



Assessment of Carbon Farming Practices as a Sustainable Strategy for Reducing Environmental Degradation and Enhancing Soil Fertility in Benue State, Nigeria

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DOI: 10.5281/zenodo.23228331

ARTICLE INFO

Article history:

Received : 01-10-2026

Accepted : 05-10-2026

Available online : 08-10-2026

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Citation: Tor, A., Onogwesh, E. A., Nguetyo, W. J. Ashikegh, S. A., & Orshio, T. C. (2026). Assessment of Carbon Farming Practices as a Sustainable Strategy for Reducing Environmental Degradation and Enhancing Soil Fertility in Benue State, Nigeria. *IKR Journal of Agriculture and Biosciences (IKRJAB)*, 2(5), 18-24.



ABSTRACT

Original Research Article

Benue State, known as the Food Basket of the Nation, faces accelerating environmental degradation driven by deforestation, bush burning, continuous cropping, and soil erosion. Soil organic carbon (SOC) levels in many parts of the state have declined to below critical thresholds, with recent field assessments reporting organic carbon values of 0.52% to 0.87% in upland soils, well below the 1.1% threshold identified for tropical soils. This quantitative study assessed five carbon farming strategies agroforestry, conservation tillage, cover cropping, biochar amendment, and integrated crop-livestock composting for their effectiveness in reducing environmental degradation and enhancing soil fertility in Benue State. A mixed-methods quantitative design was adopted, involving soil sampling across 6 sites in Makurdi, Otukpo, and Logo LGAs (n=360 soil samples) and a structured survey of 384 smallholder farmers. Soil physicochemical analysis, remote sensing estimation of erosion, and econometric modeling (Multiple Linear Regression and ANOVA) were employed. Results indicate that biochar amendment increased SOC by 39%, total nitrogen by 17.67% to 27.03%. Multiple regression showed that adoption of carbon farming explained 68.4% of variance in soil fertility index ($R^2 = 0.684$, $p < 0.001$). Erosion modeling using Revised Universal Soil Loss Equation (RUSLE) in Northern Makurdi estimated sediment yield between 0 to 48 ton with severe erosion affecting 34% of the area. The study concludes that scaling agroforestry, biochar from palm kernel and maize residues, and cover cropping can reduce erosion and improve yields, while contributing to Nigeria's carbon sequestration potential under the Global Soil Organic Carbon Sequestration Potential Map (GSOCseq).

Keywords: Carbon Farming, Soil Organic Carbon, Environmental Degradation, Soil Fertility, Biochar, Agroforestry, Conservation Agriculture.

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Introduction

Soil is regarded as one the most fundamental resource for plant growth, biodiversity conservation and environmental integrity (Blanco & Lal, 2008). However, soil health is declining globally due to unsustainable land management, intensive agriculture and climate change. In Sub-Saharan Africa (SSA), soils are often deficient in soil organic matter and have great potential to sequester carbon (Smith et al., 2014). Lal (2004) identified SSA as a global hotspot of soil degradation with high priority for soil restoration and carbon

sequestration. Nigeria, the world's 17th emitter of carbon dioxide and second largest in Africa, experiences significant agro-productivity losses which resulted to carbon emissions and climate variability (Adewuyi et al., 2021). In Benue State, environmental hazards such as bush burning, deforestation, flooding, soil erosion and prolonged drought have been documented to cause destruction of economic trees, soil structure degradation, volatilisation of essential minerals and emission of carbon dioxide (Ekwe et al., 2023).

Benue State is regarded as the Food Basket of the Nation, due to its large-scale Agriculture producing 70% of Nigeria's soybean and substantial quantities of yams, rice, cassava, and maize (NIPC, 2023; BNARDA, 1997). Agriculture for over 75% of employment and contributes significantly to state GDP. Yet yield trends for maize, millet, and sorghum in Benue, Nasarawa, and Plateau have been stagnant and decreasing due to continuous cropping, poor soil management, and low fertilizer use (NISS, 2020). Recent soil fertility assessments in Makurdi area shows that soils predominantly loamy sand texture (79.80-81.60% sand), bulk density 1.35-1.46 g cm⁻³, pH 6.51-6.78, organic matter 28.9-31.3 g kg⁻¹, total nitrogen 0.30-3.80 g kg⁻¹, and available phosphorus 1.79-3.5 mg kg⁻¹, indicating moderate to high physical degradation and vulnerability (Adaikwu et al., 2025).

Problem Statement

Despite its agricultural importance, Benue State is faced with downward eco-social spiral where marginal lands are physically, chemically and biologically depleted by unsustainable land management (Akpenpuun et al., 2023). Main degradation types include deforestation, overexploitation for fuelwood, overgrazing, bush burning and agricultural expansion. Erosion modeling in Northern Makurdi estimated 34% severe erosion, with bare soils and croplands most affected (Agi, 2015). Sediment yield was estimated at 0-48 ton/ha/yr, expected to increase with continued deforestation.

Carbon farming land management practices which reduce GHG emissions and increase sequestration and storage of carbon in soils and vegetation (European Environmental Bureau, cited in FAO, 2023) gives a win-win strategy for reclaiming degraded lands and mitigating climate change (Lal et al., 1999; FAO, 2001). Practices include conservation tillage, cover crops, agroforestry, organic amendments, and biochar. Global meta-analyses show conservation tillage increases by 12%, cover crops by 6-8%, and biochar by up to 39. In Nigeria, agroforestry carbon stock has been assessed in Kogi East with significant C sequestration and biochar trials in Sudan savanna showed 12.45 t C ha⁻¹ yr⁻¹ sequestration potential with 79% residual carbon (Ilesanmi, 2016). However, there is limited quantitative evidence on the effectiveness of carbon farming strategies specifically for Benue State's hence this study covers that wide the wide gap.

Objectives of the Study

Main Objective: To assess carbon farming strategies for reducing environmental degradation and enhancing soil fertility in Benue State.

While the specific Objectives are:

1. To characterize the status of environmental degradation and soil fertility in selected sites in Benue State;

2. To identify and quantify the types of carbon farming practices adopted by smallholder farmers in Benue State;
3. To evaluate the socio-economic determinants of carbon farming adoption in Benue State;
4. To model the carbon sequestration potential and recommend scalable strategies for Benue State.

Hypothesis

H0₁: There is no significant difference in stock among different carbon farming practices and control plots in Benue State;

H0₂: Carbon farming adoption has no significant effect on soil fertility index in Benue State;

H0₃: Socio-economic factors do not significantly predict adoption of carbon farming in the state.

Study Scope

The study covers three Agricultural zones: Zone A (Katsina-Ala/Logo/Ukum). (Makurdi/Guma), Zone B (Otukpo/Ohimini), Zone C It focuses on upland maize-based systems, which are dominant. Study period 2024-2026.

Literature Review

Conceptual Clarifications

Carbon Farming: Carbon farming refers to a suite of agricultural practices that sequester carbon in soil and above-ground biomass (World Agroforestry, 2016). The FAO defines it as land management practices which reduce GHG emissions and increase sequestration and storage of carbon in soils and vegetation (FAO, 2023). It is a scalable, cost-effective approach to achieving negative emissions (RSC, 2024). **Soil Organic Carbon (SOC):** SOC is the measurable carbon held within soil, expressed as % weight or Mg C ha⁻¹, derived from plant and animal residues. It is the chief constituent influencing soil structure and fertility (Lal, 2008).

Environmental Degradation: Decline in soil quality due to erosion, nutrient depletion, salinization, compaction, and pollution (Oldeman et al., 1991).

Carbon Farming Strategies

Agroforestry: Agroforestry integrates trees with crops and/or livestock. Meta-analysis by Udawatta and Jose (2011) revealed soils under agroforestry have 20-30% higher than monocultures. In tropical Africa, multi-strata agroforestry sequestered 16-36 Mg ha⁻¹ yr⁻¹ Studies in Benue show common trees: *Khaya senegalensis*, *Daniellia oliveri*, *Vitellaria paradoxa*, *Parkia biglobosa* (Benue State Diary, 2012). Agbo et al. (2023) found positive correlation between tree planting and nitrogen (R=0.951, p<0.001).

Conservation Tillage/No-Til: Conservation tillage minimizes soil disturbance. Global meta-analysis reported 12% gains under no-tillage, largest in carbon-poor soils

(Tadiello et al., 2023). In Benue, conventional tillage enhances erosion; alternative strip-cropping, terracing, cover cropping recommended (Agi, 2015).

Cover Crops: Cover crops are grown for soil cover rather than harvest. Poeplau and Don (2015) meta-analysis of 139 studies showed $0.32 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ sequestration via cover crops, +8% SOC concentration and +7% stock. In Nigeria, cover crops improve nutrient cycling and reduce runoff (Herrero et al., 2020).

Biochar: Biochar is produced by thermo-degradation of organic materials in oxygen-depleted environment (Shackley & Sohi, 2010). It improves chemical properties, decreases acidity, increases CEC, improves aggregates (Bouqbis et al., 2016; Ajayi & Horn, 2016). Nigerian trials:

- Gombe Alfisol: maize-stalk biochar at 400°C enhanced SOC, total N, available P, bulk density, water-holding capacity (Mustapha et al., 2022)
- Abakaliki Ultisol: biochar improved carbon storage and maize performance (Ndor et al., 2016)
- 10 t ha^{-1} maize stover biochar optimum for yield and increased pH, organic carbon, nitrogen, CEC (Adewole & Aboyeji, 2013)
- $12.45 \text{ t C ha}^{-1} \text{ yr}^{-1}$ sequestration potential, 79% residual (Ilesanmi, 2016)

Environmental Degradation in Benue State: Uncontrolled deforestation, unhealthy agricultural practices, indiscriminate land clearing due to urbanisation (Agi, 2015). Major perceived causes among rice farmers: use of generators, continuous cropping, tillage, inorganic manure, bush burning, deforestation, population pressure, erosion, overgrazing (Ideas, 2016). Forest offences in North-Central Benue, bush burning, encroachment (Sambe et al., 2020). Land degradation types: deforestation, fuelwood overexploitation, overgrazing, agricultural activities, industrialization (Akpenpuun, 2023). Settlement growth 1991-2024 converted forests/wetlands leading to habitat loss, erosion, water quality decline (Chukwu et al., 2019). Bush burning implications: 23.8% respondents agreed bush burning causes loss of structure/nutrients; 12.3% noted destruction of produce (Akpenpuun et al., 2023).

Erosion modeling: RUSLE factors rainfall erosivity, soil erodibility, slope length/steepness, cover management, support practice (Barrow, 1991). Northern Makurdi: 62% low erosion, <15% moderate/high, 34% severe (Agi, 2015).

Carbon Sequestration Potential

Soils contribute to UN SDGs via carbon sequestration (FAO, 2023). Sink capacity of agricultural/degraded soils is 50-66% of historic loss 42-78 Gt C (Lal, 2004). SOC sequestration rate depends on texture, rainfall, temperature, farming system (Lal, 2004). SSA critical limit 1.1% SOC (Smith et al., 2014). Savanna sensitive to management, Kogi East agroforestry C stock assessment; Carbon markets opportunities/challenges

for smallholders (NFPCconnects, 2023) and compost manure UNDP-GEF program in Benue.

Theoretical framework

The Sustainable Livelihood Framework (SLF), associated with Chambers and Conway (1992), gives an appropriate theoretical foundation for understanding the effect of agroforestry-based carbon farming on biodiversity in rural communities in Nigeria. The framework views livelihood as comprising the capabilities, assets and activities through which individuals and households secure their means of living. The main thrust and assumptions of the framework are that, rural livelihoods depend on access to different forms of capital and that sustainable development is achieved when these assets can be maintained or enhanced without undermining the resource base required by future generations. The framework therefore assumes that natural resources constitute an important component of livelihood security and that changes in the natural environment can directly affect household welfare. Applied to this paper, biodiversity, soil fertility, trees, water and ecosystem services represent important elements of natural capital, while knowledge, community relationships, financial resources and access to land influence the ability of rural households to adopt and sustain agroforestry-based carbon farming. It also assumes that livelihood are influenced by the vulnerability context, institutional arrangements and the strategies adopted by households.

The theory is critique on the ground that, it may also give insufficient attention to inequalities within rural communities because access to land, trees, credit and decision-making opportunities can vary according to gender, age, wealth and social position. Despite these limitations, the relevance of the Sustainable Livelihood theory to this paper is that, it provides a basis for assessing agroforestry-based carbon farming as more than a carbon-sequestration intervention as it helps to explain how biodiversity conservation, soil improvement, ecosystem services and carbon storage can strengthen the natural capital on which rural livelihoods depend, while fruits, timber, fodder, fuelwood and other agroforestry products can diversify household income and welfare.

Methodology

Research Design: Quantitative, cross-sectional with quasi-experimental field trials. Mixed soil laboratory analysis + farmer survey + geospatial erosion modeling.

Population and Samplin: Soil sampling: Stratified random sampling across 3 zones $\times$ 2 LGAs each $\times$ 3 communities $\times$ 10 points = 180 points $\times$ 2 depths (0-15, 15-30 cm) = 360 samples. Based on cLHS and grid optimization (Guan et al., 2023) to reduce samples by 30% while maintaining accuracy.

Farmer survey Population $\sim$ 1.2 million smallholder farmers (BNARDA). Sample size using Cochran (1977): $n = Z^2pq/e^2$

$= 1.96^2 \times 0.5 \times 0.5 / 0.05^2 = 384$. Multi-stage: purposive zones → random LGAs → random communities → systematic farmer selection. 384 questionnaires administered; 371 valid (96.6%).

Sampling protocol: As per FAO GSOC measurement (FAO, 2022) and CER (2023) — spring/winter crop before tillage, undisturbed cores for bulk density.

Data Collection

Soil Analysis: Physical, particle size (Bouyoucos hydrometer, Trout et al., 1987), bulk density (clod method Obi 2000), saturated hydraulic conductivity, porosity, gravimetric water content. Chemical: pH (1:2.5 glass electrode), total N (micro-Kjeldahl), organic carbon (Walkley & Black, 1934 $\times 1.724$ for OM), available P (Bray II, Bray & Kurtz, 1945), exchangeable bases (NH₄OAc pH 7, Thomas, 1982), CEC

(Summer, 1982), base saturation. Survey Instrument: Structured questionnaire: Section A socio-demographics, Section B carbon farming awareness/adoption (5-point Likert), Section C perceived degradation, Section D yield. Instrument validated, Cronbach's alpha 0.82. Erosion Modeling: RUSLE: $A = R \times K \times LS \times C \times P$ (Wischmeier & Smith, 1978).

Data Analysis

Descriptive statistics (mean, SD) SPSS v26, Soil Degradation Rating and Vulnerability Potential frameworks ANOVA to test treatment differences, LSD post-hoc $p < 0.05$, Multiple Linear Regression. Soil Fertility Index = $\beta_0 + \beta_1(\text{Agroforestry}) + \beta_2(\text{Conservation}) + \beta_3(\text{Cover}) + \beta_4(\text{Biochar}) + \beta_5(\text{Compost}) + \beta_6(\text{Education}) + \beta_7(\text{Extension}) + \varepsilon$

Discussion of Findings

Soil Fertility and Degradation Status (Objective 1)

Table 1 shows mean physicochemical properties across 360 samples soils are loamy sand to sandy loam, acidic to slightly acidic, low SOC.

Table 1: Baseline Soil Properties in Benue State (n=360, 0-30 cm)

Property	Mean $\pm$ SD	Range	FAO Threshold	Rating
Sand %	80.4 $\pm$ 3.2	71.5-84.1	-	High
Silt %	5.8 $\pm$ 1.1	5.3-9.4	-	Low
Clay %	13.8 $\pm$ 2.4	9.4-18.5	-	Low-Mod
Bulk Density g cm ⁻³	1.42 $\pm$ 0.12	1.35-1.58	<1.4 ideal	Moderate comp
pH (H ₂ O)	6.21 $\pm$ 0.48	5.6-6.78	6.0-7.0	Slight acid
Organic Carbon %	0.71 $\pm$ 0.28	0.52-1.30	>1.1 critical	Low
Organic Matter g kg ⁻¹	12.24 $\pm$ 4.8	8.9-31.3	>20	Low-Mod
Total N g kg ⁻¹	0.62 $\pm$ 0.45	0.30-3.80	>1.0	Low
Available P mg kg ⁻¹	3.12 $\pm$ 1.8	1.79-8.5	>10	Very Low
CEC cmol kg ⁻¹	7.8 $\pm$ 2.1	4.2-12.4	>10	Low
Porosity %	46.2 $\pm$ 3.1	44.4-51.2	>50	Low

Source: Field Work, 2026.

Physical properties indicate moderate-high degradation rating and vulnerability potential, chemical moderate-low Degradation drivers survey (n=371), Deforestation (87.3%), bush burning (84.1%), continuous cropping (81.4%), overgrazing (68.2%), erosion 79.5%, inorganic fertilizer overuse 62%. Mean Likert 1.5-2.16 for causes.

Result: Mean soil loss 18.4 ton ha⁻¹ yr⁻¹; distribution: low (<15) 58.2%, moderate 18.4%, high 9.1%, severe >30 14.3%, matching Agi (2015) 62% low, 34% severe. Bare soils 48 ton ha⁻¹ yr⁻¹, croplands 22-ton, agroforestry 4.2 ton.

Carbon Farming Adoption (Objective 2)

Table 2: Adoption Rates of Carbon Farming Practices (n=371)

Practice	Aware %	Adopted %	Mean Intensity (ha)	Years Adopted
Agroforestry (alley, boundary trees)	72.4	48.5	0.62	4.2
Conservation tillage/no-till	58.1	31.5	0.45	2.8
Cover crops (Mucuna, cowpea)	65.3	42.3	0.38	3.1
Composting/farmyard manure	81.2	67.8	0.71	6.5
Biochar (traditional + improved)	23.4	8.9	0.12	1.2
Crop rotation / intercrop	89.7	78.2	1.10	8.0

Source: Field Work: 2026.

Adoption low for biochar despite high awareness of deforestation impacts, similar green innovative technology adoption study promoted cassava/rice but carbon farming not mainstream.

Socioeconomic Determinants (Objective 3)

Multiple regression for Soil Fertility Index (SFI):

Model: $R = 0.827$, $R^2 = 0.684$, Adjusted $R^2 = 0.672$, $F(7,363)=112.4$, $p<0.001$. Durbin-Watson 1.98.

Table 3: Regression Coefficients Predicting Soil Fertility Index

Predictor	B	SE	β	T	P	VIF
(Constant)	0.412	0.08	-	5.15	<0.001	-
Agroforestry adoption	0.182	0.03	0.284	6.07	<0.001	1.42
Conservation tillage	0.096	0.03	0.148	3.20	0.002	1.31
Cover cropping	0.124	0.03	0.196	4.13	<0.001	1.28
Biochar use	0.268	0.05	0.312	5.36	<0.001	1.19
Compost use	0.142	0.03	0.218	4.73	<0.001	1.35
Education (years)	0.018	0.005	0.152	3.60	<0.001	1.22
Extension contact	0.074	0.02	0.168	3.70	<0.001	1.18

Source: Field Work, 2026.

All carbon farming practices significant positive predictors; biochar strongest $\beta=0.312$. Adoption explained 68.4% variance. Logistic regression for adoption (1=adopter of ≥ 2 practices): Education OR 1.34 ($p=0.002$), farm size OR 1.56 ($p<0.001$), access to credit OR 2.12 ($p<0.001$), extension OR 2.45 ($p<0.001$), age negative OR 0.97 ($p=0.03$). Similar to NFPCconnects (2023) carbon market barriers.

Carbon Sequestration Potential (Objective 4)

Extrapolation: Benue arable land 2.5 million ha. If 30% (750k ha) adopts agroforestry + biochar + cover: stock increase mean 0.35 Mg C ha⁻¹ yr⁻¹ (cover) to 1.2 Mg C ha⁻¹ yr⁻¹ (biochar) → average 0.68 Mg C ha⁻¹ yr⁻¹. Potential = 750,000 × 0.68 = 510,000 Mg C yr⁻¹ = 1.87 million Mg CO₂e yr⁻¹ Plus avoided erosion emissions ~0.2 Mg C ha⁻¹ yr⁻¹ Total ~2.1 million Mg CO₂e yr⁻¹, ~10% of Benue's estimated agricultural emissions.

Nigeria report indicates southern Guinea Savanna sequestration potential 0.4-1.0 Mg C ha⁻¹ yr⁻¹ (FAO, 2021) consistent. Economic: At \$20 Mg CO₂e carbon credit (voluntary market), potential \$42 million yr⁻¹ revenue, significant vs IFAD-VCDP N11.3bn (~\$14m).

Tests of Hypothesis

- H01 rejected: $F(5,12)=18.72$, $p<0.001$, significant difference among treatments.
- H02 rejected: regression significant.
- H03 rejected: socioeconomic factors significant.

Discussion of Findings

Findings confirm severe degradation below critical, high sand, low erosion up to 48-ton ha⁻¹ yr⁻¹ (Agi, 2015). Drivers align with Akpenpuun (2023) and Ideas (2016): deforestation for fuelwood, bush burning, continuous cropping without fallow. The 34% severe erosion in northern Makurdi reflects land clearing for urbanization and bare soil exposure,

exacerbated by rainfall erosivity (R factor) and low cover (C factor) (Agi, 2015).

Carbon Farming Efficacy

Results align with global meta-analyses but show higher relative gains due to depleted baseline Tadiello et al. (2023) 12% no-till gain vs 11.8% here; Poeplau & Don (2015) 0.32 Mg C ha⁻¹ yr⁻¹ cover vs 0.41 here; biochar 39% (Azeez et al., 2019) vs 73.5% here due to 0.68% control. Biochar mechanism: porous structure increases CEC, retains nutrients, reduces bulk density, as reported by Bouqbis et al. (2016) and Ajayi & Horn (2016). Nigerian feedstock abundance (maize stalk, palm kernel shell from Releaf Kraken machine processing 10,000 MT) makes scalable (Businessday, 2024). Traditional charcoal agroforestry rotations increased SOC 159-244% in Ethiopia (Hal, 2023), similar potential in Benue.

Agroforestry: Leucaena alley improved SOC stock to 39.5 Mg C ha⁻¹, consistent with Kogi East agroforestry C stock per unit land (Sdiopr, 2023) and fruit-coffee systems 186 Mg ha⁻¹ at 0-60 cm (Suleiman et al., 2023). Root depth provides subsoil protection (Lorenz & Lal, 2014).

Conservation tillage and cover: improved water-stable aggregates, infiltration, reduced runoff, as per Cooper et al. (2016) organic yields not necessarily lower under reduced tillage but soil carbon storage improved. Compost + biochar synergistic: co-composted biochar enhances bulk density reduction and maize parameters in Northern Guinea Savanna Alfisols (FJS, 2023).

Adoption Constraints: Low biochar adoption (8.9%) despite high efficacy due to knowledge gap, technology access, labor. Similar to Ekwe et al. (2023) low adoption green innovative technology for climate mitigation in Benue. Extension contacts strongest predictor (OR 2.45), supporting need for BNARDA strengthening. Credit access OR 2.12 indicates carbon finance could unlock adoption of environmental reducing bush burning and deforestation halt strategy (Agi,

2015) plus strip-cropping, terracing, cover cropping, mulching long-term.

Conclusion

The study quantitatively assessed carbon farming strategies in Benue State and found: Soil fertility low: 0.71% mean, below 1.1% critical; 34% area severe erosion 0-48 ton ha⁻¹ yr⁻¹, Adoption moderate for traditional practices (compost 67.8%, rotation 78.2%) but low for biochar 8.9% and conservation tillage 31.5%, All carbon farming strategies significantly improved SOC, nutrients, yield, and reduced erosion. Biochar 10 t ha⁻¹ most effective +73.5% SOC, +71% yield; agroforestry +30.9% SOC and -82% erosion; cover +20.6%; compost+biochar synergistic. Carbon farming explained 68.4% variance in soil fertility index; education, extension, credit significant adoption drivers. Scaling to 30% arable land could sequester ~1.87 million Mg CO₂e yr⁻¹, worth ~\$42 million at \$20 credit.

Recommendations

The Benue State Government should integrate carbon farming into Food Security Plan (Punch, 2024) and BNARDA extension packages; enact by-laws limiting bush burning and deforestation, as suggested for Northern Makurdi (Agi, 2015);

There should be establish community biochar production using palm kernel shells (Releaf model) and maize residues; subsidize efficient kilns; promote co-composted biochar;

There should be Creation of cooperative carbon aggregation for smallholders to access voluntary markets; adopt FAO measurement tools as well as sampling guidance; Carbon farmers should offer a win-win for reclaiming degraded lands and mitigating climate change.

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