therefore responded to the monsoon in almost exactly the same proportion, and season and depth can be treated as additive main effects over the range observed rather than as interacting factors.

3.5 Partitioning of variation among species, season and depth

Expressing the sum of squares attributable to each factor as a percentage of the total explained by the three main effects revealed a systematic gradient across properties (Table 3). Species dominated the variation in pH (75.6%) and electrical conductivity (61.5%), properties governed largely by the chemical signature of litter and root exudates. Depth was the leading factor for available phosphorus (45.6%), available nitrogen (38.8%) and available potassium (36.9%), and was of comparable weight to species for total nitrogen (30.9%) and organic carbon (29.3%). Season, by contrast, contributed a strikingly uniform share to every property, ranging only from 17.5% for pH to 25.5% for available potassium. Season is thus never the dominant source of variation, but it is never negligible either, accounting for approximately one-fifth to one-quarter of the explained variation regardless of which property is considered.

3.6 Consequences for estimated carbon stocks

Applying the mean bulk density of the profile to the seasonal organic carbon concentrations yields markedly different estimates of the 0–30 cm soil organic carbon stock depending on when the soil is sampled: 13.5 Mg ha−1 in summer, 15.5 Mg ha−1 in winter, 16.4 Mg ha−1 in spring and 18.9 Mg ha−1 in the rainy season (Table 4). The difference between the summer and rainy-season estimates is 5.4 Mg C ha−1, or 39.6% of the summer value, obtained from the same soils within a single year.

Table 1. Seasonal means of soil chemical properties pooled across six species, two depths and two locations, with seasonal amplitude and coefficient of variation.

Property	Winter	Spring	Summer	Rainy	Amplitude (%)	CV (%)
pH	7.98^{b}	8.08^{b}	8.28^{a}	7.88^{c}	5.0	2.1
EC (dS m^{-1})	0.450^{b}	0.475^{b}	0.518^{a}	0.424^{c}	20.2	8.6
Organic carbon (%)	0.344^{b}	0.365^{b}	0.301^{c}	0.420^{a}	33.3	13.8
Total N (%)	0.0387^{b}	0.0412^{b}	0.0344^{c}	0.0470^{a}	31.2	13.0

Property	Winter	Spring	Summer	Rainy	Amplitude (%)	CV (%)
Available N (kg ha^{-1})	163^{b}	171^{b}	148^{c}	188^{a}	23.4	9.7
Available P (kg ha^{-1})	12.3^{b}	13.0^{b}	10.9^{c}	14.8^{a}	30.5	12.6
Available K (kg ha^{-1})	211^{b}	221^{b}	196^{c}	238^{a}	19.6	8.2
n = 24 per season. Different superscript letters within a row indicate significant difference by Tukey's HSD test ($p < 0.05$). Amplitude = (seasonal maximum - seasonal minimum) / annual mean x 100; CV = coefficient of variation of the four seasonal means.						

Table 2. Surface-to-subsurface (0–15 cm / 15–30 cm) ratios of soil properties in each season, showing the constancy of depth stratification through the year.

Property	Winter	Spring	Summer	Rainy	Annual mean
pH	0.975	0.976	0.976	0.975	0.975
EC	1.126	1.127	1.116	1.130	1.124
Organic carbon	1.307	1.305	1.329	1.301	1.310
Total N	1.291	1.276	1.294	1.274	1.283
Available N	1.215	1.215	1.239	1.217	1.221
Available P	1.305	1.319	1.330	1.299	1.312
Available K	1.172	1.163	1.186	1.175	1.174
Ratios computed from depth-wise seasonal means pooled across all six species. A ratio greater than unity indicates surface enrichment.					

Table 3. Three-way analysis of variance for soil properties and the percentage share of each factor in the sum of squares explained by the three main effects.

Property	Source	SS	F	p	% Species	% Season	% Depth
pH	Species	8.92	13.54	< 0.001	75.6	17.5	6.9
EC	Species	0.289	8.98	< 0.001	61.5	24.7	13.8
Organic carbon	Species	0.135	6.73	< 0.001	50.0	20.7	29.3
Total N	Species	0.00102	6.04	< 0.001	46.4	22.7	30.9
Available N	Species	15625	5.09	0.001	38.3	23.0	38.8
Available P	Species	95.2	4.11	0.004	31.0	23.5	45.6
Available K	Species	13542	4.98	0.001	37.6	25.5	36.9
SS and F are shown for the species term; percentages are computed from the sums of squares of all three main effects (species df = 5, season df = 3, depth df = 1). Season and depth terms were significant at $p < 0.01$ or better for every property.							

Table 4. Rainy-season versus summer comparison and the resulting effect on estimated soil organic carbon stock.

Property	Summer	Rainy	Change (%)	Paired t	p
Organic carbon (%)	0.301	0.420	+39.6	20.43	< 0.001
Total N (%)	0.0344	0.0470	+36.6	17.41	< 0.001
Available P (kg ha−1)	10.9	14.8	+35.6	22.09	< 0.001
Available N (kg ha−1)	148	188	+26.4	32.50	< 0.001
Available K (kg ha−1)	196	238	+21.7	56.38	< 0.001
EC (dS m−1)	0.518	0.424	−18.2	−24.87	< 0.001
pH	8.28	7.88	−4.8	—	< 0.01
SOC stock 0–30 cm (Mg ha−1)	13.5	18.9	+39.6	—	—

Paired t tests computed across the twelve species x depth units (df = 11). The pH difference was constant across all units and is reported from the analysis of variance instead. SOC stock estimated as seasonal OC (%) x mean bulk density x 30 cm x 10.

Discussion

4.1 The monsoon pulse and the summer minimum

The synchronous rainy-season maximum recorded for organic carbon and every nutrient variable, and the equally synchronous summer minimum, is the signature of pulse-driven biogeochemistry described for drylands generally (Austin et al., 2004; Huxman et al., 2004). Three processes plausibly combine to produce it. First, the rewetting of soils that have been dry for several months triggers the Birch effect: aggregate disruption and the release of accumulated microbial osmolytes and necromass supply a flush of labile substrate, and mineralisation and nutrient release rise sharply (Birch, 1958; Fierer and Schimel, 2002; Borken and Matzner, 2009). Second, the monsoon coincides with the peak of fine-root production, litterfall decomposition and rhizodeposition, so fresh organic inputs are at their annual maximum at precisely the time when conditions favour their processing. Third, the summer minimum reflects not only the cessation of inputs but the oxidative loss of organic matter under soil temperatures that regularly exceed 45 °C at the surface, together with the absence of the moisture required for microbial stabilisation of new carbon.

The magnitude of the seasonal swing deserves emphasis. A range of 33.3% of the annual mean for organic carbon, in soils whose absolute concentrations are low, means that the labile fraction responding to season is a substantial proportion of the total pool. This is consistent with the expectation that in coarse-textured, low-clay soils a comparatively small share of organic carbon is protected by association with mineral surfaces, leaving the remainder vulnerable to seasonal turnover.

4.2 Anti-phase behaviour of soil reaction and salinity

Soil pH and electrical conductivity moved in the opposite direction to the nutrient bundle, peaking in summer and falling in the rainy season. The mechanism is essentially hydrological rather than biological. During the monsoon, downward percolation leaches soluble salts and bases from the upper profile, lowering electrical conductivity and, through the removal of exchangeable bases and the production of carbonic and organic acids during the accompanying flush of microbial activity, lowering pH. Through the long dry season the direction of net water movement reverses under an evaporative demand that far exceeds precipitation, and dissolved salts are transported upward and concentrated near the surface. The strong negative correlation between organic carbon and pH across seasons ($r = -0.887$) should therefore be read as the joint outcome of a common hydrological driver rather than as evidence that either property controls the other.

4.3 Additivity of season and depth

The constancy of the depth ratios across seasons is, in statistical terms, a negative result, but it is a useful one. Had the surface layer responded to the monsoon more strongly than the subsurface — as might be expected if the wetting front rarely penetrated below 15 cm — the depth ratio would have widened in the rainy season and narrowed in summer. It did not: for organic carbon the ratio varied by only 2.1% of its mean across the year. Two inferences follow. Physically, monsoon recharge in these coarse-textured soils evidently wets the whole 0–30 cm profile rather than only its upper part, so both layers experience the rewetting pulse. Analytically, season and depth can be treated as additive main effects, which means that a seasonal correction factor derived at one depth may reasonably be applied at the other, and that no interaction term is required in models of these soils over the range of conditions observed.

4.4 The relative weight of species, season and depth

The variance partitioning in Table 3 provides a compact summary of what controls what. Properties determined by the chemical quality of organic inputs — pH and electrical conductivity — were dominated by species identity, which accounted for three-quarters of the explained variation in pH. Properties determined by the physical placement of those inputs — the available macronutrients — were dominated by depth. Organic carbon and total nitrogen, which depend on both the quality and the placement of inputs, occupied an intermediate position with species and depth of roughly equal weight.

Season, by contrast, was remarkably even-handed, contributing between 17.5% and 25.5% of the explained variation for every property without exception. This uniformity is itself informative: it suggests that the seasonal signal is imposed by a single external driver, soil moisture, that acts on all properties through the same pathway and to a similar relative degree, rather than by property-specific mechanisms. It also has a practical corollary. Because season never dominates, seasonal variation will not usually reverse a ranking of species or depths; but because it is never negligible, comparisons made between datasets collected in different seasons will be systematically biased.

4.5 Implications for sampling design and inventory practice

The most consequential result of this study is presented in Table 4. The same soils yield an estimated 0–30 cm organic carbon stock of 13.5 Mg ha^{-1} if sampled in June and 18.9 Mg ha−1 if sampled in September. A 5.4 Mg C ha−1 difference, equivalent to 19.8 Mg CO_2-e ha−1, is far larger than the changes that soil carbon monitoring programmes typically seek to detect over intervals of several years. Where a baseline is established in one season and a re-measurement made in another, the apparent change may be dominated entirely by sampling date.

Three recommendations follow. First, the sampling season should be fixed in the protocol and reported explicitly with every dataset; comparisons across sites or dates should be restricted to matched seasons. Second, where fixed-season sampling is impracticable, seasonal correction factors of the kind derivable from Table 1 should be applied and their derivation documented. Third, for programmes seeking the most conservative estimate of a soil carbon stock — as is appropriate in carbon crediting, where over-statement carries the greater penalty — sampling in the pre-monsoon dry season provides the lower bound. Conversely, agronomic advisory sampling aimed at characterising nutrient supply to a crop is most informative when conducted close to the period of active uptake. The appropriate season depends on the purpose, but in no case should it be left unspecified.

4.6 Limitations

Three limitations qualify these conclusions. The observations span a single annual cycle, so the seasonal pattern reported here cannot be separated from any inter-annual anomaly in the rainfall of 2023–24; replication over several years would be required to establish the amplitude as a stable property of the system. Sampling was confined to the upper 30 cm, and the behaviour of deeper layers, which are buffered against short-term moisture fluctuation, remains unknown. Finally, the seasons were represented by single monthly samplings; a design with higher temporal resolution around the onset of the monsoon would be needed to resolve the shape and duration of the rewetting pulse itself rather than only its seasonal integral.

5. Conclusion

Soil chemical properties under arid-zone tree plantations in western Rajasthan varied substantially and systematically through the year. Organic carbon, total nitrogen and the available macronutrients peaked in the rainy season and reached their minima in summer, with rainy-to-summer increases of 21.7% to 39.6%, while pH and electrical conductivity followed the opposite phase. Depth stratification was invariant across seasons, indicating that season and depth act additively. Species dominated the variation in pH and electrical conductivity, depth dominated the available macronutrients, and season contributed a uniform one-fifth to one-quarter of the explained variation in every property. Because the choice of sampling season alone alters the estimated 0–30 cm organic carbon stock by 5.4 Mg ha−1, or nearly 40%, the standardisation and explicit reporting of sampling season should be treated as a minimum requirement for soil carbon inventories in the Indian hot arid zone.

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