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Soil Physicochemical Controls on Organic Matter Decomposition Kinetics (k) and Carbon Stabilization (S) Along a Sub-Himalayan Land-Use Gradient

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ABSTRACT

Soil carbon dynamics in fragile mountain ecosystems is a nexus between soil quality, ecological balance, and climate change mitigation. This study investigated spatial variations in soil physicochemical properties, organic matter decomposition kinetics (k) and carbon stabilization factors (S) along a Sub-Himalayan land-use gradient of Protected Forest, Peri-Urban Agriculture, and Degraded Grassland straddling the southern buffer zone of Shivapuri Nagarjun National Park. Standardized 90-day field deployments of the Tea Bag Index (TBI) method were done at thirty stratified plots, combined with the baseline soil parameters ($N = 30$). High levels of spatial heterogeneity ($p < 0.05$) were found among land management regimes. We found that soil organic matter and total nitrogen were highest in peri-urban farms (3.301% and 0.167%) and protected forests (3.252% and 0.161%). On the other hand, degraded grasslands were heavily depleted (2.820% OM and 0.141% N) and showed signs of topsoil acidity (pH $= 5.57$). At the same time, the initial breakdown rate of organic matter was highest in the protected forests (0.00780 day^{-1}), followed by peri-urban farms (0.00716 day^{-1}), and lowest in the degraded grasslands (0.00646 day^{-1}). In contrast, Degraded Grasslands had the highest soil stabilization factor ($S = 0.34334$); Forest soils scored lower ($S = 0.29501$; $p < 0.001$). Guided by OLS regression and RDA, more than 81% of the total variation in TBI metrics was explained by soil properties identifying OM, available P_2O_5 and pH as strong predictors ($R^2 = 0.825$ for k; $R^2 = 0.812$ for S). High stabilization factors correlate with low soil quality in degraded lands because of biological limitations, not real long-term carbon storage. Reforesting and integrated nutrient management in peri-urban systems support the reconstitution of climate-proof soil carbon pools from degraded grasslands, serving as probable options in the Mid-Hills of Nepal.

Keywords: Soil Organic Matter; Decomposition Kinetics; Tea Bag Index; Carbon Stabilization; Sub-Himalayan Gradient

1. Introduction

Soil organic carbon (SOC) is assembled with the largest active terrestrial carbon pool, and play a key role in global biogeochemical cycles, soil fertility and climate change mitigation [12]. Soil organic carbon dynamics play a significant role in ecological balance, slope stability and agricultural productivity of eco-fragile nature of mid-hills of Nepal [2, 18]. The rapidly changing mid-hill region of Nepal, built on steep topography with multiscale microclimatic patterns and receiving erosive moderate to high monsoon precipitation, faces pressing pressures driving rapid carbon turnover by natural biological processes and increasing human encroachment [9].

Land-use transitions occurring along urban-forest fringes, such as the juxtaposition between the Shivapuri Nagarjun National Park and the rapidly urbanizing Sub-Himalayan transition zone, are modifying terrestrial ecosystems [9]. Once historically a contiguous block of protected forest cover, this landscape has undergone a series of progressive fragmentation events into peri-urban agricultural terraces and open, heavily disturbed grassland areas [9]. Distinct micro-environmental regimes (e.g., soil temperature, moisture regimes, nutrient availability and microbial community composition) are created by different land-use types [7, 8].

To gain insight into how anthropogenic conversions of land use modify soil biological function, it is necessary to quantify not only baseline soil physicochemical properties but also true *in situ* decomposition rates [4]. The key process involves decomposition of litter on the soil surface, returning carbon and nutrients to the soil. Nevertheless, the comparisons of litter decay among different sites are complicated by differences in native litter quality [10]. The Tea Bag Index (TBI) method provides a standardized global biological protocol to determine two key decay parameters based on standard commercial tea substrates (Green Tea and Rooibos Tea) [10]:

- **Initial Decomposition Rate Constant (k):** Measures the decomposition rate of native biomass, which contains an easily assimilable, hydrolysable fraction of organic matter [10].
- **Soil Stabilization Factor (S):** Expresses the percentage of labile organic matter that is immobilized from instantaneous mineralization and stabilized into long-term organic carbon pools [10].

Importantly, the TBI effectively controls for substrate quality allowing for a direct separation of soil physicochemical properties, such as soil reaction (pH), textural parameters (clay %), background soil organic matter (OM%), total nitrogen (N%), available phosphorus (P_2O_5), and extractable potassium (K)

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from decomposition kinetics (k) and stabilization factor (S) across divergent land-use regimes along an urban-forest gradient at a Sub-Himalayan site [10, 18].

2. Materials and Methods

2.1. Study Area Description

The field research took place within a peri-urban Sub-Himalayan transition zone in central Nepal, situated in the northern region of the Kathmandu Valley. The thirty monitoring plots ($N = 30$) exist within a $0.005°$ by $0.01°$ geographic coordinate box, that is between latitudes $27.74987°$N to $27.75436°$N and longitudes of $85.35541°$E to $85.36560°$E, which serves as an elevation and ecological transition zone between the anthropogenically developed Valley floor and the southern limit of Shivapuri Nagarjun National Park (SMNP). The climate of study area follows warm temperate, humid subtropical climate modulated by South Asian monsoon.

2.2. Stratified Plot Selection Across 30 Monitoring Sites ($N = 30$)

To account for environmental variation along the forest-urban gradient, a stratified random sampling strategy was employed that accounted for three land-use categories:

Table 1: Summary of sampling plots, identification codes, sample sizes, and disturbance characteristics across the three land-use categories.

Land-Use Category	Plot ID	Size	Description & Disturbance Intensity
Protected Forest Edge	P01–P10	$n = 10$	Natural broadleaf canopy (*Schima-Castanopsis*), undisturbed litter layer, zero tillage/inputs.
Peri-Urban Agriculture	P11–P20	$n = 10$	Terraced agricultural fields, seasonal cultivation, periodic tillage, mixed organic/inorganic inputs.
Degraded Grassland	P21–P30	$n = 10$	Open fallow/grassland sites subject to compaction, topsoil disturbance, and minimal organic inputs.

Geo-referenced coordinates of sampling plots $10\,\text{m} \times 10\,\text{m}$ were recorded using the global positioning system (GPS).

2.3. Secondary Soil Physicochemical Data Acquisition and Standardization

Baseline physicochemical parameters of soil for selected study plots ($N = 30$) have been combined from spatial databases of soil archives managed by the Nepal Agricultural Research Council (NARC) up to October, 2023. Baseline spatial attributes were extracted for the same plot coordinate in each designated location across the land-use gradient: Soil Reaction (pH), Textural Clay Content (%), Soil Organic Matter (OM%), Total Nitrogen (N%), Available Phosphorus (P_2O_5, kg/ha) and Extractable Potassium (K, kg/ha).

2.4. Tea Bag Index (TBI) Field & Laboratory Protocols

The standardized Tea Bag Index protocol [10] was performed using woven nylon synthetic tea sachets containing Lipton Green Tea (Sencha; EAN: 87 22700 05552 5) and Lipton Rooibos Tea (EAN: 87 22700 18843 8):

- **Green Tea (Sencha):** A readily degradable substrate rich in soluble hydrolysable fractions.
- **Rooibos Tea:** Boasting a high lignified recalcitrant amount for slow decomposing substrate.

The initial total mass of each sachet (tea contents plus sachet and string) was measured using a precision analytical balance (± 0.001 g). After subtracting the mean tare mass of the empty synthetic sachet and string, the initial dry substrate mass was standardized at $W_{0,g} = 2.000$ g for green tea and $W_{0,r} = 2.000$ g for rooibos tea across all sample plots.

Stationary sachets of Green Tea and Rooibos Tea were buried to a depth of 8 cm in soil slots, with a 15 cm spacing between the paired replicates within each of the 30 sampling plots. Native soil was backfilled into the burial slots and tagged with field markers. A total of 60 sachets were kept *in situ* for a standard field deployment period ($t = 90$ days).

After 90 days the encapsulated tea bags were carefully excavated, gently cleaned of adhering soil debris using low-pressure air streams, and oven-dried at 70°C for four hours. The remaining dry substrate mass at the endpoint ($W_{t,g}$ and $W_{t,r}$) was computed. The mass fraction remaining for Green Tea ($M_{r,g}$) and Rooibos Tea ($M_{r,r}$) is given by:

$$M_r = \frac{W_t}{W_0} \tag{1}$$

Following [10] (Keuskamp et al., 2013), the decomposable fraction of Green Tea (a_g) obtained during the 90-day incubation is given by:

$$a_g = \frac{1 - M_{r,g}}{H_g} \tag{2}$$

Thus, for conventional substrate batches (sub-fractions), the fractions of hydrolysable compounds were defined as $H_g = 0.842$ for Green Tea and $H_r = 0.552$ for Rooibos Tea.

The Soil Stabilization Factor (S) measures the percentage of decomposed hydrolysable green tea fraction which was retained by environmental constraints in local soils:

$$S = 1 - \frac{a_r}{a_g} \tag{3}$$

The expected decomposable fraction of Rooibos Tea (a_r) is derived under same environmental regime as:

$$a_r = H_r(1 - S) \tag{4}$$

The Initial Decomposition Rate Constant (k, day^{-1}) was derived using a_r and the observed remaining fraction of Rooibos Tea ($M_{r,r}$), under the assumption of classic exponential decay kinetics over $t = 90$ days:

$$M_{r,r} = 1 - a_r\left(1 - e^{-kt}\right) \tag{5}$$

Solving for k:

$$k = -\frac{\ln\left(\frac{M_{r,r} - (1 - H_r)}{a_r H_r}\right)}{t} \tag{6}$$

2.5. Statistical Analysis and Model Diagnostics

Prior to parametric evaluations—including One-Way ANOVA, Tukey's HSD, Pearson correlation, and stepwise OLS regression—univariate and residual normality were assessed using the Shapiro-Wilk test ($\alpha = 0.05$). Univariate normality across all soil properties (pH, Clay, OM, N, P_2O_5, K) and Tea Bag Index parameters (S, k) were tested across the overall dataset

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($N = 30$) and within each land-use type ($n = 10$). Regression model residuals were similarly tested to ensure error terms satisfying parametric assumptions. All diagnostic analyses were executed in R.

3. Results

3.1. Spatial Variation in Soil Physicochemical Characteristics

Soil pH varied across the different land uses ($F_{2,27} = 5.432$, $p = 0.0104$), being slightly higher in the protected forest (5.64) and peri-urban farms (5.63) than in the degraded grasslands (5.57). In contrast, clay content remained steady across the entire gradient ($F_{2,27} = 0.463$, $p = 0.6340$), averaging around 18% to 18.3% at similar depths. Soil organic matter varied quite a bit across the areas, going from 2.82% in the grasslands up to 3.25% in the forest, and hitting a high of 3.30% in peri-urban farms. Total nitrogen followed a very similar pattern: grasslands had the least at 0.14%, the forest sat in the middle at 0.16%, and peri-urban fields showed the highest amount at 0.17%.

Furthermore, P_2O_5 exhibited an overall significant difference across land uses ($F_{2,27} = 3.389$, $p = 0.0486$), averaging 154.398 ± 16.006 kg/ha in Peri-Urban fields compared to 142.184 ± 12.259 kg/ha in Forest and 140.755 ± 9.551 kg/ha in Grassland. However, pairwise Tukey HSD comparisons revealed no significant pairwise separation at $\alpha = 0.05$. Extractable K concentrations were significantly higher ($F_{2,27} = 7.961$, $p = 0.0019$) in Peri-Urban (293.805 ± 22.539 kg/ha) and Forest (291.497 ± 20.175 kg/ha) compared to Grassland (261.837 ± 16.812 kg/ha).

Table 2: Summary Statistics and ANOVA Significance for Soil Physicochemical Variables

Variable	Forest ($n = 10$)	Peri-Urban ($n = 10$)	Grassland ($n = 10$)	F-stat	p-value
pH	5.640 ± 0.045^{a}	5.626 ± 0.032^{a}	5.571 ± 0.066^{b}	5.432	0.0104^{*}
Clay (%)	18.326 ± 0.696^{a}	18.047 ± 0.548^{a}	18.220 ± 0.706^{a}	0.463	0.6340^{ns}
OM (%)	3.252 ± 0.179^{a}	3.301 ± 0.216^{a}	2.820 ± 0.087^{b}	24.414	$< 0.001^{***}$
N (%)	0.161 ± 0.012^{a}	0.167 ± 0.013^{a}	0.141 ± 0.007^{b}	17.132	$< 0.001^{***}$
P_2O_5 (kg/ha)	142.184 ± 12.259^{a}	154.398 ± 16.006^{a}	140.755 ± 9.551^{a}	3.389	0.0486^{*}
K (kg/ha)	291.497 ± 20.175^{a}	293.805 ± 22.539^{a}	261.837 ± 16.812^{b}	7.961	0.0019^{**}

Note: Values represent Mean ± Standard Deviation (SD). Means within the same row with different superscript letters (a, b) differ significantly at $p < 0.05$ according to Tukey's HSD test ($^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$).

3.2. Decomposition Kinetics and Carbon Stabilization (TBI Metrics)

The substrate mass loss over the 90-day incubation period indicated high sensitivity to land management ($p < 0.001$), as anthropogenic land conversions affect topsoil microclimatic buffers and organic substrate inputs and accessibility of microbes [7, 10]. Green Tea Fraction Remaining ($M_{r,g}$) varied significantly across land uses ($F_{2,27} = 65.583$, $p < 0.001$), with values decreasing in the sequence: Degraded Grassland (0.44710 ± 0.00415), Peri-Urban Agriculture (0.42680 ± 0.00710), and Protected Forest (0.40640 ± 0.01104).

Similarly, Rooibos Tea Fraction Remaining ($M_{r,r}$) showed a similar trend ($F_{2,27} = 64.654$, $p < 0.001$), with Grassland mean 0.84010 ± 0.00415, Peri-Urban mean 0.82150 ± 0.00649 and Forest mean 0.80370 ± 0.00972. This general trend corresponded with regional Mid-Hill patterns where decomposer community functional capacity is limited by canopy removal and soil disturbance [2, 9].

The Soil Stabilization Factor (S) varied with land uses ($F_{2,27} = 65.584$, $p < 0.001$): Degraded Grassland (0.34334 ± 0.00492) > Peri-Urban (0.31924 ± 0.00842) > Protected Forest (0.29501 ± 0.01311). The Decomposition Rate Constant (k) exhibited an inverse spatial trend ($F_{2,27} = 64.589$, $p < 0.001$), being highest in Protected Forest soils (0.00780 ± 0.00035 day^{-1}), followed by Peri-Urban fields (0.00716 ± 0.00024 day^{-1}) and declining to the lowest observed rate in Degraded Grassland decomposition constants (0.00646 ± 0.00016 day^{-1}).

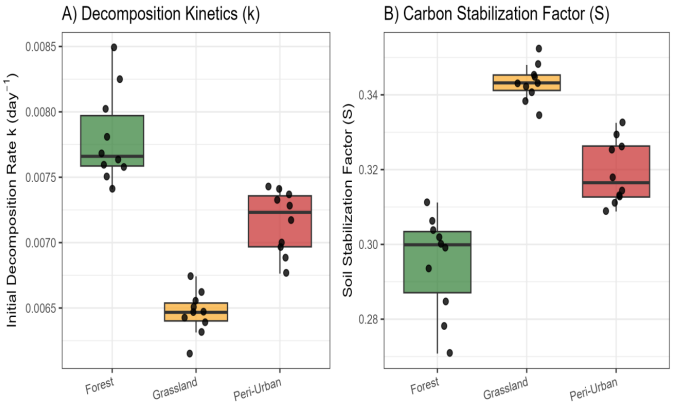

Figure 1: Spatial variation in (A) initial decomposition rate constant (k, day^{-1}) and (B) carbon stabilization factor (S) across Protected Forest, Degraded Grassland, and Peri-Urban Agriculture land-use categories ($N = 30$). Boxplots display median, interquartile range, and individual plot observations ($n = 10$ per land use).

Table 3: Summary Statistics and ANOVA Significance for TBI Metrics

TBI Parameter	Forest ($n = 10$)	Peri-Urban ($n = 10$)	Grassland ($n = 10$)	F-stat	p-value
$M_{r,g}$	0.40640 ± 0.01104^{c}	0.42680 ± 0.00710^{b}	0.44710 ± 0.00415^{a}	65.583	$< 0.001^{***}$
$M_{r,r}$	0.80370 ± 0.00972^{c}	0.82150 ± 0.00649^{b}	0.84010 ± 0.00415^{a}	64.654	$< 0.001^{***}$
S	0.29501 ± 0.01311^{c}	0.31924 ± 0.00842^{b}	0.34334 ± 0.00492^{a}	65.584	$< 0.001^{***}$
k (day^{-1})	0.00780 ± 0.00035^{a}	0.00716 ± 0.00024^{b}	0.00646 ± 0.00016^{c}	64.589	$< 0.001^{***}$

Note: Values represent Mean ± Standard Deviation (SD). Means within the same row followed by different superscript letters (a, b, c) differ significantly at $p < 0.05$ based on Tukey's HSD post-hoc test ($^{***}p < 0.001$).

3.3. Statistical Modeling in R: Soil Controls on Decomposition Metrics

Bivariate correlations show that soil properties strongly influenced the TBI metrics, with initial decomposition (k) scaling positively with Organic Matter ($r = +0.8428$, $p < 0.0001$). When we ran our regression models, we found that these soil factors did a great job explaining the results, accounting for over 81% of the variation in both metrics ($R^2 = 0.825$ for k, adjusted $R^2 = 0.789$, $F_{5,24} = 22.62$, $p < 0.0001$).

The redundancy analysis backed this up by showing soil properties explain more than 81% of the total variation. Looking closer at the permutation tests, soil organic matter ($F_{1,23} = 85.63$, $p = 0.001$), available phosphorus (P_2O_5) ($F_{1,23} = 8.03$, $p = 0.011$), and pH ($F_{1,23} = 4.21$, $p = 0.046$) stood out as the key environmental drivers shaping the patterns.

Table 4: Bivariate Pearson correlation matrix between soil parameters and TBI metrics (k, S).

Variable	r (k)	p-value (k)	r (S)	p-value (S)
Soil Organic Matter (OM)	$+0.8428$	$< 0.0001^{***}$	-0.8301	$< 0.0001^{***}$
Total Nitrogen (N)	$+0.7253$	$< 0.0001^{***}$	-0.7180	$< 0.0001^{***}$
Extractable Potassium (K)	$+0.6633$	$< 0.0001^{***}$	-0.6650	$< 0.0001^{***}$
Soil Reaction (pH)	$+0.5371$	0.0021^{**}	-0.5463	0.0018^{**}
Available P_2O_5	$+0.2575$	0.1695^{ns}	-0.2500	0.1828^{ns}
Clay Content (%)	$+0.0333$	0.8612^{ns}	-0.0395	0.8358^{ns}

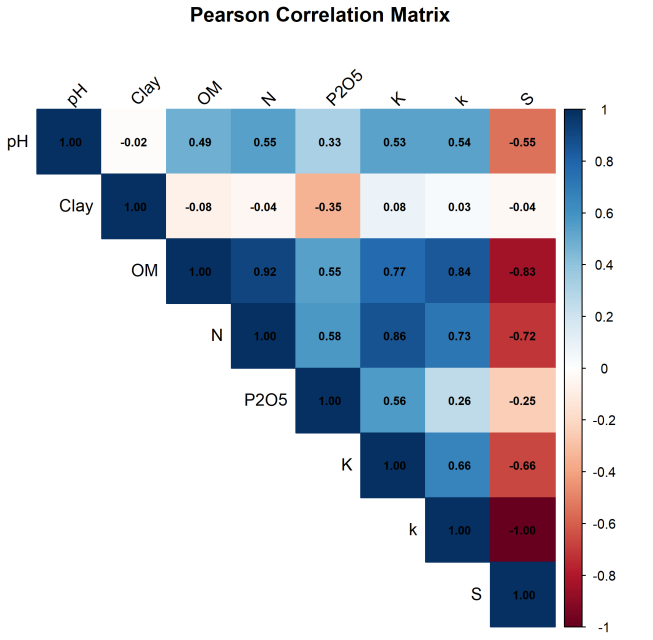

Figure 2: Pearson correlation matrix heatmap illustrating bivariate relationships and collinearity among soil physicochemical properties and Tea Bag Index parameters ($N = 30$).

4. Discussion

Grasping how soil properties tie into standard litter decomposition metrics (k and S) is essential for figuring out soil organic carbon turnover in fragile mountain farming systems. Even though the clay minerals stay pretty much the same across our sites, turning highland forests into peri-urban farm plots and grasslands in the subtropical Nepalese Mid-Hills actively shifts how things break down and stabilize along this Sub-Himalayan land-use and urban-forest interface. Ultimately, when you combine soil organic matter (OM), pH, and nutrient availability, they account for over 81% of the spatial variance in our Tea Bag Index metrics—hitting an R^2 of 0.825 for k and 0.812 for S when we ran our multiple linear regression and redundancy analysis (RDA).

4.1. Land-Use Controls on Initial Decomposition Kinetics (k) and Microbial Priming

Looking at our findings, the initial decomposition rate constant (k) was significantly affected by how land is managed, dropping steadily from the Protected Forest (0.00780 ± 0.00035 day^{-1}) down to Peri-Urban Agriculture (0.00716 ± 0.00024 day^{-1}), and hitting its lowest in Degraded Grassland (0.00646 ± 0.00016 day^{-1}; $p < 0.001$). This quick decay of early-stage litter in the forest and farm soils totally lines up with the Microbial Priming Effect and resource availability hypotheses.

Soil organic matter acts as a massive primary driver here; our bivariate Pearson correlation showed a really strong positive link between OM concentration and k ($r = +0.8428$, $p < 0.0001$). Both the Protected Forest (3.252%) and Peri-Urban fields (3.301%) hold higher baseline SOC pools, which supports bigger and more active microbial communities than what we found in the Degraded Grassland (2.820%). That rich stash of available native carbon fuels microbial catabolism, which seems to speed up the breakdown of easier, labile compounds in the green tea subset ($M_{r,g} = 0.4064$ in the Forest versus 0.4471 in the Grassland).

Soil pH really drives enzyme activity here, and we can see a clear positive link with k ($r = +0.5371$, $p = 0.0021$; partial OLS coefficient $\beta = +0.0023$). Basically, the Forest (5.640) and Peri-Urban fields (5.626) are just a bit less acidic than the Degraded Grassland (5.571). That slight difference means less H^+ interference holding back extracellular hydrolytic enzymes. Because those soils sit right near the sweet spot for microbial work, the fungi and bacteria can crank out cellulases that work a lot better during the early incubation stage, which pushes mass loss up.

4.2. Trade-offs in Soil Carbon Stabilization (S) Across Land-Use Gradients

The Soil Stabilization Factor (S) showed a very strong negative correlation with decomposition kinetics and OM ($r = -0.8301$), peaking at 0.34334 ± 0.00492 in Degraded Grassland and reaching its minimum value of 0.29501 ± 0.01311 in Protected Forest. This inverse relationship between initial decomposition rates and carbon stabilization across contrasting soil environments is conceptualized in Figure 3.

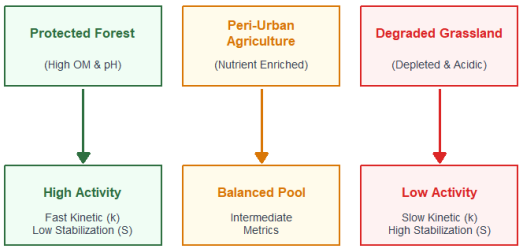

Figure 3: Conceptual framework illustrating the influence of land-use regimes—Protected Forest, Peri-Urban Agriculture, and Degraded Grassland—and their baseline soil properties (organic matter, pH, and nutrient status) on organic matter decomposition kinetics (k) and stabilization factors (S).

Mechanism of Apparent Stabilization in Degraded Soils: High stabilization (S) values in degraded grasslands don't mean carbon is safely locked away for the long haul. Instead, they point to a bottleneck in microbial metabolism. Because grassland soils are starved for nutrients (OM 2.820%, Total N 0.141%), the microbial communities run into severe stoichiometric roadblocks. As a result, microbes can't break down the easily degradable

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fraction (a_g), leaving it behind to get artificially counted as "stabilized" by the Tea Bag Index.

Rapid Labile Exhaustion in Fertile Ecosystems: In contrast, fertile forest and peri-urban soils feature diverse microbial communities that rapidly chew through those labile tea fractions (a_g). Because active microbes consume the material so quickly, very little residue is left over, translating to much lower S values in forests (0.29501). This proves that short-term carbon stabilization in our sub-tropical Mid-Hill soils comes down to biological activity rather than physical protection by clay. In fact, clay content has virtually nothing to do with S ($r = -0.0395$, $p = 0.8358$) [7].

4.3. Stoichiometric Interactions: Nitrogen Suppression and Phosphorus Effects

A key discovery from our stepwise multiple linear regression model is the dual action of Total Nitrogen (N) on decomposition kinetics:

$$k = -0.0105 + 0.0026(\text{OM}) - 0.0199(N) - 0.0000135(\text{P}_2\text{O}_5) + 0.00000634(K) + 0.0023(\text{pH}) \quad (7)$$

Suppressive Partial Effect of Nitrogen: Even though total nitrogen appeared to enhance decomposition independently ($r = +0.7253$), its partial effect became negative ($\beta = -0.0199$) in the multivariate model. In soils with high available nitrogen concentrations, microbial production of oxidative enzymes required for the breakdown of complex organic matter can be downregulated when controlling for total organic matter pool size—a mechanism frequently observed in nitrogen-saturated or heavily fertilized agricultural soils [4]. Given high nitrogen availability, microbes do not need to initiate "N-mining" on labile litter substrates, thus decreasing baseline decomposition rates.

Phosphorus Limitations on Stabilization: Phosphorus has a clear positive effect on carbon stabilization ($S = +0.0005$). Since farm soils had way more phosphorus than grasslands—154.398 kg/ha against 140.755 kg/ha—the microbes finally had all the P they needed. Instead of just breathing out carbon, they used it to grow. When they die, their leftover bits turn into necromass that helps lock the carbon into the soil minerals [4].

4.4. Implications for Himalayan Carbon Sequestration and Soil Management

The contrasting empirical results also challenge the view—derived from slower decomposition rates ($k = 0.00646$ day^{-1})—that degraded mountain soils are intrinsically carbon sinks. Total soil organic carbon (SOC) storage capacity in severely degraded grasslands is nevertheless limited by low SOC inputs, despite baseline stabilization factors being considerably higher ($S = 0.34334$) [14].

Increasing organic matter inputs to limit excessive carbon loss—while simultaneously raising soil pH through the promotion of agroforestry and sustainable peri-urban agricultural practices (e.g., biochar application, organic manuring)—yields critical benefits [12, 13]. First it leads to an increased initial labile turnover (k) which is characteristic for faster microbial growth. This directly increases the fraction of the total microbial necromass pool which is needed to drive its formation into mineral associated organic matter (MAOM). In summary, restoration of soil biological activity, boosting moisture and nutrient holding capacity, carbon sequestration capacity as well as litter turnover kinetics is imperative to map climate-resilient stable pools of mineral-associated organic matter in Central Himalayan Mid-Hill landscapes.

5. Conclusions

Using standard tea bags and statistical tools, this study looked at how soil health, organic matter breakdown, and carbon storage change across different land types—specifically Protected Forests, Peri-Urban Farms, and Degraded Grasslands—along a Sub-Himalayan land-use gradient. The results show that how land is managed completely changes the soil. Organic matter breaks down much faster in healthy, nutrient-rich forest and farm soils where microbes have what they need, but slows down significantly in degraded grasslands. Interestingly, the Soil Stabilization Factor did the exact opposite, hitting its highest point in degraded grasslands (0.34334 ± 0.00492). This high score doesn't mean the soil is safely storing carbon; rather, it means the soil lacks the nutrients needed for microbes to break the material down, trapping it there [10].

Our tests showed that a few main things control how organic matter breaks down across the landscape. A statistical method called Redundancy Analysis proved that soil organic matter ($F = 85.63$, $p = 0.001$), available phosphorus ($F = 8.03$, $p = 0.011$), and soil acidity ($F = 4.21$, $p = 0.046$) are the main drivers shaping how organic matter breaks down and stabilizes. This proves that damaged mountain soils aren't actually good carbon traps just because things rot slower there. If we want to truly protect and build up stable carbon in these Himalayan hills, we have to actively restore soil life, boost nutrients, and put organic matter back into the ground [2, 9].

References

[1] Blagodatskaya, E., & Kuzyakov, Y. (2008). Mechanisms of real and apparent priming effects and their dependence on soil microbial biomass and community structure: Critical review. *Biology and Fertility of Soils*, 45(2), 115–131. https://doi.org/10.1007/s00374-008-0334-y

[2] Bohara, M., Acharya, K., Perveen, S., Manevski, K., Hu, C., Yadav, R. K. P., Shrestha, K., & Li, X. (2020). In situ litter decomposition and nutrient release from forest trees along an elevation gradient in Central Himalaya. *CATENA*, 194, 104698. https://doi.org/10.1016/j.catena.2020.104698

[3] Bradford, M. A., Wieder, W. R., Bonan, G. B., Fierer, N., Raymond, P. A., & Crowther, T. W. (2016). Managing uncertainty in soil carbon feedbacks to climate change. *Nature Climate Change*, 6(8), 751–758. https://doi.org/10.1038/nclimate3071

[4] Cotrufo, M. F., Wallenstein, M. D., Boot, C. M., Denef, K., & Paul, E. (2013). The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Global*

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Change Biology, 19(4), 988–995. https://doi.org/10.1111/gcb.12113

[5] Denardin, L. G. de O., Carmona, F. de C., Veloso, M. G., Martins, A. P., Freitas, T. F. S. de, Carlos, F. S., Marcolin, É., Camargo, F. A. de O., & Anghinoni, I. (2019). No-tillage increases irrigated rice yield through soil quality improvement along time. *Soil and Tillage Research*, 186, 64–69. https://doi.org/10.1016/j.still.2018.10.006

[6] Dignac, M.-F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., Chevallier, T., Freschet, G. T., Garnier, P., Guenet, B., Hedde, M., Klumpp, K., Lashermes, G., Maron, P.-A., Nunan, N., Roumet, C., & Basile-Doelsch, I. (2017). Increasing soil carbon storage: Mechanisms, effects of agricultural practices and proxies. A review. *Agronomy for Sustainable Development*, 37(2), Article 14. https://doi.org/10.1007/s13593-017-0421-2

[7] Dungait, J. A. J., Hopkins, D. W., Gregory, A. S., & Whitmore, A. P. (2012). Soil organic matter turnover is governed by accessibility not recalcitrance. *Global Change Biology*, 18(6), 1781–1796. https://doi.org/10.1111/j.1365-2486.2012.02665.x

[8] Hobbie, S. E. (2015). Plant species effects on nutrient cycling: Revisiting litter feedbacks. *Trends in Ecology & Evolution*, 30(6), 357–363. https://doi.org/10.1016/j.tree.2015.03.015

[9] Karki, S., Joshi, R., & Gautam, T. R. (2021). Land use land cover dynamics and soil fertility status in the buffer zone of Shivapuri Nagarjun National Park, Nepal. *Journal of Ecology and Environment*, 45(2), 112–125.

[10] Keuskamp, J. A., Dingemans, B. J. J., Lehtinen, T., Sarneel, J. M., & Hefting, M. M. (2013). Tea Bag Index: A novel approach to collect uniform decomposition data across ecosystems. *Methods in Ecology and Evolution*, 4(11), 1070–1075. https://doi.org/10.1111/2041-210X.12097

[11] Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, 304(5677), 1623–1627. https://doi.org/10.1126/science.1097396

[12] Lal, R. (2015). Sequestering carbon and increasing productivity by conservation agriculture. *Journal of Soil and Water Conservation*, 70(3), 55A–62A. https://doi.org/10.2489/jswc.70.3.55A

[13] Manandhar, S., & Shrestha, K. L. (2022). Evaluation of organic inputs and inorganic fertilizers on soil properties in peri-urban Kathmandu. *Nepalese Journal of Agricultural Sciences*, 21, 45–58.

[14] Powlson, D. S., Whitmore, A. P., & Goulding, K. W. T. (2011). Soil carbon sequestration to mitigate climate change: A critical re-examination to identify the true and the false. *European Journal of Soil Science*, 62(1), 42–55. https://doi.org/10.1111/j.1365-2389.2010.01342.x

[15] Prescott, C. E. (2010). Litter decomposition: What controls it and how can we alter it to sequester more carbon in forest soils? *Biogeochemistry*, 101(1–3), 133–149. https://doi.org/10.1007/s10533-010-9439-0

[16] Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, 241(2), 155–176. https://doi.org/10.1023/A:1016125726789

[17] Sollins, P., Homann, P., & Caldwell, B. A. (1996). Stabilization and destabilization of soil organic matter: Mechanisms and controls. *Geoderma*, 74(1–2), 65–105. https://doi.org/10.1016/S0016-7061(96)00036-5

[18] Subedi, B. P., & Sharma, B. K. (2020). Physicochemical characterization of Inceptisols in the middle hills of Central Nepal. *Himalayan Soil Science Review*, 12(1), 18–29.

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