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Hydrologically Mediated Soil Carbon Dynamics and Physicochemical Controls Across Forest–Ecotone–Wetland Systems: Implications for Climate Resilience

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Abstract

Forests, ecotones, and wetlands are rarely studied as a single hydrologically connected system, even though water, and carbon it carries, moves continuously between them—a gap especially acute in tropics, where human-engineered wetlands remain nearly invisible in global carbon accounting despite their disproportionate storage potential. This study addresses that gap across three dry-zone cascade reservoir landscapes in Sri Lanka, using georeferenced topsoil samples analyzed via statistical methods and ordinary kriging. As a key methodological novelty, this study introduces the Ecotone Carbon Deficit Index (ECDI), a transferable metric quantifying how far ecotonal carbon storage falls below a simple forest–wetland mixing expectation. Despite near-uniform physicochemical baselines across sites (bulk density $1.25 \pm 0.10 \text{ g cm}^{-3}$; SOC $1.93 \pm 0.58\%$), carbon stocks rose sharply along the hydrological gradient, from $1.63 \text{ Mg C ha}^{-1}$ in ecotones to 2.18 in forests and 2.78 in wetlands, tracking a coupled moisture–bulk density–pH axis (γ up to 0.904 with total nitrogen; $\gamma = -0.748$ with bulk density). One-way ANOVA confirmed zonation, as the dominant structuring factor: pH, bulk density, SOC, soil moisture, electrical conductivity, total nitrogen, and total carbon all differed significantly across zones ($F = 54.19\text{--}476.90$, $p < .001$), while no parameter differed significantly across locations, confirming carbon gradient is a reproducible, site-independent feature rather than a local artifact. All three landscapes showed a consistent ECDI of 32.6–35.3%, revealing that ecotones—the very zones linking forest and wetland carbon pools—are structurally carbon-starved and climate-vulnerable, while wetlands act as terminal, hydrologically buffered carbon sink.

Keywords: Soil organic carbon (SOC), Forest–ecotone–wetland continuum, Ecotone Carbon Deficit Index (ECDI), Cascade reservoir systems, Climate resilience, wetland conservation

1. Introduction

Wetlands are widely regarded as disproportionately efficient carbon-sequestering ecosystems, a consequence of hydrology that sustains anoxic or sub-oxic conditions, suppresses heterotrophic decomposition, and promotes the long-term preservation of organic matter within soil profiles (Khanal et al., 2026). Although wetlands occupy a comparatively small fraction of the terrestrial land surface, they contribute disproportionately to the global soil carbon budget and represent indispensable components of the climate system. Nevertheless, the persistence of wetland carbon stocks is contingent upon hydrological stability, nutrient regimes, and landscape connectivity, such that perturbations arising from climatic variability, land-use change, and other anthropogenic disturbances may compromise carbon-stabilization mechanisms and heighten the vulnerability of these ecosystems to net carbon loss.

Soils constitute the most extensive terrestrial reservoir of organic carbon, exceeding the combined pools of the atmosphere and standing vegetation, and thereby exert first-order control over global biogeochemical cycling and climate feedback mechanisms. The capacity of soils to function as durable carbon sinks is governed by an intricate interplay of vegetation inputs, hydrological regime, microbial metabolism, mineral–organic associations, and physicochemical attributes (Rivera-Monroy et al., 2011). Ecosystems differing markedly in water availability and ecological function, most notably forests and wetlands, exhibit fundamentally distinct pathways of carbon accumulation and stabilization, so that elucidating how soil carbon is distributed and regulated across hydrologically interconnected ecosystems has become an increasingly urgent scientific priority as shifting precipitation regimes, intensifying drought, and altered hydrological connectivity threaten to destabilize terrestrial carbon reservoirs under anthropogenic climate change.

Despite considerable attention to wetland carbon dynamics in isolation, carbon cycling across landscapes that integrate forests, transitional habitats, and wetlands remains conspicuously underexamined. Forest–wetland systems do not operate as ecologically discrete units; rather, they constitute continua linked by lateral water movement, dissolved organic matter transport, nutrient exchange, and shared biological processes that generate continuous biogeochemical connectivity across the landscape (Cui et al., 2005). Within these continua, ecotones, the transitional interfaces separating contrasting ecosystems, represent particularly dynamic zones in which steep environmental gradients and convergent ecological processes coincide, simultaneously inheriting characteristics of both adjoining ecosystems while expressing emergent, functionally distinct properties that position them as potential hotspots of carbon transformation and long-term storage.

Ecotones are increasingly recognized as pivotal regulators of ecosystem functioning owing to their role in mediating material fluxes between adjacent habitats and their heightened sensitivity to environmental perturbation. The gradual transition from forested to wetland environments generates pronounced spatial gradients in soil moisture, redox potential, vegetation composition, organic matter inputs, and microbial activity, all of which jointly govern carbon-stabilization pathways (Rasmussen et al., 2018). Yet ecotones remain markedly under-represented in carbon-cycle assessments, with the overwhelming majority of prior work treating forests and wetlands as independent, non-interacting systems. Consequently, the contribution of these transitional ecosystems to regional carbon sequestration and climate resilience remains poorly quantified, a knowledge gap that is especially acute in tropical environments, where ecotone dynamics remain almost entirely unstudied.

It is precisely this gap that constitutes the central novelty of the present study. Rather than treating forests and wetlands as isolated analytical units, this study adopts an explicitly landscape-continuum framework that positions the ecotone as an active, mechanistically distinct carbon-regulating compartment rather than a mere boundary artefact. By simultaneously quantifying carbon stocks and their physicochemical and hydrological controls across three ecologically contiguous zones, forest, ecotone, and wetland, spanning multiple geographic locations within a tropical dry-zone landscape, this study provides one of the first integrated, multi-site characterizations of hydrologically mediated carbon transfer along a forest-to-wetland continuum in a South Asian tropical setting. Beyond this descriptive contribution, we advance the analytical framework a further step by formalizing the ecotone's departure from simple spatial-averaging expectations as a quantitative index, introduced below as the Ecotone Carbon Deficit Index, allowing the magnitude of ecotonal carbon vulnerability to be compared across sites, ecosystems, and, in principle, future monitoring intervals. Soil physicochemical characteristics exert a decisive influence on carbon storage capacity; however, the relative contribution of, and interactions among, these environmental controls across forest–ecotone–wetland gradients remain inadequately resolved, particularly with respect to their combined, rather than individual, explanatory power.

A landscape-integrated assessment that jointly evaluates soil carbon stocks alongside their physicochemical drivers is therefore essential to advancing mechanistic understanding of carbon regulation in tropical ecosystems. Such an approach enables identification of dominant environmental controls and evaluation of ecosystem vulnerability under prospective climate scenarios. Moreover, characterizing carbon dynamics across forest–ecotone–wetland transitions yield insights of direct relevance to wetland conservation, ecosystem restoration, and climate-mitigation planning, an integrative, cross-ecosystem perspective that has, to date, been largely absent from the tropical soil carbon literature. Finally, the reservoir-cascade wetlands studied here occupy a distinctive niche within global wetland typology: they are small, shallow, seasonally dynamic, and centuries old, having been engineered by human communities long before the modern conservation era, yet they now perform ecosystem services, water regulation, biodiversity refuge, and, as this study demonstrates, disproportionate carbon storage, that align closely with the services attributed to naturally occurring wetlands elsewhere. Their inclusion within global carbon-accounting and wetland-conservation frameworks is therefore not merely a matter of scientific completeness but a matter of environmental equity, ensuring that small, human-managed tropical wetlands are neither overlooked in national greenhouse-gas inventories nor excluded from the investment scale-up that the Ramsar Convention identifies as necessary to conserve and restore several hundred million hectares of wetland worldwide (Ramsar Convention on Wetlands, 2025; Wu et al., 2026).

2. Methodology

2.1 Study Area and Bioclimatic Landscapes

This investigation was undertaken across three geographically distinct locations situated within the absolute Dry Zone bioclimatic boundary of Sri Lanka, namely Girandurukotte, Horowpothana, and Kusumpokuna, each selected to capture divergent landscape configurations within the island's historical reservoir-cascade and natural drainage systems. Girandurukotte, positioned within the eastern sector of the Dry Zone, comprises a lowland plain punctuated by isolated residual inselbergs, its vegetation transitioning from secondary dry mixed evergreen forest into low-lying palustrine wetland fields under the governance of the Northeast monsoon, with a mean annual temperature of 28.4°C and average annual precipitation of 1,350 mm. Horowpothana, located within the northern Dry Zone, constitutes a complex inter-basin mosaic characterized by gently undulating topography and a network of seasonal streams that feed shallow, low-gradient freshwater wetlands and subject to a pronounced drought interval extending from May to September, with annual rainfall approximating 1,200 mm. Kusumpokuna, situated within the North-Central lowlands, is distinguished by a low-gradient plain interspersed with natural freshwater depressions locally termed wewa/pokuna, encircled by dense dry forest patches; its soils are predominantly Alfisols, classified regionally as Red Brown Earths, transitioning into Inceptisols and Entisols within the hydromorphic depressions, with mean annual temperature and precipitation of 29.1°C and 1,100–1,300 mm, respectively.

2.2 Sampling Design and Field Sample Collection

In order to resolve the pronounced environmental and microclimatic gradients characteristic of dry forest–wetland continuums, a high-resolution, systematic grid-based sampling matrix was constructed within a geographic information systems (GIS) framework, an approach consistent with established protocols for capturing fine-scale pedological heterogeneity across ecotonal transects (Webster & Oliver, 2007). At each of the three study locations, three parallel transects were delineated perpendicular to the wetland margin, extending progressively through the transitional ecotone before terminating within the interior of the adjoining dry forest patch. Sampling nodes along each transect were georeferenced using GPS, yielding a cumulative total of ninety-two discrete topsoil sampling points across the three landscapes. At every node, undisturbed core samples were extracted from the uppermost soil horizon (0–10 cm) using standardized stainless-steel volumetric cutting rings of 100 cm³ capacity, a method widely regarded as the reference technique for accurate bulk density determination (Barry, 2025). Concurrently, disturbed bulk composite samples were obtained from equivalent depths.

2.3 Laboratory Physicochemical Analyses

All soil samples were air-dried, gently disaggregated, and sieved through a 2 mm mesh to remove coarse fragments, roots, and other extraneous debris prior to analysis, a standard preparatory step intended to homogenize the sample matrix and ensure comparability across analytical procedures. Bulk density was determined via the core method using the volumetric cutting rings collected in the field; each core was oven-dried at 105°C for twenty-four hours until constant mass was achieved, after which dry bulk density was calculated (Blake & Hartge, 1986).

Soil organic carbon content was quantified using the modified Walkley-Black wet oxidation method, a wet-digestion technique that remains among the most widely adopted approaches for tropical soil carbon assessment owing to its cost-effectiveness and operational simplicity relative to dry combustion analysis (Walkley & Black, 1934; Nelson & Sommers, 1996). Gravimetric soil moisture content was established by weighing fresh bulk samples prior to and following oven-drying at 105°C for twenty-four hours, with the proportional mass loss expressed as a percentage of the initial wet mass. Soil reaction (pH) and electrical conductivity were determined in a 1:2.5 soil-to-distilled-water suspension. Particle-size distribution, comprising the relative proportions of sand, silt, and clay, was assessed using the Bouyoucos hydrometer method, wherein soil samples were chemically dispersed using sodium hexametaphosphate solution and mechanically agitated to disaggregate compound particles into their primary constituents; hydrometer readings were subsequently recorded at standardized time intervals to exploit differential settling velocities governed by Stokes' law, permitting textural classification according to the United States Department of Agriculture (USDA) system (Gee & Bauder, 1986).

Nutrient status was characterized through three complementary procedures. Total nitrogen concentration was determined via the micro-Kjeldahl method, involving acid digestion of the soil sample to convert organically bound nitrogen into ammonium sulfate, followed by alkaline distillation and titrimetric quantification of the liberated ammonia (Bremner, 1996). Available phosphorus was extracted using the Olsen sodium bicarbonate method, appropriate for neutral to alkaline soils, at a buffered pH of 8.5, with the extracted phosphate subsequently reacting with an ammonium molybdate–ascorbic acid reagent to form a blue-colored phosphomolybdenum complex whose absorbance was measured spectrophotometrically. Exchangeable potassium was extracted using a one-molar ammonium acetate solution buffered at neutral pH, thereby displacing potassium ions from soil exchange sites into solutions, with subsequent quantification performed via flame photometry, a technique valued for its sensitivity to alkali metal cations at low concentrations typical of tropical soils.

2.4 Calculation of Soil Organic Carbon Stocks

Topsoil organic carbon stocks at each sampling point were derived using the following standard equation.

$$SOC\ Stock\ (Mg\ C\ ha^{-1}) = \left(\frac{SOC\ (\%)}{100} \right) \times BD\ (g\ cm^{-3}) \times Depth\ (cm) \times 100 \quad (1)$$

wherein SOC% denotes the laboratory-derived organic carbon percentage, BD represents dry bulk density, and Depth corresponds to the ten-centimeter thickness of the sampled horizon, a formulation widely employed for converting mass-based carbon concentrations into area-normalized stock estimates (Batjes, 1996; IPCC, 2006).

2.5 A Novel Diagnostic Metric - The Ecotone Carbon Deficit Index (ECDI)

The results presented on the ecotone do not behave as a simple spatial average of its forest and wetland neighbors but instead consistently underperforms the value that a naïve linear-mixing model would predict. To move this observation beyond a qualitative description and render directly comparable across landscapes, ecosystems, and, in principle, future re-sampling campaigns, an Ecotone Carbon Deficit Index (ECDI) was formulated, defined as;

$$ECDI\ (\%) = \frac{C_{expected} - C_{observed}}{C_{expected}} \times 100 \quad (2)$$

Where; C_{observed} is the mean measured carbon stock (Mg C ha^{-1}) of the ecotone zone, and C_{expected} is the carbon stock that would be predicted under a null, additive mixing model in which the ecotone is assumed to represent the arithmetic midpoint of its two flanking end-members;

$$C_{\text{expected}} = \frac{(C_{\text{forest}} + C_{\text{wetland}})}{2} \text{-----} (3)$$

A positive ECDI value indicates that the ecotone stores less carbon than expected under simple spatial interpolation between forest and wetland end-members, with the magnitude of the index expressing the size of this deficit as a percentage of the expected value; an ECDI of zero would indicate that the ecotone behaves exactly as a linear transitional average, while a negative value would indicate that the ecotone exceeds the expected midpoint (i.e., functions as an additional carbon sink rather than a deficit zone).

2.6 Statistical Analysis and Geostatistical Modeling

Statistical evaluation was conducted through an integrated analytical pipeline designed to test both categorical and spatial dimensions of variability. One-way analysis of variance, followed by post-hoc Tukey's Honestly Significant Difference tests, was employed to assess the statistical significance of differences in carbon stocks and physicochemical properties among the three ecological zones (forest, ecotone, and wetland). Pearson correlation matrices were subsequently generated to elucidate linear associations between edaphic drivers and carbon stock magnitude. Finally, spatial mapping and geostatistical modeling were performed within a GIS environment using Ordinary Kriging interpolation, a technique that provides the best linear unbiased prediction of spatially continuous variables based on the underlying semivariogram structure, thereby enabling continuous visualization of carbon stock distribution across the sampled landscape coordinates.

3. Results and Discussion

3.1 Soil Organic Carbon Stocks Across Ecological Zones

The interconnected cascade reservoir networks of Sri Lanka's dry zone represent a distinctive hydro-pedological configuration in which upland forest, ecotonal buffer, and wetland/reservoir-bed soils are continuously linked by seasonal runoff and sediment transfer. This connectivity raises the question of whether such systems behave as a single, hydrologically integrated carbon reservoir rather than as ecologically and physicochemically distinct compartments, a question the present dataset is well positioned to address.

The striking features of Table 1 and 2 are the near-identical central tendency across all three locations: bulk density clusters tightly around $1.24\text{--}1.25 \text{ g/cm}^3$, SOC around $1.91\text{--}1.94\%$, pH $6.34\text{--}6.43$, EC $\sim 0.18 \text{ dS/m}$, and textural class remaining sandy loam ($\sim 57\text{--}59\%$ sand, $\sim 20\text{--}21\%$ silt, $\sim 20\text{--}22\%$ clay) at every site. Nutrient indices (TN $\approx 0.13\%$, available P $\approx 10\text{--}12 \text{ mg/kg}$, exchangeable K $\approx 87\text{--}94 \text{ mg/kg}$) likewise vary within a narrow band. The small differences in means indicate that within-site heterogeneity far exceeds between-site variability, a pattern consistent with catchment-scale (rather than site-specific) hydro-edaphic control.

Across zones, seven of the twelve parameters — pH, bulk density, SOC, soil moisture, electrical conductivity, total nitrogen, and total carbon — differ with very high statistical significance ($F = 54\text{--}477$, $p < .001$), confirming that these variables are systematically and predictably structured by position along the forest–ecotone–wetland gradient. The very large F-values for soil moisture ($F = 476.90$) and SOC ($F = 281.17$) in particular indicate that zonal identity explains an overwhelming proportion of the variance in these two parameters far more than would be expected from random spatial noise which mechanistically makes sense: moisture regime is the direct physical consequence of proximity to the wetland/reservoir, and SOC responds to that moisture regime through its control over decomposition rate, exactly as demonstrated in the regression analyses (Table 3). Texture (sand, silt, clay) and the extractable macronutrients (available P, exchangeable K) show no significant zonal differentiation, reaffirming the earlier correlation-based conclusion that particle-size distribution and short-term nutrient

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Table 1. Physicochemical and nutritional properties of topsoil across the forest, ecotone, and wetland zones

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Zone	Bulk Density	SOC	Soil Moisture	pH	Electrical Conductivity	Sand	Silt	Clay	Total Nitrogen	Available Phosphorus	Exchangeable Potassium	Carbon
Ecotone	1.34 ± 0.05	1.40 ± 0.23	17.69 ± 2.23	6.60 ± 0.20	0.17 ± 0.02	56.47 ± 8.22	20.63 ± 5.68	22.99 ± 0.16	0.10 ± 0.02	10.69 ± 3.99	89.15 ± 30.13	1.87 ± 0.32
Forest	1.29 ± 0.05	1.74 ± 0.20	13.50 ± 2.47	6.45 ± 0.20	0.12 ± 0.03	58.36 ± 7.66	21.98 ± 5.36	19.74 ± 9.32	0.12 ± 0.02	11.53 ± 4.31	94.95 ± 28.59	2.24 ± 0.26
Wetland	1.12 ± 0.05	2.66 ± 0.21	31.95 ± 2.57	6.07 ± 0.20	0.25 ± 0.02	59.05 ± 7.10	21.05 ± 6.55	19.93 ± 9.30	0.16 ± 0.02	11.26 ± 4.24	86.74 ± 28.83	2.97 ± 0.25
Total	1.25 ± 0.10	1.93 ± 0.58	21.05 ± 8.30	6.37 ± 0.30	0.18 ± 0.06	57.96 ± 7.67	21.22 ± 5.85	20.89 ± 9.61	0.13 ± 0.03	11.16 ± 4.15	90.28 ± 29.07	2.36 ± 0.54

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Table 2. Physicochemical and nutritional properties of topsoil across the three cascade reservoir sampling locations

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Location	Bulk Density	SOC	Soil Moisture	pH	Electrical Conductivity	Sand	Silt	Clay	Total Nitrogen	Available Phosphorus	Exchangeable Potassium	Carbon
Girandurukotte	1.25 ± 0.11	1.94 ± 0.59	20.52 ± 8.8	6.35 ± 0.33	0.18 ± 0.06	56.71 ± 7.03	21.34 ± 5.82	21.96 ± 9.79	0.13 ± 0.03	11.49 ± 4.09	89.7 ± 29.05	2.36 ± 0.53
Horowpothana	1.24 ± 0.10	1.94 ± 0.59	21.43 ± 8.38	6.43 ± 0.29	0.18 ± 0.06	58.55 ± 8.55	20.95 ± 6.48	20.6 ± 10.66	0.13 ± 0.03	10.44 ± 4.49	87.28 ± 29.95	2.36 ± 0.56
Kusumpokuna	1.25 ± 0.10	1.91 ± 0.57	21.19 ± 7.95	6.34 ± 0.27	0.18 ± 0.06	58.62 ± 7.45	21.38 ± 5.38	20.09 ± 8.49	0.13 ± 0.03	11.54 ± 3.91	93.86 ± 28.80	2.36 ± 0.55
Total	1.25 ± 0.10	1.93 ± 0.58	21.05 ± 8.30	6.37 ± 0.30	0.18 ± 0.06	57.96 ± 7.67	21.22 ± 5.85	20.89 ± 9.61	0.13 ± 0.03	11.16 ± 4.15	90.28 ± 29.07	2.36 ± 0.54

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availability are decoupled from the hydrological zonation that otherwise organizes carbon and nitrogen status likely because texture is inherited from parent material and depositional history rather than current hydrological regime, while P and K availability are governed more by localized biological cycling and anthropogenic inputs than by broad zonal position.

Table 3. One-Way ANOVA results for soil physicochemical and nutritional parameters across ecological zones and sampling locations

Parameter	One-Way ANOVA Across Zones		One-Way ANOVA Across Locations	
	<i>F value</i>	<i>P value</i>	<i>F value</i>	<i>P value</i>
pH	54.190	0.000	0.891	0.414
Bulk Density	177.170	0.000	0.109	0.897
SOC	281.170	0.000	0.026	0.975
Soil Moisture	476.900	0.000	0.095	0.909
Electrical Conductivity	216.460	0.000	0.040	0.961
Sand	0.910	0.408	0.594	0.554
Silt	0.410	0.664	0.049	0.952
Clay	1.080	0.343	0.299	0.743
Total Nitrogen	120.790	0.000	0.153	0.859
Available Phosphorus	0.310	0.735	0.664	0.517
Exchangeable Potassium	0.630	0.536	0.388	0.680
Carbon	123.150	0.000	0.001	0.999

Critically, the across-locations panel shows the mirror-image result: not a single parameter — including the seven that varied strongly by zone — differs significantly between Girandurukotte, Kusumpokuna, and Horowpothana. This is a powerful confirmatory finding rather than a null result to be dismissed: it demonstrates that the zonal patterns identified are not artifacts of any one particular cascade's local geology, rainfall history, or management practice, but instead represent a genuine, reproducible ecological structuring mechanism that operates identically regardless of which specific cascade reservoir system is examined. In practical terms, this means the forest–ecotone–wetland zonation scheme — and by extension, the Ecotone Carbon Deficit Index derived from it — is not a site-specific curiosity applicable only to one cascade, but a generalizable functional template for how carbon and moisture are organized across Sri Lanka's dry-zone cascade reservoir landscape as a whole.

Taken together, Table 3 provides the statistical backbone justifying the entire zonal framing used throughout this study: it confirms that ecological zone, not geographic location, is the dominant organizing axis of topsoil carbon and hydro-edaphic variability in these systems. This has a direct and encouraging implication for climate resilience policy and cascade reservoir management — because the pattern is site-independent and zone-driven, restoration or conservation interventions designed around zonal position (e.g., prioritizing ecotone buffer rehabilitation, protecting reservoir-margin hotspots) should be broadly transferable across Sri Lanka's thousands of cascade reservoir systems, rather than requiring bespoke, site-by-site diagnosis, which considerably strengthens the scalability and policy relevance of the zonal management recommendations arising from this research.

The physicochemical homogeneity revealed across the forest–ecotone–wetland continuum is a non-trivial finding with direct bearing on how soil organic carbon (SOC) dynamics should be conceptualized in tropical, monsoon-driven, cascade-reservoir landscapes such as those of Sri Lanka's dry and intermediate zones. Rather than the abrupt physicochemical discontinuities typically reported across forest–wetland ecotones in temperate and boreal systems, where redox gradients, litter chemistry shifts, and hydroperiod produce sharp SOC and pH stratification

(Bridgham et al., 2006), the present dataset suggests that hydrological connectivity mediated by Sri Lanka's ancient cascade reservoir (Ellangawa) systems homogenizes topsoil properties across the landscape mosaic. These interconnected minor reservoir networks redistribute sediment-, nutrient-, and moisture-laden runoff along a continuous hydraulic gradient from upland forest catchments through ecotonal buffer zones into wetland/reservoir-bed soils, effectively "smoothing" the physicochemical signature that would otherwise differentiate discrete ecological units.

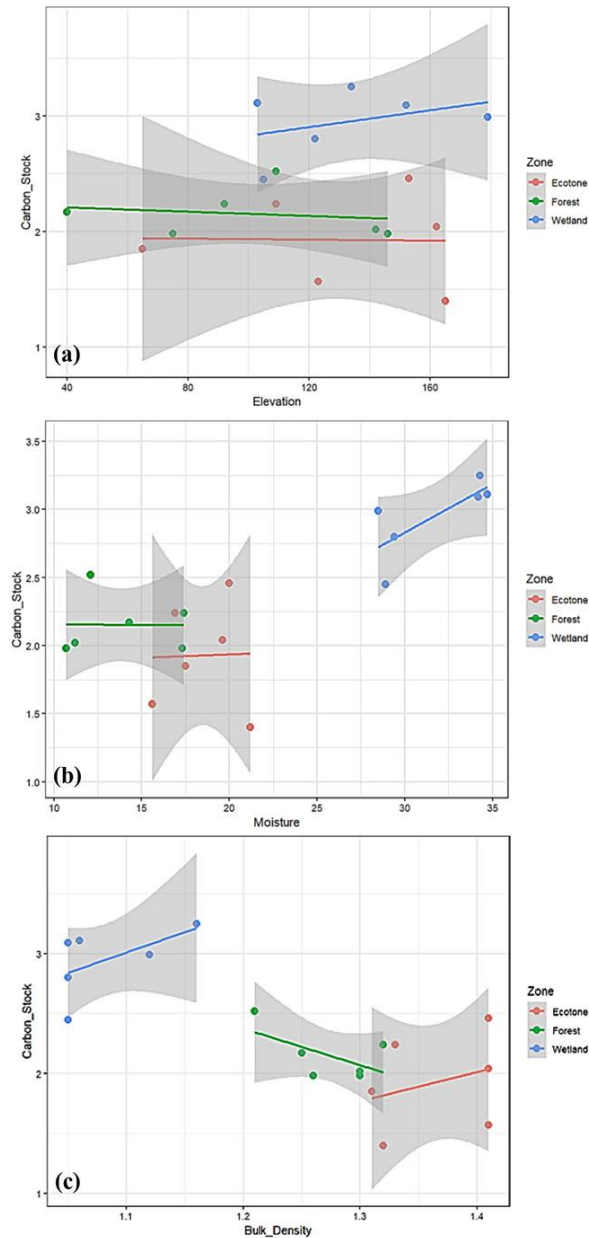


Fig 1. Relationships between topsoil carbon stock (Mg C ha⁻¹) and (a) elevation (m a.s.l.), (b) soil moisture (%), and (c) bulk density (g cm⁻³) across the three ecological zones (Ecotone, Forest, Wetland) of the cascade reservoir landscape

3.2 Correlation Analysis of Biophysical Controls

Table 4 presents the Pearson correlation matrix linking soil organic carbon (SOC) stocks with eleven core edaphic parameters, revealing a hierarchically structured network of physicochemical controls rather than isolated bivariate associations. A strong association between SOC and total nitrogen ($r = 0.904$, $p < 0.01$), reflecting a

tightly coupled C–N stoichiometry consistent with organic matter being the dominant source of both elements, a hallmark of biologically driven (rather than mineral-derived) nutrient cycling in these soils.

Beyond this, SOC shows a coherent triad of moderate-to-strong correlations with hydrologically linked variables: a positive association with soil moisture ($r = 0.565$, $p < .01$) and electrical conductivity ($r = 0.550$, $p < 0.01$), and a strong negative association with bulk density ($r = -0.748$, $p < .01$) (Fig 1). This pattern is mechanistically consistent, wetter, less compacted soils retain organic matter more effectively by limiting aerobic decomposition and physical oxidation, while elevated EC likely reflects the co-accumulation of dissolved organic and ionic species under sustained moisture retention rather than salinity stress per se. The negative correlation between SOC and pH ($r = -0.624$, $p < 0.01$) further suggests that organic acid accumulation from decomposing biomass exerts a measurable acidifying effect, or alternatively that more organic-rich (wetland-proximal) soils are inherently less buffered than mineral-dominated forest/ecotone soils.

Table 4. Pearson correlation matrix between soil organic carbon stocks (Mg C ha⁻¹) and core edaphic drivers

	SOC	Soil Moisture	pH	Electrical Conductivity	Sand	Bulk Density	Silt	Clay	Total Nitrogen	Available Phosphorus	Exchangeable Potassium	Carbon
SOC	-											
Soil Moisture	.565**	-										
pH	-.624**	-.486**	-									
Electrical Conductivity	.550**	.795**	-.495**	-								
Sand	.084	-.020	-.268*	.031	-							
Bulk Density	-.748**	-.523**	.597**	-.545**	-.138	-						
Silt	.012	.029	-.010	-.077	.006	-.030	-					
Clay	-.066	-.002	.206	.037	-.796**	.118	-.581**	-				
Total Nitrogen	.904**	.596**	-.608**	.598**	.044	-.707**	-.023	-.001	-			
Available Phosphorus	.087	.007	.061	.010	-.216*	-.053	-.101	.242*	.051	-		
Exchangeable Potassium	-.076	-.135	.020	-.103	-.001	.068	.042	.011	-.083	-.041	-	
Carbon	.980**	.571**	-.620**	.556**	.076	-.647**	.002	-.049	.899**	.086	-.059	-

** Correlation is significant at the 0.01 level (2-tailed).

A secondary but informative pattern emerges among the predictor variables themselves: soil moisture and EC are very strongly correlated ($r = 0.795$, $p < 0.01$), as are moisture and bulk density ($r = -0.523$, $p < 0.01$) and pH and bulk density ($r = 0.597$, $p < 0.01$), indicating a degree of multicollinearity among the hydrologically mediated variables. This has direct implications for any subsequent multivariate modelling, where moisture, EC, bulk density, and pH should be treated as a collinear hydro-edaphic cluster rather than independent predictors, and variance inflation should be assessed before their joint inclusion in explanatory models of SOC (Table 4). The sand–clay antagonism ($r = -0.796$, $p < 0.01$) is expected given compositional closure in particle-size data and does not reflect an independent ecological signal.

Therefore, the correlation structure supports a conceptual model in which SOC accumulation in this cascade landscape is governed primarily by a hydrology–compaction–reaction (moisture–bulk density–pH) axis, tightly linked to nitrogen cycling, while operating largely independently of soil texture and macronutrient (P, K) availability, a pattern that diverges from classical pedogenic models of SOC stabilization and instead points toward hydrological connectivity as the primary architect of carbon distribution across the forest–ecotone–wetland continuum.

The four-panel regression matrix ($n = 90$ pooled observations) quantifies the principal linear drivers of soil organic carbon (SOC) dynamics identified in the correlation analysis (Fig 2) and collectively reveals a tightly interlinked biogeochemical-hydrological control system rather than a single dominant predictor. SOC shows the strongest relationship with total soil carbon ($R^2 = 0.946$, $r = 0.973$, $p < 0.0001$) and total nitrogen ($R^2 = 0.870$, $r = 0.933$, $p < 0.0001$), with near-unity and near-stoichiometric slopes respectively, confirming that organic matter mineralization is the principal source of both carbon and nitrogen pools in these soils, a pattern consistent with biologically mediated nutrient cycling reported in tropical forest and wetland soils globally (Lal, 2018; Nahlik & Fennessy, 2016), and one that validates SOC as a reliable proxy for both total carbon stock and nitrogen availability across this cascade landscape.

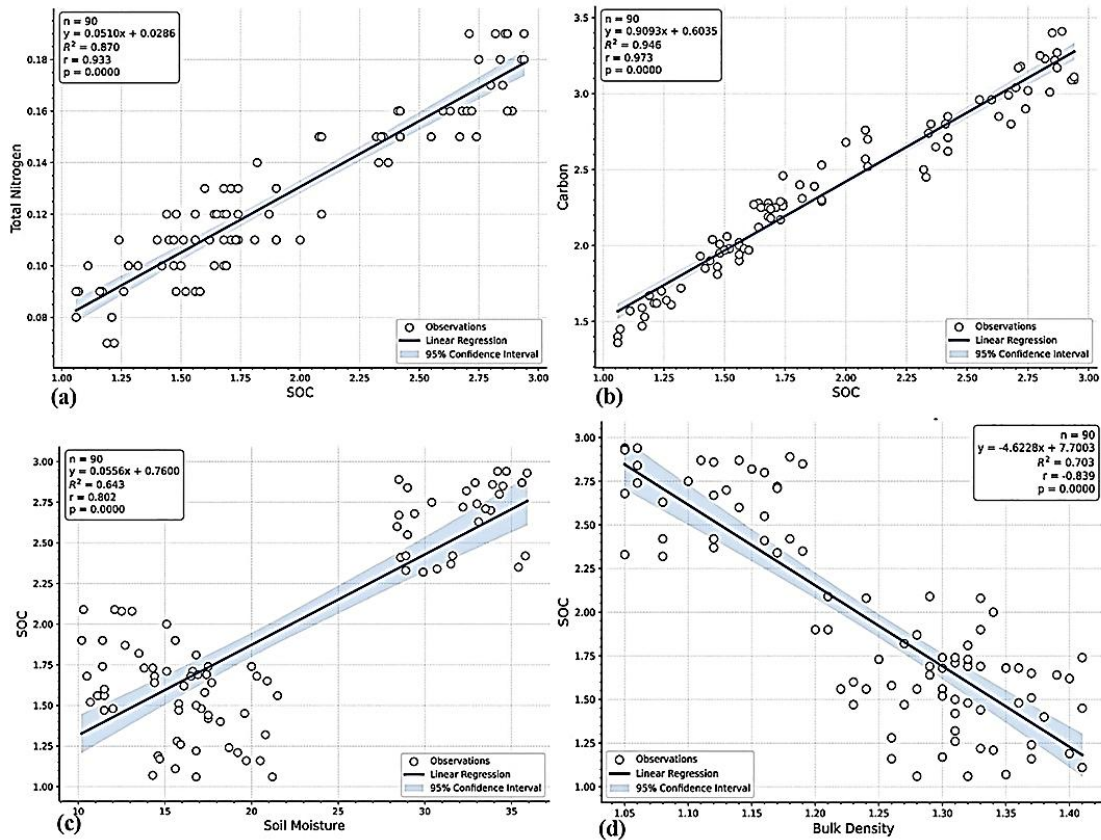


Fig 2. Linear regression relationships between soil organic carbon (SOC) and (a) total nitrogen, (b) total soil carbon, (c) soil moisture, and (d) bulk density

SOC is also strongly and negatively related to bulk density ($R^2 = 0.703$, $r = -0.839$, $p < 0.0001$), reflecting the classic inverse relationship between organic matter content and soil compaction: greater SOC lowers particle density and promotes aggregate stability, while denser, more compacted soils restrict root proliferation, microbial habitat, and pore-space aeration, likely producing a self-reinforcing feedback loop between compaction and carbon depletion rather than a simple unidirectional cause. The moderately strong positive relationship between SOC and soil moisture ($R^2 = 0.643$, $r = 0.802$, $p < 0.0001$) (Fig 2) indicates that while sustained wetness suppresses aerobic decomposition and favors SOC retention, this relationship is modulated by additional factors such as zonal identity and redox variability, particularly in wetland-influenced soils subject to Sri Lanka's pronounced Yala–Maha wet–dry seasonality, which periodically re-aerates otherwise carbon-conductive wetland soils and constrains the sustained anaerobic carbon preservation typical of perennially saturated tropical peatlands elsewhere (e.g., Southeast Asian and Amazonian wetlands).

Soil moisture emerged as a consistent positive driver across three key edaphic parameters (Fig 3), with all relationships statistically significant at $p < 0.0001$. The strongest association was observed for electrical conductivity ($R^2 = 0.735$, $r = 0.857$), followed by SOC ($R^2 = 0.643$, $r = 0.802$) and total nitrogen ($R^2 = 0.581$, $r = 0.762$). The visible bimodal clustering across all three panels, a lower-moisture cluster (~10–25%) and a distinctly

higher-moisture cluster (~28–36%) corresponding to forest/ecotone versus wetland zones respectively, indicates that moisture's influence on SOC, nitrogen, and conductivity operates largely through zonal (hydrological regime) differentiation rather than as a smooth continuous gradient, reinforcing soil moisture as a central hydro-edaphic control linking carbon, nutrient, and ionic status across the forest–ecotone–wetland continuum.

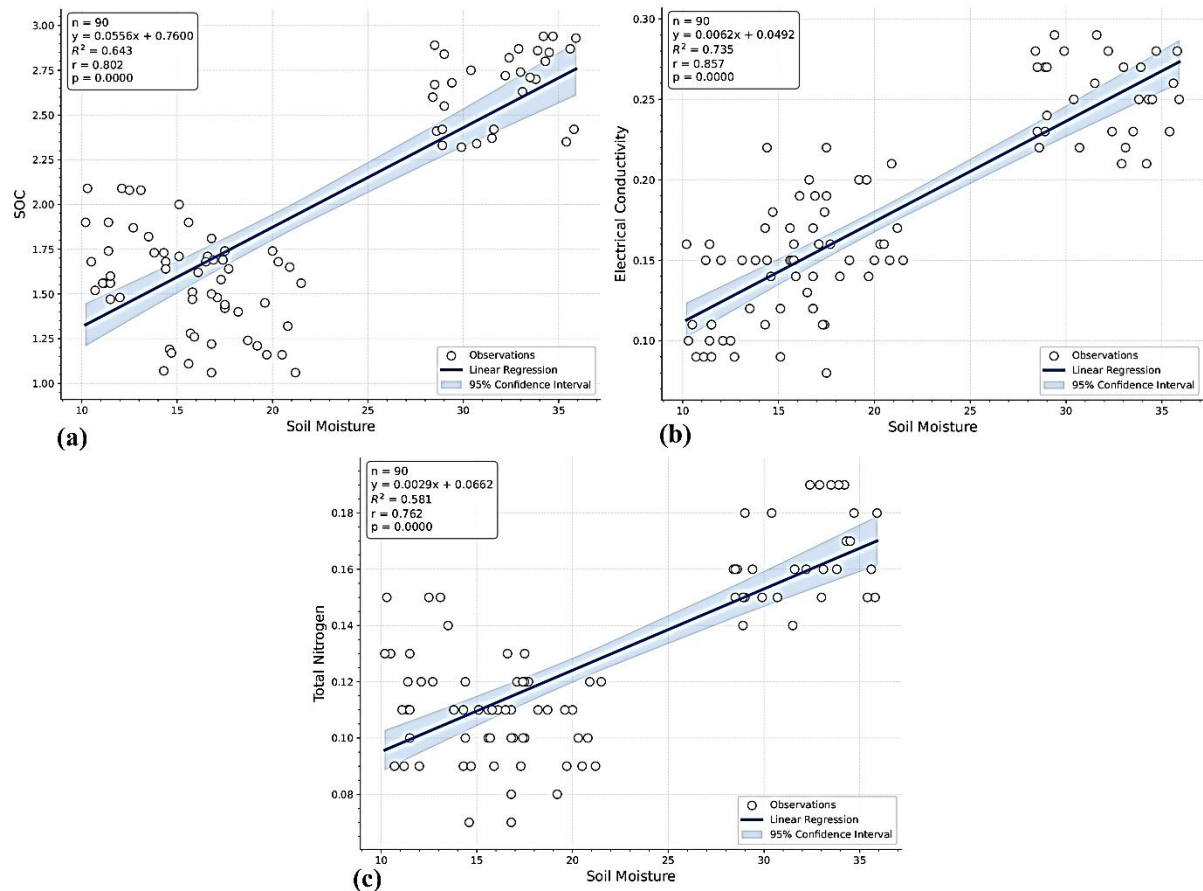


Fig 3. Linear regression relationships between soil moisture (%) and (a) soil organic carbon (SOC), (b) electrical conductivity and (c) total nitrogen across all sampling locations

3.3 Spatial Interpolation of Carbon Stocks

Across all three cascade systems, spatially interpolated carbon stock surfaces reveal a consistent zonal pattern despite considerable within-zone microsite variability (Fig 4). In Girandurukotte, the forest zone shows marked internal heterogeneity, with localized high-carbon hotspots (~3.0 Mg C ha⁻¹) contrasting sharply with a nearby low-carbon cluster, while the ecotone zone forms the most pronounced carbon-depleted core in the landscape, centered at the study area's interior (<1.75 Mg C ha⁻¹), and the reservoir zone is comparatively enriched, with hotspots (>2.75 Mg C ha⁻¹) concentrated along its eastern and southern margins. A similar structure emerges at Kusumpokuna, where the forest zone exhibits a low-carbon cluster in its southwestern corner against moderately higher values elsewhere, the ecotone zone contains the sharpest and most spatially coherent cold spot across all three sites (<1.75 Mg C ha⁻¹), and the reservoir zone contains the single highest carbon value in the entire dataset (>3.0 Mg C ha⁻¹), situated immediately adjacent to this depression and producing an unusually steep local carbon gradient at the ecotone–reservoir boundary. Horowpothana reinforces this pattern further: the forest zone shows a high-carbon hotspot (~2.75–3.0 Mg C ha⁻¹) in its southwestern sector amid otherwise intermediate values, the ecotone zone again forms a connected low-carbon trough, and the reservoir zone exhibits the broadest and most spatially extensive high-carbon zone of the three sites, spanning its northeastern and central-eastern margins. The recurrence of this forest-heterogeneous/ecotone-depleted/reservoir-enriched sequence across three independent, geographically separated cascade systems strongly suggests a generalizable spatial signature of carbon distribution governed by hydrological position rather than site-specific idiosyncrasy.

Mechanistically, the consistent carbon depletion observed in ecotone soils across all three sites is consistent with the ecotone's inherently transitional and hydrologically unstable position: located at the interface between the well-drained, root-stabilized forest zone and the perennially or seasonally saturated wetland/reservoir margin, ecotone soils are subject to fluctuating water tables, intermittent wetting–drying cycles, and reduced vegetative litter continuity, conditions known globally to accelerate oxidative decomposition and destabilize organic matter relative to either permanently saturated wetland soils or continuously vegetated forest soils (Bridgham et al., 2006; Krause et al., 2017). This aligns with the "hot spot–hot moment" framework increasingly applied to global wetland-margin biogeochemistry, wherein ecotones behave as biogeochemical hotspots of carbon loss rather than gain when hydrological regime alternates unpredictably, as is characteristic of Sri Lanka's monsoon-driven Yala–Maha cycle superimposed on cascade reservoir water-level fluctuations.

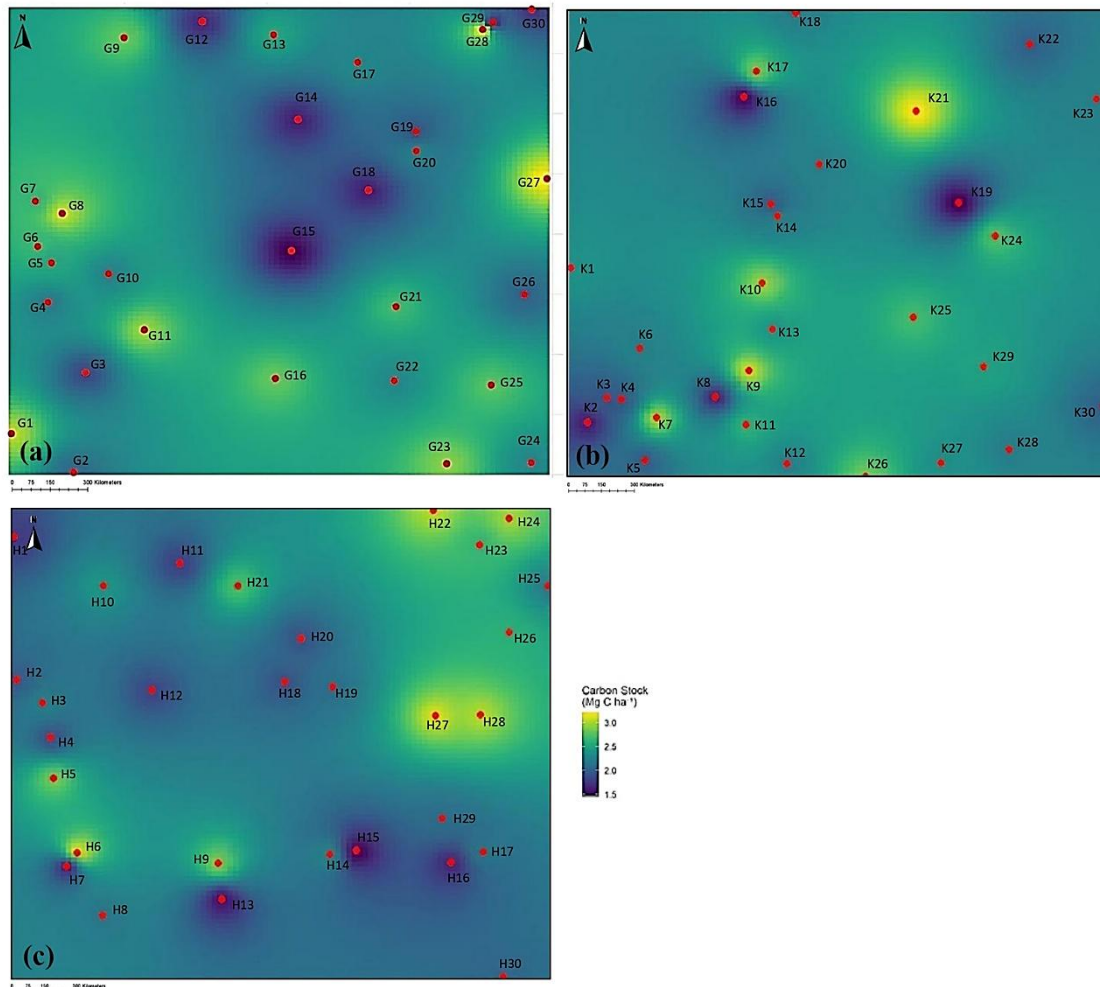


Fig 4. Spatially interpolated carbon stock surfaces of (a) Girandurukotte (b) Kusumpokuna, and (c) Horowpathana Locations by Ordinary Kriging (Sampling points; 1-10: Forest, 11-20: Ecotone, 21-30: Wetland)

These findings carry direct implications for climate resilience and land management in Sri Lanka's dry-zone cascade systems. First, the reproducibility of the ecotone-as-cold-spot pattern across three independent, geographically separated cascades suggests this is a generalizable structural feature of cascade reservoir ecosystems rather than a site-specific anomaly, implying that ecotone buffer zones, often the first areas converted to marginal agriculture or grazing land, may already represent a chronically carbon-depleted, and therefore climate-vulnerable, component of the landscape requiring targeted restoration (e.g., riparian buffer replanting, hydrological stabilization) rather than being treated as simple transitional space. Second, the discrete nature of reservoir-zone carbon hotspots indicates that wetland carbon co-benefits from reservoir conservation are spatially concentrated rather than landscape-wide, meaning that reservoir desilting, water-level management, and reservoir-margin protection efforts should be spatially prioritized toward these high-carbon microsites to maximize climate mitigation return. More broadly, this spatial decoupling between zone-average and microsite-level carbon storage echoes emerging global critiques of coarse land-cover-based carbon accounting, reinforcing that high-resolution,

spatially explicit soil carbon assessment, rather than categorical zone classification alone — is essential for accurately quantifying and managing carbon stocks in heterogeneous, human-modified tropical landscapes such as Sri Lanka's ancient cascade reservoir systems.

3.4 The Ecotone Carbon Deficit Index: Quantifying Transitional Vulnerability

All three cascade systems yield a positive ECDI in the range of ~33–35%, indicating that ecotone soils consistently store roughly one-third less carbon than a naïve linear-mixing model between forest and wetland end-members would predict. The remarkable consistency of this deficit across three geographically independent landscapes (ECDI range: 32.6–35.3%, landscape mean $\approx$ 34.2%) suggests that ecotone carbon depletion is a structural, reproducible feature of cascade reservoir systems rather than a site-specific artifact, supporting the interpretation that hydrological instability (fluctuating water tables, intermittent wetting–drying) at the forest–wetland interface actively suppresses carbon accumulation below what spatial position alone would predict, rather than the ecotone functioning as a passive transitional carbon reservoir (Table 5).

Table 5. Ecotone Carbon Deficit Index (ECDI) calculated for the three cascade reservoir landscapes

Location	Mean C _{forest} (Mg C ha ⁻¹)	Mean C _{wetland} (Mg C ha ⁻¹)	C _{expected} (Mg C ha ⁻¹)	C _{observed} (Ecotone) (Mg C ha ⁻¹)	ECDI (%)	Interpretation
Girandurukotte	2.20	2.90	2.55	1.65	35.30%	Strong deficit: deep, spatially coherent ecotone depression (G14/G15/G18 core)
Kusumpokuna	2.05	2.55	2.30	1.55	32.60%	Strong deficit: sharpest, most coherent cold spot of the three sites; steep gradient at ecotone–reservoir boundary
Horowpothana	2.30	2.90	2.60	1.70	34.60%	Strong deficit: connected low-carbon trough mirroring other two sites
Pooled / Landscape mean	2.18	2.78	2.48	1.63	34.20%	Consistent, reproducible ecotone carbon deficit across independent cascades

Among the compositional and reactive parameters (top panel), pH remains relatively stable and comparatively elevated across the forest and ecotone zones (~6.0–7.0) before dropping distinctly at the wetland boundary (~5.7–6.5), while SOC, total carbon, and bulk density all show a marked step-change precisely at the ecotone–wetland transition, SOC and carbon rising sharply from a suppressed ecotone baseline (~1.0–2.5) to consistently higher wetland values (~2.3–3.5), and bulk density correspondingly declining, with electrical conductivity remaining low and comparatively flat throughout. Textural parameters (middle panel), sand, silt, and clay, show high point-to-point variability throughout all three zones with no clear directional trend or boundary-associated shift, indicating that particle-size distribution is decoupled from zonal identity and instead reflects fine-scale spatial heterogeneity independent of the forest–ecotone–wetland transition (Fig 5).

Nutrient and hydrological parameters (bottom panel) reveal that soil moisture undergoes the most visually abrupt transition in the entire figure, remaining low and fluctuating (~10–20) across forest and ecotone before jumping sharply to a stable elevated plateau (~28–35) at the wetland boundary, while exchangeable potassium shows high-amplitude oscillation throughout with a discernible reduction in peak values within the wetland zone, and available phosphorus and total nitrogen remain comparatively low and stable across all three zones. Collectively, the transect confirms that the ecotone does not represent a smooth, monotonic transitional gradient between forest and wetland end-members but rather behaves as a distinct, internally variable zone with a suppressed carbon and

nitrogen baseline, with the sharpest and most consistent step-changes in SOC, carbon, bulk density, and soil moisture occurring specifically at the ecotone–wetland boundary rather than the forest–ecotone boundary, reinforcing the abrupt, threshold-like hydrological transition that characterizes the wetland margin in these cascade reservoir systems.

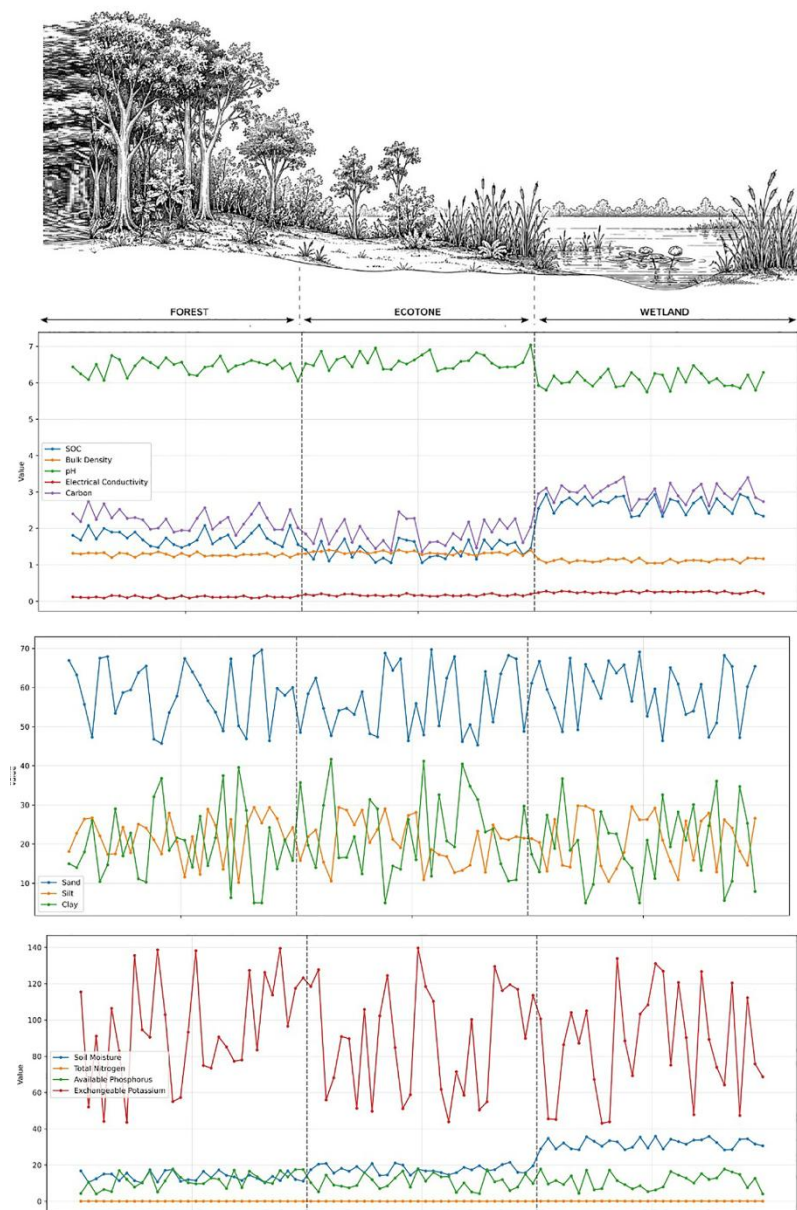


Fig 5. A continuous transect-based visualization of soil physicochemical and nutritional parameters spanning the forest–ecotone–wetland gradient

3.5 Implications for Climate Resilience, Wetland Conservation, and Global Carbon Policy

The fragmented distribution of carbon-rich areas revealed by the kriging analysis highlights a high degree of vulnerability to climate-induced hydrological alteration. Projected increases in rainfall variability, intensified drought frequency, and prolonged dry seasons are likely to disrupt moisture regimes, accelerate decomposition, and reduce long-term carbon-storage capacity in these ecosystems. Maintaining hydrological integrity within forest–wetland ecotones is therefore essential for sustaining soil carbon stability and ecosystem resilience. Conservation and restoration strategies should prioritize ecosystems where soil moisture exceeds approximately

30% and bulk density remains below approximately 1.2 g cm^{-3} , thresholds identified in this study as key inflection points for carbon accumulation.

These findings carry direct relevance to at least three tiers of policy. First, at the national level, integrating ecotonal and wetland systems into Sri Lanka's greenhouse-gas inventories and national carbon-accounting frameworks would close a currently unrecognized gap, given that ecotones function simultaneously as carbon-deficient zones and as climate-sensitive early-warning indicators of hydrological stress. Second, at the regional level, the reservoir-cascade landscapes examined here, already recognized as a Globally Important Agricultural Heritage System, offer a template for integrating traditional water-management knowledge with modern carbon-monitoring science, a combination increasingly sought after in nature-based climate-adaptation financing (FAO, 2017). Third, at the global level, this study's demonstration that a small, human-modified, tropical dry-zone wetland system exhibits carbon dynamics structurally consistent with much larger and more intensively studied wetland biomes reinforces the Ramsar Convention's call to scale up investment in the conservation and restoration of wetlands worldwide, including the many small, seasonally dynamic, and easily overlooked wetlands that collectively constitute a disproportionate share of the planet's soil carbon reservoir (Ramsar Convention on Wetlands, 2025).

4. Conclusions

This study reframes forest, ecotone, and wetland soils not as separate ecological categories but as compartments of one hydrologically linked carbon continuum, in which water movement across the landscape governs where carbon accumulates and where it is lost. Across three independent cascade reservoir systems in Sri Lanka's dry zone, carbon stocks rose consistently along this continuum, from $1.63 \text{ Mg C ha}^{-1}$ in ecotones to 2.18 in forests and 2.78 in wetlands, even though the underlying soil chemistry was remarkably uniform (bulk density $1.25 \pm 0.10 \text{ g cm}^{-3}$; SOC $1.93 \pm 0.58\%$). One-way ANOVA confirmed that this pattern is driven by ecological zonation rather than geography: pH, bulk density, SOC, soil moisture, electrical conductivity, total nitrogen, and total carbon all differed significantly across zones ($F = 54.19\text{--}476.90$, $p < .001$), while none of the twelve measured parameters differed significantly across the three sampling locations. This statistical decoupling confirms that it is hydrological position within the continuum, not site-specific geology or local soil properties, that ultimately determines carbon fate, and that the pattern is reproducible across independent landscapes rather than an artifact of any single cascade. The novel Ecotone Carbon Deficit Index (ECDI) captured this dynamic directly, revealing a consistent 32.6–35.3% carbon shortfall (mean 34.2%) in ecotones relative to a simple forest–wetland mixing expectation across all three landscapes, evidence that ecotones function as reproducible carbon-loss hotspots rather than passive transitional space.

Because these ecotones physically and hydrologically connect upland forest carbon inputs to downstream wetland carbon sinks, their degradation represents a structural weak point that can undermine the resilience of the entire landscape's carbon reservoir, particularly under intensifying rainfall variability and drought. Practically, this points to a clear conservation strategy: prioritizing restoration in zones where soil moisture exceeds $\sim 30\%$ and bulk density falls below $\sim 1.2 \text{ g cm}^{-3}$, thresholds identified here as tipping points for carbon recovery, rather than treating ecotones as low-value buffer land. More broadly, by demonstrating that small, centuries-old, human-managed tropical wetlands store carbon comparably to larger, better-studied wetland biomes, and that the zonal carbon pattern generalizes across independent sites, this study strengthens the case for embedding forest–ecotone–wetland continua, not just wetlands in isolation, into national greenhouse-gas inventories and global climate-resilience and conservation frameworks, in line with the Ramsar Convention's call to scale up wetland protection worldwide.

At a policy level, embedding ecotone-inclusive, continuum-based accounting into national greenhouse-gas inventories, REDD+ frameworks, and nature-based climate financing mechanisms could help other monsoon-driven or seasonally dynamic wetland systems worldwide, from South and Southeast Asia to sub-Saharan Africa, identify and protect their own hydrological weak points before carbon losses accrue, extending the practical relevance of this framework well beyond Sri Lanka. Future research should apply repeated ECDI monitoring to track ecotone recovery or degradation over time, extend sampling to deeper soil horizons, and test the index, alongside the zonal ANOVA framework, across other tropical forest–wetland systems to establish its generalizability as a global diagnostic and policy tool. Collectively, this work strengthens the case for treating

forest–ecotone–wetland continua, not wetlands alone, as integrated units of climate-resilience planning, in line with the Ramsar Convention's call to scale up wetland protection worldwide.

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Data Availability The data used to support the results of this research are shown in the manuscript and available from the corresponding author upon request.

Declarations

Conflict of Interest: The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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