

Bridging the Scale Gap in Dryland Carbon Accounting: A Multi-Scalar Hybrid Methodology and the Composite Ecosystem Stability Index (CESI) for the Sudan Savanna

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Abstract

*Accurate carbon accounting in data-sparse dryland ecosystems is hampered by methodological silos: field studies are too localized, remote sensing lacks ground validation, and spatial models often rely on uncalibrated global defaults. This study presents a novel multi-scalar hybrid methodology that integrates field biophysics, multi-temporal remote sensing, and the InVEST ecosystem service model to assess carbon dynamics in the Sudan Savanna of Kebbi State, Nigeria. A two-phase design was employed: Phase 1 established a high-resolution biophysical baseline across 160 stratified field plots in four institutional landscapes; Phase 2 upscaled these findings using Landsat and Sentinel-2 imagery and a field-calibrated InVEST model. To synthesize the ecological health of the landscape, we developed a novel Composite Ecosystem Stability Index (CESI), integrating species richness, Shannon diversity, Pielou's evenness, and Total Carbon Stock. The field data revealed a mean carbon stock of 38.76 tC/ha, with significant variation across land-use types (Green Areas: 60.36 tC/ha; Bareland: 19.54 tC/ha). A critical methodological challenge was identified: field-measured soil organic carbon (SOC) (1.9–5.87 tC/ha to 30 cm) was an order of magnitude lower than IPCC Tier 2 values used for landscape modeling (25–95 tC/ha to 100 cm), highlighting the limitations of using global defaults and shallow sampling depths. The CESI proved to be a robust diagnostic tool, revealing that carbon-rich monocultures (dominated by *Azadirachta indica*) can exhibit lower ecological stability than more diverse, mixed-use systems. This integrated framework provides a replicable, field-validated protocol for sub-national carbon accounting in drylands, offering a critical bridge between localized field ecology and macro-scale policy modeling.*

Keywords: Multi-scalar methodology; Field biophysics; Remote sensing; Composite Ecosystem Stability Index (CESI)

Introduction

The quantification of terrestrial carbon stocks is a cornerstone of global climate mitigation efforts (IPCC, 2019). However, a persistent challenge in carbon accounting is the "scale gap" between the localized, high-precision measurements obtained from field inventories and the broad, spatially continuous estimates derived from remote sensing and ecosystem models

(Avitabile *et al.*, 2016). This gap is particularly acute in dryland ecosystems, such as the Sudan Savanna of West Africa, which are characterized by high spatial heterogeneity, open-canopy vegetation, and a significant proportion of carbon stored belowground (Jobbagy & Jackson, 2000). In these environments, the uncritical application of global or pan-tropical models can lead to substantial errors in carbon stock estimation (Chave *et al.*, 2014; Mugasha *et al.*, 2013).

Current methodologies in the region are often siloed. Field-based ecological studies provide detailed, species-specific data but are limited to spatial extent and are often not extrapolated to the landscape level (Ogunleye *et al.*, 2021). Conversely, remote sensing studies provide wall-to-wall coverage but often lack rigorous ground-truthing, relying on generic allometric equations and global carbon density defaults that may not reflect local conditions (Olorunfemi *et al.*, 2020). Ecosystem service models like InVEST offer a powerful platform for translating land-cover maps into carbon metrics, but their outputs are only as reliable as the biophysical parameters used to calibrate them (Sharp *et al.*, 2020; Tallis & Polasky, 2009). This methodological fragmentation creates significant uncertainty in carbon inventories, hindering the development of evidence-based climate policies and limiting access to carbon finance mechanisms like REDD+ (Federal Republic of Nigeria, 2021).

A critical, yet often overlooked, aspect of carbon accounting is the need for integrated metrics that capture not just the quantity of carbon stored, but also the ecological stability of the system storing it. A landscape dominated by a single, fast-growing exotic species may store a large amount of carbon in the short term, but it may be highly vulnerable to pests, diseases, or climate shocks, making its long-term carbon storage potential precarious (Brockerhoff *et al.*, 2018). Conversely, a more diverse ecosystem may store less carbon per hectare but be more resilient. Existing carbon assessments rarely account for this dimension of stability. Composite indices, which aggregate multiple ecological indicators into a single score, offer a potential solution (Jain & Mohapatra, 2023). However, their application to West African savanna ecosystems has been limited.

To address these methodological gaps, this study presents a comprehensive, two-phase hybrid methodology. Our objectives are: (1) to establish a high-resolution, field-based biophysical and floristic baseline for carbon stocks in institutional landscapes of Kebbi State; (2) to integrate these field data with multi-temporal remote sensing and the InVEST model to upscale carbon stock estimation to the state level; and (3) to develop and apply a novel Composite Ecosystem Stability Index (CESI) to evaluate the ecological integrity of different land-use types. We also critically examine the methodological challenges of applying global defaults to local dryland ecosystems, specifically highlighting the discrepancy between field-measured and modeled soil organic carbon.

Methods

Study Area and Field Sampling

The study was conducted in Kebbi State, North-Western Nigeria. Four tertiary institutions (AFUSTA Aliero, Adamu Augie College of Education Argungu, FUBK Birnin Kebbi, and Kebbi State Polytechnic Dakingari) were selected as field sites, representing a microcosm of land-use types. A two-phase stratified random sampling design was used, with 160 plots (40 per site) across four LULC classes (Green Area, Built-up Area, Farmland, Bareland/Fallow).

Phase 1: Field Biophysical Inventory

All trees with DBH ≥ 5 cm were identified and measured (DBH and height). Floristic metrics (Shannon-Wiener H' , Pielou's Evenness J , Importance Value Index IVI) were calculated. Carbon stocks were estimated for four pools: AGB (using the Chave *et al.*, 2014 allometric equation with species-specific wood density), BGB (using a root-to-shoot ratio of 0.47), LB (gravimetric analysis), and SOC (Walkley-Black method, 0-30 cm depth).

Phase 2: Remote Sensing and InVEST Modeling

Multi-temporal Landsat (2005, 2015) and Sentinel-2 (2025) imagery were classified using Maximum Likelihood Classification. The InVEST Carbon Storage model (v3.9.0) was parameterized using IPCC Tier 2 carbon density values for tropical drylands (IPCC, 2019). The model was run using the 2005, 2015, and 2025 LULC maps. The field data from Phase 1 were used as independent validation benchmarks, not as direct inputs to the InVEST model, to assess the model's performance.

Composite Ecosystem Stability Index (CESI)

The CESI was developed to integrate four key indicators of ecosystem health: species richness (S), Shannon diversity (H'), Pielou's evenness (J), and Total Carbon Stock (TCS). Each indicator was normalized to a 0-1 scale using min-max normalization. The CESI was calculated as the weighted sum of the normalized indicators:

$$CESI = W_1(S_{norm}) + W_2(H'_{norm}) + W_3(J_{norm}) + W_4(TCS_{norm})$$

Equal weights (0.25) were assigned to each indicator to ensure a balanced assessment. The CESI values were then used to rank LULC types and study sites on a scale from "Very Low" to "Very High" stability.

Methodological Comparison: Field SOC vs. IPCC Tier 2 SOC

A direct comparison was made between the field-measured SOC stocks (to 30 cm depth) and the IPCC Tier 2 SOC values used in the InVEST model (representing 100 cm depth). The discrepancy was analyzed in terms of three factors: (1) sampling depth difference, (2) representativeness of institutional campus soils versus the broader landscape, and (3) the known analytical under-recovery of the Walkley-Black method compared to dry combustion (Nelson & Sommers, 1996).

Results

Table 1: Summary of Total Carbon Stock (TCS) and CO₂-eq by LULC Type Across the Four Study Sites (Mean Values).

LULC Type	Mean (tC/ha)	TCS	Mean (tCO ₂ /ha)	CO ₂ -eq	Mean (tC/ha)	SOC	Mean (tC/ha)	AGC
Bareland/Fallow	19.54		71.71		2.18–2.62		13.62	
Built-up Area	38.28		140.49		3.56–4.35		24.63–37.33	
Farmland	36.85		135.24		3.42–4.12		24.63–27.31	
Green Area	60.36		221.52		4.61–5.87		35.98–55.66	

Source: Field work 2025

Table 1 summarizes the field-based carbon stocks, providing the ground-truth data for the

landscape-level modeling. The hierarchy of carbon storage is clear: Green Area > Built-up Area > Farmland > Bareland/Fallow. This confirms that land use and management are dominant drivers of carbon storage. The field-measured AGB values (from 13.62 tC/ha in Bareland to 55.66 tC/ha in Green Areas) are realistic for the Sudan Savanna and fall within the range reported in other regional studies (Dayamba *et al.*, 2016; Nacoulma *et al.*, 2018). However, the field-measured SOC values (2.18–5.87 tC/ha) are strikingly low. This is a critical finding that we address in the methodological comparison. The table also reveals that Green Areas, despite being dominated by exotic species, store over three times more carbon than degraded Barelands. This highlights the significant sequestration potential of managed institutional landscapes.

Table 2: Composite Ecosystem Stability Index (CESI) Across LULC Types and Study Sites.

	Species Richness (S)	Shannon (H')	Pielou (J)	TCS (tC/ha)	CESI	Stability Class
LULC Type						
Bareland/Fallow	8	1.52	0.73	19.54	0.000	Very Low
Built-up Area	9	1.68	0.76	38.28	0.379	Low
Farmland	10	1.72	0.75	36.85	0.429	Moderate
Green Area	12	1.89	0.76	60.36	0.844	Very High
Study Site						
SS1	14	1.84	0.70	32.28	0.217	Low
SS2	12	1.52	0.61	35.49	0.057	Very Low
SS3	15	1.99	0.73	40.76	0.657	High
SS4	18	2.12	0.74	46.51	1.000	Very High

Source: Field work 2025

Table 2 presents the CESI, a novel composite index that integrates diversity and carbon storage. The results reveal a clear gradient of ecosystem stability across LULC types, from Very Low in Bareland/Fallow (CESI = 0.000) to Very High in Green Areas (CESI = 0.844). This aligns with ecological theory (the diversity-stability hypothesis) and supports the use of CESI as a diagnostic tool. The site-level analysis reveals a more nuanced story. SS4, with the highest species richness (S=18) and Shannon diversity (H'=2.12), has the highest CESI (1.000). In contrast, SS2, despite having moderate carbon stocks (35.49 tC/ha), has a Very Low CESI (0.057) due to its low diversity (H'=1.52) and low evenness (J=0.61). This finding is critical: it demonstrates that high carbon stocks do not automatically equate to high ecological stability. SS2's carbon is likely stored in a few dominant species (probably *A. indica*), making it vulnerable to disturbance. The CESI thus provides a more holistic measure of ecosystem health than carbon stock alone.

Table 3: Comparison of Field-Measured SOC and IPCC Tier 2 SOC Values.

Parameter	Field Measurement (Phase 1)	InVEST Model Input (IPCC Tier 2)	Key Difference
SOC Stock (tC/ha)	1.9 – 5.87	25 – 95	Order of magnitude higher in model
Sampling Depth	0 – 30 cm	0 – 100 cm	Model includes deeper, older SOC
Analytical Method	Walkley-Black oxidation)	(wet Dry combustion (assumed)	WB under-recovers stable C

Spatial Coverage	Institutional campuses	Landscape-wide	Field data may not be representative
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Source: Field work 2025

Table 3 is a critical methodological comparison that exposes a major challenge in dryland carbon accounting. The field-measured SOC (1.9–5.87 tC/ha) is an order of magnitude lower than the IPCC Tier 2 values (25–95 tC/ha) used to parameterize the InVEST model. This is not an error; it is a result of three methodological factors. First, the field data only sample the top 30 cm of soil, while the Tier 2 values represent the top 100 cm, where a significant portion of soil carbon is stored. Second, the Walkley-Black method used in the field is known to under-recover stable, recalcitrant carbon fractions compared to dry combustion. Third, the field data are from institutional campuses, which may have different soil properties (e.g., sandier, more eroded) than the broader landscape. This table highlights the critical need for caution when comparing field data with model outputs and underscores the importance of standardizing methods and reporting depths. The large discrepancy does not invalidate the InVEST model; rather, it highlights the need for local calibration and for using field data as a validation tool, not as a direct substitute for Tier 2 values in landscape-level models.

Discussion

This study successfully developed and applied a multi-scalar hybrid methodology that bridges the gap between localized field ecology and macro-scale carbon modeling. The integration of field data, remote sensing, and the InVEST model provides a robust framework that overcomes the limitations of any single approach. Our findings also highlight critical methodological challenges and offer a new tool, the CESI, for assessing ecosystem stability.

The field-based biophysical baseline (Phase 1) revealed carbon stocks (mean TCS = 38.76 tC/ha) that are consistent with other studies in West African savannas (Dayamba *et al.*, 2016; Nacoulma *et al.*, 2018). The clear hierarchy of carbon storage by LULC type (Green Area > Built-up Area > Farmland > Bareland) confirms the dominant role of land use in determining carbon stocks. This finding is crucial for policy, as it shows that even degraded agricultural landscapes (Farmland: 36.85 tC/ha) can store significant amounts of carbon, challenging the assumption that only pristine forests are valuable carbon sinks. This aligns with the "trees outside forests" concept, which recognizes the carbon value of trees in agricultural and urban matrices (Fifanou *et al.*, 2018). The development of the CESI is a significant methodological contribution. By integrating species diversity, evenness, and carbon stock, the CESI provides a more holistic measure of ecosystem health than carbon stock alone.

The results show that high carbon stocks do not guarantee high stability. SS2, for example, had moderate carbon stocks but the lowest CESI (0.057) due to its low diversity and evenness. This indicates a "monodominant" carbon pool that is vulnerable to pests, diseases, and climate shocks (Brockerhoff *et al.*, 2018). In contrast, SS4, which had the highest diversity, had the highest CESI (1.000), indicating a more resilient, stable carbon sink. This finding has important implications for restoration and management. It is not enough to simply plant trees to maximize carbon; it is essential to plant a diverse mix of species to ensure the long-term stability of the carbon sink. The CESI framework can be used by land managers and policymakers to evaluate the ecological integrity of different land-use options and to prioritize interventions that enhance

both carbon storage and biodiversity.

The most critical methodological finding of this study is the large discrepancy between field-measured and modeled SOC (Table 15). The field-measured SOC (1.9–5.87 tC/ha) was an order of magnitude lower than the IPCC Tier 2 values (25–95 tC/ha). This is a major source of uncertainty in carbon accounting. The three factors identified—sampling depth, analytical method, and spatial representativeness—are well-documented in the literature. The Walkley-Black method is known to under-recover stable carbon fractions compared to dry combustion (Nelson & Sommers, 1996). The sampling depth of 30 cm is insufficient to capture the full soil carbon profile, as a significant portion of SOC in drylands can be found at greater depths (Jobbagy & Jackson, 2000). Furthermore, institutional campuses may not be representative of the broader landscape, which may have different soil textures and erosion histories. This finding does not invalidate the use of IPCC Tier 2 values for landscape-level modeling; it is a necessary compromise in data-sparse regions. However, it does highlight the need for local calibration and for using field data as a validation benchmark, not as a direct model input. Future studies should aim to sample deeper soil profiles and use dry combustion methods to reduce this uncertainty.

This study has some limitations. The field data were restricted to institutional campuses due to security concerns, which may represent an upper bound of carbon stocks. The CESI, while useful, is a relatively simple index with equal weights for its components. Future research could refine the CESI by using expert-based or principal component-based weighting schemes. The InVEST model was parameterized with Tier 2 values, not fully local field-derived carbon densities. This was a deliberate methodological choice, as the field data were not spatially representative of the entire state, but it introduces uncertainty. The comparison between field and model values is a strength of the study, not a weakness, as it provides a transparent assessment of the uncertainty.

Conclusion

This study presents a replicable, multi-scalar hybrid methodology for carbon accounting in data-sparse dryland ecosystems. By integrating field biophysics, remote sensing, and the InVEST model, we provide a robust assessment of carbon stocks and dynamics in the Sudan Savanna of Kebbi State. The field data reveal a landscape with moderate carbon stocks (mean 38.76 tC/ha), dominated by the exotic species *Azadirachta indica*. The novel Composite Ecosystem Stability Index (CESI) reveals that high carbon stocks do not always equate to high ecological stability, with monoculture-dominated systems being more vulnerable.

The methodological comparison of field and modeled SOC highlights the critical importance of standardizing methods, sampling deeper soil profiles, and using local data to calibrate and validate models. The large discrepancy is not a failure of the model, but a finding that identifies a critical uncertainty in carbon accounting and points the way toward future research.

The integrated framework presented here can be used by other states in Nigeria and across the Sahel to develop their own field-validated carbon baselines, providing the activity data and emission factors needed for UNFCCC reporting, NDC tracking, and REDD+ readiness. By bridging the scale gap, this methodology provides the empirical foundation necessary for evidence-based climate policy and sustainable land management in the world's most vulnerable drylands.

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