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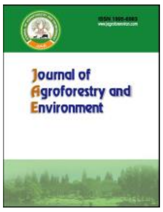

Integrated Bamboo Agroforestry for Carbon Finance and Smallholder Livelihoods in the Ethiopian Afromontane Highlands: A Study on Carbon Finance

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Abstract: Carbon finance projects face a temporal disconnect: carbon revenues accrue over decades, while smallholder farmers require immediate returns. This study evaluates an integrated agroforestry model centred on Yushania alpina with native companion species, intercropping, biochar soil amendment, peer-to-peer learning, and pilot cooperative finance in the Ethiopian highlands. A mixed-methods design was applied on 66 stratified random plots (0.2 ha each) in Sidama Region (June 2024–April 2026). Survival of Y. alpina reached 95% across 170 ha, and companion species 91%. Mean survival in 66 plots was 90.6%, with 98.5% of plots rated good or excellent. Weeding effectiveness was the strongest predictor of survival ($\beta = 12.4$, $p < 0.001$). All interviewed farmers adopted intercropping; 64% reduced synthetic fertiliser use. A trust index increased by 68% ($p < 0.001$). Biochar experimental plots raised potato yield by 22–31% and soil pH from 5.2 to 6.4. Per-hectare afforestation cost was USD 1,984, 40–50% above regional benchmarks. The model is ecologically effective, but carbon finance viability is constrained by high costs and insufficient input access. Blended finance, community biochar hubs, formalised peer-to-peer learning, and infrastructure investment are needed. (Word count: 186).

Keywords: Carbon finance; Yushania alpina; Biochar; Peer-to-peer learning; Ethiopia.

INTRODUCTION

Nature-based carbon removal projects typically generate verified emission reductions over multi-decadal periods, while smallholder farmers operate under acute seasonal food security timelines (Smith et al. 2020). Without effective bridging mechanisms, the near-term opportunity cost of converting land from annual cropping to tree-based systems can undermine the permanence of carbon removals. This problem is acute in the Ethiopian Afromontane highlands, where three additional factors exacerbate the carbon finance gap: (i) high per-hectare afforestation costs (seedlings, labour, fencing, monitoring); (ii) poor rural infrastructure (roads, storage, digital connectivity); and (iii) limited access to external funding from government or development partners.

A further, often under-quantified barrier is a deficit of trust in external interventions. Drawing on diffusion of innovations theory (Rogers 2003), adoption of novel agricultural practices is mediated by social networks and the perceived credibility of information sources. Where historical interactions with extension services have been inconsistent or perceived as extractive, farmers may exhibit rational skepticism (Chomba et al. 2016). Peer-to-peer learning, which leverages homophily and shared experiential knowledge, can accelerate diffusion by establishing trust through observable trialability (Franz and Piercy 2020).

Sidama Regional State, Ethiopia, is characterised by steep slopes (>30%), high population density, and widespread soil acidity (pH <5.5) that drives declining yields (Elias 2018; Hurni et al. 2015). Restoration interventions must concurrently establish woody perennials for future carbon sequestration and generate immediate agricultural productivity gains to secure farmer participation. The African Bamboo Carbon Project in Hula and Bursa woredas has implemented a structured agroforestry model centred on *Yushania alpina* (highland bamboo) with native companion species. This study assesses both the ecological effectiveness and the financial–institutional challenges determining carbon finance viability.

The specific objectives (June 2024–April 2026) were to: (1) document establishment success and survival rates across two growing cycles; (2) quantify the influence of post-planting practices on survival through regression analysis; (3) evaluate the role of peer-to-peer learning in building trust and adoption of biochar and intercropping; (4) assess access to biochar, cooperative finance, and the performance of biochar experimental plots; (5) identify and quantify major challenges to carbon finance; and (6) provide evidence-based recommendations.

MATERIALS AND METHODS

Study area

The study was conducted in Bursa and Hula woredas, Sidama Regional State, Ethiopia, at 2,200–2,800 m a.s.l. The region has a bimodal rainfall regime: the *Belg* (short rains) from March to May and the primary *Kiremt* rains from June to September. Soils are predominantly Nitisols and Acrisols with high exchangeable acidity and phosphorus fixation. Project operations started in June 2024 with the Kiremt season (Fig. 1).

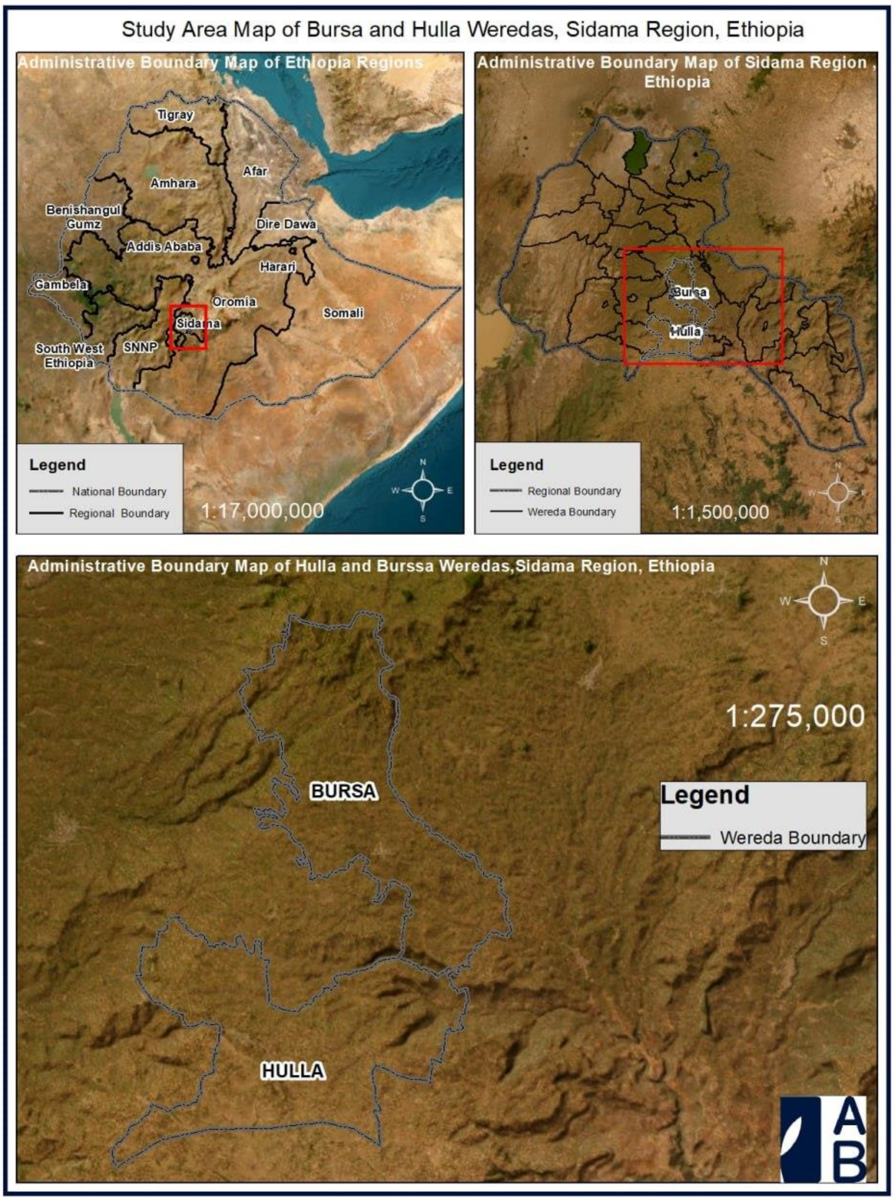

Figure 1: Map of the study area showing the distribution of the 66 sample plots across Hula and Bursa woredas; Basemap: ESRI Satellite Imagery; Administrative Boundaries: OCHA Data Exchange; Study Area Map: Produced by AB's GIS and Remote Sensing Officer.

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Experimental farm design and species selection

A standardised central-block with mixed-species hedgerow model was applied on 170 hectares across two planting cohorts (Kiremt 2024 and Kiremt 2025). The central area of each plot was designated for *Y. alpina* to optimise rhizome development, while the peripheral area was planted with three companion species (Table 1). Species were selected for multiple ecosystem functions and highland suitability (Negash 2021).

Table 1. Planting density and spacing regime

Species	Local name	Primary function	Spacing (m)	Density (plants ha^{-1})
Yushania alpina	Highland bamboo	Erosion control, carbon sink, biomass	5 × 5	400
Millettia ferruginea	Birbra	Nitrogen fixation, timber	3 × 3	1,111
Hagenia abyssinica	Kosso	Conservation, medicinal	3 × 3	1,111
Morus alba	Mulberry	Fodder, sericulture, living fence	1.8 × 1.8	~3,086

Capacity building

A dual-track approach was implemented:

- **Formal cascade training:** Six woreda agricultural experts received Training of Trainers (ToT) and subsequently trained 830 smallholder farmers on pit preparation, planting, and mulching. Ten Model Farmers received advanced training in biochar production and facilitation.
- **Peer-to-peer learning:** Model Farmers hosted demonstration plots and facilitated small-group discussions (5 farmers per session). Each conducted at least four sessions over the 22-month period, reaching approximately 100 additional farmers beyond formal training.

Data collection and survival monitoring

Data were collected at three points: post-Kiremt 2024 (December 2024), post-Kiremt 2025 (December 2025), and a final assessment (01–09 April 2026). A stratified random sample covering 20% of the total area (34 ha) was surveyed using KoboToolbox, recording GPS coordinates, geotagged photographs, and species-specific survival. Within this, 66 plots of 0.2 ha each (33 Hula, 33 Bursa) were selected for detailed growth and post-planting care assessment. Structured interviews were conducted with 50 purposively selected farmers representing both planting cohorts and participation in peer-learning versus formal training only.

Biochar experimental plots

Four community hubs (two per woreda) hosted biochar experiments using a randomised complete block design with potato intercrops at three biochar rates (0, 2.5, 5 t ha^{-1}). Soil pH (1:2.5 water) and tuber yield were measured after six months (February 2026). Biochar was produced from bamboo waste in low-cost kilns.

Trust index

A composite trust index was constructed from four Likert-scale items administered at baseline (June 2024) and final assessment (April 2026): (1) “I trust information from peer farmers more than from external agents”; (2) “I believe the project recommendations will benefit my farm”; (3) “I am willing to adopt new practices if a neighbour has success first”; (4) “I trust the long-term intentions of this project.” Items were scored 1–5 and the mean rescaled to 0–100 (Cronbach’s $\alpha = 0.78$). Change was analysed with a paired t-test.

Statistical analysis

Survival rates were calculated as percentage of live seedlings per plot; 95% confidence intervals used the Wilson score method. Comparisons between planting cohorts and woredas applied independent t-tests on arcsine-transformed proportions. Multiple linear regression (dependent: overall survival %) included weeding effectiveness, mulching condition, protection condition, fertilisation, and disease presence as predictors. Assumptions were checked (VIF <5). Significance was set at $\alpha = 0.05$.

Cost and infrastructure assessment

Per-hectare afforestation cost was calculated from project financial records (2024–2026) including seedlings, labour, training, monitoring, incentives, and logistics. Infrastructure deficit was scored (1–5 scale) for road condition, storage, and mobile network coverage. Regional benchmarks used published data from Kenya (TIST Kenya 2022) and Rwanda (World Bank 2024).

Ethical considerations

Verbal informed consent was obtained from all farmer participants. The study did not involve experimental manipulation of farmers or collection of sensitive personal data beyond project monitoring.

Study limitations

This is an observational study without control plots. Soil chemical properties (except pH in biochar trials) were not directly measured. Biochar adoption and fertiliser reduction data are self-reported. Independent verification of biophysical and financial outcomes is recommended.

RESULTS

Plantation establishment and survival

From the full 170 ha monitoring, survival was 95% for *Y. alpina* and 91% for each companion species, with no significant difference between the 2024 and 2025 cohorts (p

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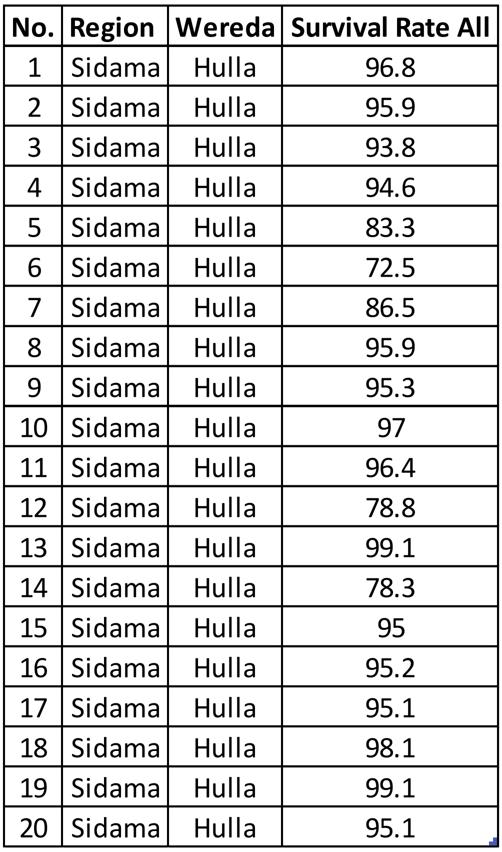
> 0.05; Table 2). In the detailed 66-plot analysis, mean survival was 90.6% (range 43.2–99.5%). Of these, 56.1% were rated “excellent” (≥90% survival) and 42.4% “good” (80–89%), meaning 98.5% were good or excellent. *Y. alpina* had the highest species-specific survival (92.6%) and a mean height of 112.8 cm. Hula woreda significantly outperformed Bursa for all species in both survival and growth ($p < 0.01$; unpublished data) (Fig. 2).

Table 2. Survival rates from full 170 ha sampling (April 2026)

Species	Total seedlings distributed	Observed survival (%)	95% CI
Yushania alpina	**40,324**	**95.0**	**93.1–96.9**
Millettia ferruginea	**27,278**	**91.0**	**88.7–93.3**
Hagenia abyssinica	**27,278**	**91.0**	**88.6–93.4**
Morus alba	**75,216**	**91.0**	**89.2–92.8**
Total/Average	**170,096**	**92.6**	**—**



No.	Region	Wereda	Survival Rate All
1	Sidama	Hulla	96.8
2	Sidama	Hulla	95.9
3	Sidama	Hulla	93.8
4	Sidama	Hulla	94.6
5	Sidama	Hulla	83.3
6	Sidama	Hulla	72.5
7	Sidama	Hulla	86.5
8	Sidama	Hulla	95.9
9	Sidama	Hulla	95.3
10	Sidama	Hulla	97
11	Sidama	Hulla	96.4
12	Sidama	Hulla	78.8
13	Sidama	Hulla	99.1
14	Sidama	Hulla	78.3
15	Sidama	Hulla	95
16	Sidama	Hulla	95.2
17	Sidama	Hulla	95.1
18	Sidama	Hulla	98.1
19	Sidama	Hulla	99.1
20	Sidama	Hulla	95.1

Figure 2: Survival rates for the 66-plot detailed sample, disaggregated by woreda. Boxplots show median, interquartile range, and 1.5 × IQR whiskers; individual plot values are overlaid as jittered points. Asterisks indicate significant differences (*p* < 0.05, *p* < 0.01) between woredas.

No.	Region	Wereda	Survival Rate All
1	Sidama	Bursa	94.6
2	Sidama	Bursa	94.6
3	Sidama	Bursa	95.5
4	Sidama	Bursa	96.3
5	Sidama	Bursa	93.2
6	Sidama	Bursa	95
7	Sidama	Bursa	43.2
8	Sidama	Bursa	95.5
9	Sidama	Bursa	98.2
10	Sidama	Bursa	77.5
11	Sidama	Bursa	96.4
12	Sidama	Bursa	93.2
13	Sidama	Bursa	65.3
14	Sidama	Bursa	95.9
15	Sidama	Bursa	97.3
16	Sidama	Bursa	95
17	Sidama	Bursa	95
18	Sidama	Bursa	93.2
19	Sidama	Bursa	96.4
20	Sidama	Bursa	96.4
21	Sidama	Bursa	94.1
22	Sidama	Bursa	95
23	Sidama	Bursa	97.7
24	Sidama	Bursa	99.5
25	Sidama	Bursa	97.7
26	Sidama	Bursa	91
27	Sidama	Bursa	94.1
28	Sidama	Bursa	93.2
29	Sidama	Bursa	94.6
30	Sidama	Bursa	95.9
31	Sidama	Bursa	96.8
32	Sidama	Bursa	99.1
33	Sidama	Bursa	96.4
34	Sidama	Bursa	95
35	Sidama	Bursa	91.9
36	Sidama	Bursa	95.9
37	Sidama	Bursa	91.9
38	Sidama	Bursa	95.5
39	Sidama	Bursa	94.6
40	Sidama	Bursa	95
41	Sidama	Bursa	94.6
42	Sidama	Bursa	55
43	Sidama	Bursa	93.7
44	Sidama	Bursa	93.7
45	Sidama	Bursa	73
46	Sidama	Bursa	96.4

Post-planting care: regression analysis

The regression model explained 68% of the variance in survival ($R^2 = 0.68$, $F = 23.4$, $p < 0.001$). Weeding effectiveness was the strongest predictor, with a full improvement associated with a 12.4 percentage point increase in survival ($p < 0.001$; Table 3). Moving from "ineffective" to "fully effective" weeding translates to approximately 25 percentage points survival gain. Disease presence reduced survival by about 10 points, and good mulching added about 9 points relative to fair condition.

Table 3. Regression coefficients for survival rate (%) (n = 66 plots)

Predictor	Unstandardised B	Std. error	Standardised β	p-value
Weeding effectiveness	+12.4	2.8	0.42	<0.001
Mulching condition	+8.7	2.2	0.31	<0.001
Protection condition	+6.1	2.3	0.22	0.010
Fertilisation applied (yes/no)	+5.2	2.1	0.18	0.016
Disease symptoms (yes)	–9.8	2.5	–0.29	<0.001

Early agroecological observations

By the second rainy season, rill and gully formation had ceased in most bamboo-dominant blocks. All 50 interviewed farmers (100%) adopted intercropping of potato and onion on previously fallow or unproductive land. Farmers adjacent to *M. ferruginea* hedgerows reported qualitatively greener leaves and larger bulbs than crops >5 m distant.

Biochar adoption and experimental results

Only 38% of interviewed farmers (19/50) had received or produced biochar; 18% accessed it through a hub. Biochar plots at four hubs showed yield increases of 22% (2.5 t ha^{-1}) and 31% (5 t ha^{-1}) over the control; soil pH rose from 5.2 (control) to 6.0 (2.5 t) and 6.4 (5 t) (unpublished hub trial data). Nine of ten Model Farmers trained peers in biochar pyrolysis. Among all interviewed farmers, 78%

reported trying biochar because they observed a neighbour's success.

Peer-to-peer learning and trust outcomes

The trust index rose significantly from 52.4 (SD = 12.1) at baseline to 88.2 (SD = 9.4) at final assessment — a 68% increase ($p < 0.001$, paired t-test). Key indicators are summarised in Table 4.

Table 4. Trust and peer-learning indicators (n = 50)

Indicator	% of respondents
Learned a new practice from a neighbour (not formal training)	90
Trust information from peer farmers more than external agents	84
Tried biochar because they observed a neighbour's success	78
Would not have adopted intercropping without multi-season peer observation	62
Regularly visit a Model Farmer's farm for informal advice	76

Immediate economic drivers

All farmers reported tangible benefits within the 22-month window (Table 5).

Table 5. Farmer-reported benefits (n = 50)

Benefit category	% of respondents	Illustrative quote (translated from Sidamigna)
Land reclamation (perceived)	94	"This land was useless for potato before. Now bamboo holds soil and I have food."
Fodder availability	82	"I cut mulberry every three days. My animals are healthier."
Reduced fertiliser cost	64	"Biochar and Birbra leaves mean I buy less DAP."
Perception of future value	100	"The trees are my bank account for my children."

Access to cooperative finance and inputs

Only 24% of farmers belonged to a cooperative with a revolving fund; 8% had received any external funding for agroforestry; and 38% had access to biochar (project monitoring data, April 2026).

Challenges to carbon finance viability

Per-hectare afforestation cost was USD 1,984 (range 1,900–2,150), 40–50% above regional benchmarks (TIST Kenya 2022; World Bank 2024). Infrastructure deficits and funding gaps are detailed in Table 6

Table 6. Key challenges to carbon finance additionality

Challenge category	Specific finding
Infrastructure deficit	72% of plots >2 hours' walk from an all-weather road; 65% had no mobile network; no cold storage for intercrops.
Per-hectare cost	Actual cost = USD 1,984 ha^{-1}; benchmarks: Kenya USD 1,200–1,400, Rwanda USD 1,300–1,500.
Lack of support funds	No donor/government co-financing; project reached only 60% of outreach target (830 vs. 1,400 farmers).

DISCUSSION

The high survival rates — 95% for bamboo and 91% for companions across 170 ha — confirm that the *Yushania alpina*-centred model is ecologically effective under smallholder management. The slightly lower survival of companion species reflects their different establishment requirements. Weeding effectiveness emerged as the most cost-effective management lever: a 25 percentage point survival gain can reduce replanting costs by approximately USD 300 ha^{-1}. The performance gap between Hula and Bursa illustrates that management quality, shaped by training and compliance, is as critical as species selection, underscoring the need for sustained local extension investment to meet carbon certification standards.

The 68% trust index increase and the overwhelming preference for peer information (84%) strongly align with

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diffusion of innovations theory (Rogers 2003). Where formal extension is weak, homophilous peer networks become primary adoption channels. The 78% biochar adoption through peer observation, despite only 38% access, shows that peer learning can partially overcome input barriers. Farmers who observed a neighbour's successful biochar trial—evidenced by greener crops, larger tubers, and improved soil texture—gained experiential knowledge that no formal training manual could replicate. This peer-based pathway proved particularly effective in the study area, where 84% of farmers reported trusting information from fellow farmers more than from external agents, and where 90% had learned a new practice from a neighbour outside of formal training. Unlike top-down extension, peer observation embeds information within a shared social and ecological context, making it immediately actionable and locally credible. Moreover, the low cost of peer dissemination—Model Farmers reached approximately 100 additional farmers at near-zero marginal cost—suggests that social learning can stretch scarce project resources further than conventional training alone (Krishnan 2014). Carbon projects should therefore budget peer-to-peer learning as a core activity, as it builds self-sustaining knowledge networks that reduce long-term monitoring costs and enhance permanence.

Biochar experimental plots demonstrated yield improvements and pH corrections consistent with findings in acidic tropical soils (Lehmann et al. 2011), yet access gaps are severe. Establishing a community biochar hub per 50 ha, linked to a cooperative-managed revolving fund, would simultaneously improve soil productivity, cut fertiliser costs, and strengthen farmer participation.

The per-hectare cost of USD 1,984 — 40–50% above regional benchmarks — threatens additionality. Carbon standards require that revenue is essential to overcome financial barriers; a structurally high cost base forces a higher credit price that may deter buyers. Poor roads, fragmented supply chains, and absent connectivity drive these costs, necessitating blended finance where governments or development banks co-invest in rural infrastructure. The project's 60% outreach shortfall, resulting from absent external funding, exemplifies the upfront investment trap of carbon finance. Catalytic grants from mechanisms like the Green Climate Fund or GIZ can help scale operations and lower unit costs, transforming temporary subsidies into long-term viability.

Carbon standards (Verra, Gold Standard, Plan Vivo) could strengthen permanence and equity by explicitly rewarding immediate co-benefits, introducing terrain-difficulty multipliers for high-cost highlands, and incorporating social capital indicators such as trust indices in verification protocols.

CONCLUSION

This preliminary study confirms that a *Yushania alpina*-centred agroforestry model achieves high survival (95% bamboo, 91% companion species) and strong early growth in the Ethiopian highlands. Structured peer-to-peer learning builds trust and drives practice adoption, while biochar hubs deliver tangible soil and yield benefits. However, carbon finance viability is constrained by per-hectare costs of USD 1,984, infrastructure deficits, and lack of external funding. Addressing these barriers requires blending finance, consolidating farmer plots into contiguous blocks to lower unit costs, formalising a Model Farmer network with a minimum of four demonstration sessions per year, establishing a biochar hub per 50 ha linked to cooperative finance, and securing government or development partner co-investment in roads and digital connectivity. Adaptive digital monitoring and regression-based field diagnostics can further improve plot-level survival and cost efficiency.

Conflict of Interest

The authors are employed by African Bamboo PLC, the implementing entity of the described intervention. This may constitute a potential conflict of interest. Independent verification of biophysical and financial outcomes is recommended.

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