

Evidence of Synergistic Associations between Integrated Conservation Agriculture and Agroforestry in Ethiopian Highland Smallholder Farming Systems

Tena Abdissa Abdissa

tenaabdissa99@gmail.com

Ethiopian Civil Service University <https://orcid.org/0009-0004-7100-0793>

Tena Abdissa Woldyes

Yimer - Mohammed

Andualem - Akililu

Research Article

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Title Page

Evidence of synergistic associations between integrated conservation agriculture and agroforestry in Ethiopian highland smallholder farming systems

Tena Abdissa Woldyes^{1*}, Yimer Mohammed¹, Andualem Akililu¹

¹ Ethiopian Public Service University, Addis Ababa, Ethiopia

* Corresponding author: Tena Abdissa Woldyes, Ethiopian Public Service University, Addis Ababa, Ethiopia. E-mail: tenaabdissa99@gmail.com

ORCID:

Cover Letter

Dear Editor-in-Chief,

I am pleased to submit our original research article entitled "Evidence of Synergistic Associations between Integrated Conservation Agriculture and Agroforestry in Ethiopian Highland Smallholder Farming Systems" for consideration in *Plant and Soil*.

While Conservation Agriculture (CA) is widely recognized as a sustainable intensification strategy, its performance in high-rainfall tropical environments remains inconsistent due to waterlogging, delayed soil warming, and residue competition. This study addresses this "performance paradox" by evaluating the integration of Agroforestry (AF) as a biologically grounded solution, and we believe it aligns closely with *Plant and Soil's* focus on advancing mechanistic understanding of plant-soil interactions.

The manuscript makes three contributions relevant to this scope. First, it provides field-based mechanistic evidence of root-mediated improvements to soil physical properties, including significantly higher saturated hydraulic conductivity, lower bulk density, and enhanced macroporosity under integrated CA-AF management, pointing to a plausible root-driven drainage pathway linking tree integration to alleviation of CA's waterlogging constraint. Second, using linear mixed-effects models, it quantifies statistical interactions between CA and AF, distinguishing quantitative overyielding, functional synergy, and efficiency stabilization effects on soil organic carbon, aggregate stability, and microbial biomass carbon outcomes central to plant-soil system functioning. Third, it situates these biophysical findings within the socio-ecological reality of smallholder systems, discussing residue competition trade-offs and institutional considerations for scaling ecological intensification.

Consistent with the cross-sectional design of this study, we present all findings as associations rather than causal effects, and we explicitly discuss the duration confound between conventional and CA-AF plots (Section 4.5) as a limitation to be resolved through future experimental trials.

We confirm that this manuscript is original, has not been published elsewhere, and is not under consideration by any other journal. All authors have approved the submission and declare no competing interests. A generative AI tool (Google Gemini) was used solely for language-clarity editing; all scientific content has been critically reviewed by the authors, who take full responsibility for it.

Sincerely,
Tena Abdissa Woldyes
Ethiopian Public Service University
Email: tenaabdissa99@gmail.com

Highlights

CA-AF raised soil organic carbon by 85% over conventional systems.
Significant CA x AF interaction for total ecosystem carbon ($b=22.4$).
Saturated hydraulic conductivity was 2.8x higher in CA-AF than CA-only.

CA-AF was a modeled net GHG sink (-8.64 Mg CO₂-eq ha⁻¹ yr⁻¹).
Despite 5.3 years under management, CA-AF showed highest SOC and MBC.

Abstract

Background and Aims Smallholder agriculture in the Ethiopian highlands faces converging land degradation and rainfall variability. Conservation Agriculture (CA) and Agroforestry (AF) are promoted independently, but evidence of their integrated biological synergy remains limited, particularly in high-rainfall environments where CA alone often underperforms. This study tested whether integrated CA-AF systems show synergistic associations with soil health and carbon outcomes exceeding single-practice effects.

Methods In a cross-sectional study of 410 households in East Wollega, plots were classified as conventional, CA-dominant, AF-dominant or integrated CA-AF (n = 102–103 each). We measured soil organic carbon (SOC) stock (0–20 cm), aggregate stability (mean weight diameter, MWD), microbial biomass carbon (MBC), saturated hydraulic conductivity (K_{sat}), bulk density and ecosystem carbon pools, and modeled net greenhouse gas (GHG) balance with the Cool Farm Tool. Linear mixed-effects models with a kebele random effect tested CA × AF interactions.

Results Integrated CA-AF had the highest SOC (41.2 ± 4.5 Mg C ha⁻¹), 84.8% above conventional plots and 2.6 Mg C ha⁻¹ (6.7%) above the additive expectation. Model-adjusted CA × AF interactions were positive for SOC, MWD and MBC (p < 0.01). K_{sat} was 2.8-fold higher, and bulk density lower, in CA-AF than in CA-only plots. Only CA-AF was a modeled net GHG sink (-8.64 Mg CO₂-eq ha⁻¹ yr⁻¹).

Conclusion Integrated CA-AF is associated with mechanistic improvements in plant-soil interactions warranting experimental evaluation for ecological intensification in high-rainfall tropical smallholder systems.

Keywords: *Conservation Agriculture, Agroforestry, Synergy, Soil Organic Carbon, Ecological Intensification, Waterlogging*

Abbreviations

AF, agroforestry; AGB, above-ground biomass; ANOVA, analysis of variance; BD, bulk density; BGB, below-ground biomass; CA, conservation agriculture; CFT, Cool Farm Tool; CRGE, Climate Resilient Green Economy; CV, coefficient of variation; DBH, diameter at breast height; DEFF, design effect; GHG, greenhouse gas; HSD, honestly significant difference; ICC, intraclass correlation coefficient; IPCC, Intergovernmental Panel on Climate Change; Ksat, saturated hydraulic conductivity; LMM, linear mixed-effects model; MBC, microbial biomass carbon; MWD, mean weight diameter; PSM, propensity score matching; R:S, root: shoot ratio; SD, standard deviation; SOC, soil organic carbon; VIF, variance inflation factor

1 Introduction

1.1 Background

Global agriculture faces interlinked crises of land degradation, climate variability and the need for sustainable intensification (FAO 2023; IPCC 2022). Conventional intensification based on intensive tillage, monocropping and high external inputs has contributed to soil degradation, biodiversity loss and increased greenhouse gas (GHG) emissions (Foley et al. 2005; Rockström et al. 2017).

Conservation agriculture (CA), founded on minimum soil disturbance, permanent soil cover and crop diversification, is a widely promoted sustainable intensification strategy (Kassam et al. 2019). However, syntheses indicate that crop and soil responses to CA are context dependent and often less favorable in humid environments, where waterlogging, delayed soil warming and nitrogen immobilization can offset its benefits (Corbeels et al. 2020; Giller et al. 2015; Pittelkow et al. 2015; Vanlauwe et al. 2015). This is a potential constraint in parts of the Ethiopian highlands, where annual rainfall exceeds 1800 mm (Section 2.1).

Agroforestry (AF), the intentional integration of trees into agricultural landscapes, delivers well-documented benefits for carbon sequestration and biodiversity (Kuyah et al. 2019; Muthuri et al. 2023), although adoption can be limited by delayed economic returns and insecure land tenure (Miller et al. 2020). Trees may also modify soil hydrology, organic inputs and microbial habitat, which suggest that AF could complement CA where CA alone underperforms.

To our knowledge, few studies have compared four farming-system types (conventional, CA-only, AF-only and integrated CA-AF) while formally testing CA $\times$ AF interactions on soil organic carbon (SOC), aggregate stability (mean weight diameter, MWD) and microbial biomass carbon (MBC) under Ethiopian highland conditions. We used a cross-sectional observational design, which permits tests of association but not causal inference (Section 2.2). Our objectives were to (i) compare SOC, MWD, MBC, saturated hydraulic conductivity (Ksat), bulk density (BD) and ecosystem carbon pools among the four systems; (ii) test whether CA $\times$ AF interactions exceed the additive expectation; and (iii) compare modeled net GHG balance among systems.

1.2 Theoretical framework and hypotheses

Integrating CA and AF is hypothesized to create complementary resource-use dynamics. Tree litter could ease the residue competition that limits soil cover under CA by providing an alternative mulch (Giller et al. 2015), and combining trees with crops is consistent with agroecological transitions that seek several ecological functions at once (Isaac et al. 2024). Most critically for high-rainfall environments, deep-rooted trees may offset the drainage penalty of CA by creating macropores that enhance infiltration. On this basis we tested three hypotheses. The quantitative overyielding hypothesis (H1) proposed that integrated CA-AF would show higher SOC and total ecosystem carbon than the additive expectation from CA-only and AF-only plots. The functional synergy hypothesis (H2) proposed that CA $\times$ AF interaction terms in linear mixed-effects models (LMMs) would be positive for SOC, MWD and MBC after controlling for environmental covariates. The efficiency synergy hypothesis (H3) proposed that CA-AF would show more stable carbon storage, reflected in a lower coefficient of variation (CV) and a higher MBC-to-SOC ratio than CA-only and AF-only systems.

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2 Materials and methods

2.1 Study area

The study was conducted in Sibu Sire and Diga districts (woredas) of East Wollega Zone, Oromia Region, Ethiopia (9°00'–9°45' N, 36°00'–37°00' E; Fig. 1). The area has a subtropical highland climate (Köppen Cwb), mean annual rainfall of 1800–2300 mm and elevations of 1500–2300 m above sea level. Dominant soils are Nitisols (~60%) and Luvisols (~35%). The mixed farming system is dominated by maize (*Zea mays* L.) as the main annual crop, and coffee (*Coffea arabica* L.) is an important perennial cash crop at lower elevations (1500–1800 m). Land-use change and soil degradation have been documented in neighboring parts of Wollega (Adugna and Abegaz 2016).

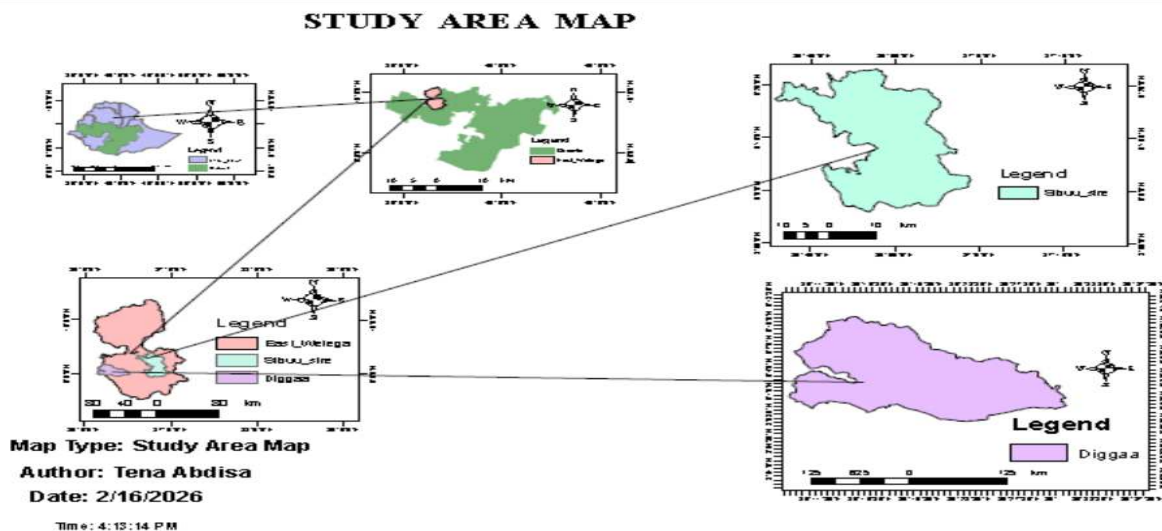


Fig. 1 Location of the study area in Sibu Sire and Diga districts (woredas), East Wollega Zone, Oromia Region, Ethiopia

2.2 Sampling design and farming-system classification

This study used a cross-sectional observational design rather than a randomized experiment. All reported relationships are therefore statistical associations, and causal interpretation is not warranted without experimental validation (Section 4.6). A multistage stratified purposive sampling design was used. After reconnaissance survey and field verification, 410 households from eight kebeles (the smallest administrative units) were classified into four mutually exclusive farming-system types with an adherence protocol (Online Resource 1). Adherence scores (0–10) were assigned for CA (tillage, soil cover, crop diversity) and for AF (tree density, arrangement, functional diversity). The systems were Conventional ($n = 102$, CA score < 6 and AF score < 6), CA-dominant ('CA-only', $n = 102$; CA score ≥ 6 and AF score < 6), AF-dominant ('AF-only'; $n = 103$; CA score < 6 and AF score ≥ 6) and integrated CA-AF ($n = 103$; CA score ≥ 6 and AF score ≥ 6). One plot per household, the main maize plot, was sampled.

An a priori power analysis (G*Power 3.1) for a one-way analysis of variance (ANOVA) with four groups, a medium effect size ($f = 0.25$), $\alpha = 0.05$ and power = 0.80 indicated a required total sample of 180 households, which the nominal sample ($n = 410$) exceeds. However, multistage sampling induces clustering at kebele level, so the effective sample size is smaller. The design effect (DEFF) was calculated as $DEFF = 1 + (m - 1) \times \rho$, where m is the mean cluster size (51.25 households per kebele) and ρ is the intraclass correlation coefficient (ICC) for SOC from the null model ($\rho = 0.12$). This gives $DEFF = 1 + (51.25 - 1) \times 0.12 = 7.03$ and an effective sample size of $n(eff) = 410/7.03 \approx 58$. At this effective sample size, power of 0.80 is reached only for large effects (Cohen's $f \approx 0.45$). The differences reported below are large, but estimates of smaller effects, and of non-primary outcomes, are correspondingly imprecise. We did not compute cluster-robust or ICC-adjusted confidence intervals for every outcome; the primary outcomes (SOC, MWD and MBC) were re-estimated after propensity score matching (PSM) as a partial check (Section 3.8).

2.3 Biological Characterization and Carbon Accounting

2.3.1 Edaphic Sampling and Laboratory Analysis

Composite soil samples were collected from sampled household's main maize plot using a five-point sampling approach at 0–20 cm depth with a stainless-steel auger (5 cm diameter). The five subsamples were composited into one plot-level sample, air-dried, ground and passed through a 2 mm sieve. SOC was determined by dry combustion with an Elementar vario MAX CN analyzer. SOC concentration (g kg^{-1}) was converted to SOC stock (Mg C ha^{-1}) using bulk density (g cm^{-3}) measured on undisturbed core samples (5 cm diameter, three replicates per plot) and the sampled depth (cm):

$$SOC\ stock = SOC\ concentration \times BD \times depth \times 0.1 \quad (1)$$

Aggregate stability was assessed as MWD following the wet-sieving procedure of Kemper and Rosenau (1986).

Field-moist soil (50 g) was placed on nested sieves (4.75, 2.00, 1.00, 0.50 and 0.25 mm) and oscillated in water at 30 cycles min^{-1} for 30 min. MWD was calculated as:

$$\sum \frac{(\bar{x}_i \times w_i)}{\sum w_i} \quad (2)$$

Where $\bar{x}_i$ is the mean diameter of sieve fraction i (mm) and w_i is the mass retained (g). Microbial biomass carbon (MBC) was determined by chloroform fumigation–extraction (Vance et al. 1987). Field-moist soil (10 g) was fumigated with ethanol-free chloroform for 24 h, with paired non-fumigated samples as controls. Both sets were extracted with 0.5 M K₂SO₄ and analyzed on a Shimadzu TOC-L analyzer:

$$MBC = \frac{(C_{fumigated} - C_{non-fumigated})}{0.45} \quad (3)$$

To examine soil-physical properties potentially linked to drainage, K_{sat} and BD were also measured. K_{sat} was determined by the constant-head method on undisturbed cores (7.5 cm diameter × 7.5 cm height, three replicates per plot):

$$K_{sat} = \frac{Q \cdot L}{A \cdot \Delta H \cdot t} \quad (4)$$

Where Q is the volume of water collected (cm³), L is the core length (cm), A is the cross-sectional area (cm²), ΔH is the hydraulic head difference (cm) and t is time (s); values (cm s⁻¹) were converted to mm h⁻¹ (1 cm s⁻¹ = 36,000 mm h⁻¹). BD was calculated from the same type of core as $BD = \frac{M_d}{V}$, where M_d is oven-dry soil mass (g) and V is core volume (cm³).

2.3.2 Tree biomass carbon

Within a 10 m × 10 m quadrat per plot, all trees with a diameter at breast height (DBH) > 5 cm were measured. Above-ground biomass (AGB, kg dry matter per tree) and below-ground biomass (BGB) were estimated with allometric equations for East African agricultural landscapes (Kuyah et al. 2012a, b): $AGB = 0.0905 \times DBH^{2.4718}$ and $BGB = 0.048 \times DBH^{2.303}$, with DBH in cm. Carbon stock was calculated as biomass × 0.47, the default of the Intergovernmental Panel on Climate Change (IPCC) for tropical tree species (IPCC 2019).

2.3.3 Litter carbon

Surface litter was collected from 0.25 m² quadrats (three per plot), oven-dried at 65 °C to constant mass, ground and analyzed for organic carbon by dry combustion.

2.3.4 Crop biomass carbon (shoots and roots)

Above-ground crop biomass at harvest was collected from 2 m × 2 m subplots (three per main plot), oven-dried at 65 °C and weighed to give shoot dry matter. Shoot carbon (Mg C ha⁻¹) was shoot biomass × 0.45 (IPCC 2019). Root carbon was estimated with species-specific root:shoot (R:S) ratios from tropical syntheses: maize (*Zea mays* L.; >85% of cultivated area), R:S = 0.20 ± 0.05 (Bolinder et al. 2007; IPCC 2019 Tier 2 defaults), and associated legumes (34% of CA-AF plots; *Phaseolus vulgaris* L. and *Vicia faba* L.), R:S = 0.18 (Seidel et al. 2024):

$$Root\ C = shoot\ biomass \times R:S \times 0.45 \quad (5)$$

$$Total\ crop\ biomass\ C = shoot\ biomass \times 0.45 \times (1 + R:S) \quad (6)$$

To verify the maize R: S assumption, roots were sampled destructively on a subset of plots (n = 15 per farming system). Measured R: S averaged 0.18 ± 0.04 (Conventional), 0.21 ± 0.05 (CA-only), 0.19 ± 0.04 (AF-only) and

0.22 ± 0.05 (CA-AF); the overall mean was 0.20 ± 0.05, with no significant difference among systems ($F = 1.24$, $p = 0.29$), supporting a constant R: S ratio across systems.

2.3.5 Total ecosystem carbon

Total ecosystem carbon (Mg C ha⁻¹) was calculated as the sum of above-ground and below-ground tree carbon, SOC (0–20 cm), litter carbon and crop shoot and root carbon.

2.3.6 GHG inventory and chamber check

Net GHG emissions were estimated with the Cool Farm Tool (CFT) v2.0 parameterized with local management data. As a partial check, soil CO₂ fluxes were measured with static closed chambers on a stratified subsample of 84 plots (21 per farming system) during the post-rainy season (November–December 2024). Chamber CO₂ flux was moderately correlated with CFT estimates (Pearson's $r = 0.78$, $n = 84$, $p < 0.001$), with a slight underestimation bias (−0.18 Mg CO₂-eq ha⁻¹ yr⁻¹). Chamber measurements cover one season and soil CO₂ only, and CH₄ and N₂O were not measured directly; chamber data therefore serve only as a qualitative check of CO₂ flux patterns, and CFT outputs are reported as modeled estimates with unquantified uncertainty. Because CFT sequestration terms depend on the tree inputs supplied (density, species, size), modelled net balances are partly determined by those inputs by construction. Chamber CO₂ flux (F) was calculated as:

$$F = \frac{K}{t} \ln \left(\frac{C_0 - C_1}{C_0 - C_2} \right) \quad (7)$$

Where K is the chamber constant, t is deployment time, and C_0 , C_1 , and C_2 are CO₂ concentrations measured at equal time intervals.

2.4 Data analysis

2.4.1 Statistical modeling and interaction analysis

LMMs were fitted with the lme4 package in R (Bates et al. 2015). The hierarchical structure (households nested within kebeles) was accommodated with nested random effects:

$$Y_{ijk} = \beta_0 + \beta_1(CA) + \beta_2(AF) + \beta_3(CA \times AF) + \beta_4(Time) + \sum \beta_n X_{nijk} + uk + vjk + \varepsilon_{ijk} \quad (8)$$

Where Y_{ijk} is the outcome, CA and AF are binary indicators for each practice ($CA = 1$ for CA-only and CA-AF; $AF = 1$ for AF-only and CA-AF), $CA \times AF$ is their interaction, X_n are covariates (elevation, slope, soil texture, land-holding size) and $Time$ is years under the current system; uk , vjk and ε_{ijk} are kebele-level, household-level and residual terms. Because each household contributed one plot, the household-level variance cannot be separated from residual variance for single-plot outcomes. ICCs were calculated to quantify variance attributable to kebele-level clustering. Convergence was verified with the Nelder–Mead optimizer with restarts, gradient and Hessian checks showed no convergence warnings. A positive β_3 ($p < 0.05$) was interpreted as statistical synergy, meaning that the joint association exceeded the sum of the individual associations, and not as evidence of a causal mechanism.

2.4.2 Synergy classification

Interactions were evaluated along three complementary dimensions. (i) Quantitative overyielding was defined as the observed CA-AF mean exceeding the additive expectation (CA-only + AF-only – Conventional). In a 2×2 factorial coding this unadjusted deviation is identical to the unadjusted interaction contrast, (CA-AF – CA-only) – (AF-only – Conventional). (ii) Functional synergy was assessed from the sign and significance of the covariate-adjusted β_3 in the LMMs. (iii) Efficiency stabilization was assessed as lower CV of SOC and a higher MBC:SOC ratio in CA-AF than in single-practice systems; because CV falls mechanically as the mean rises, this dimension is interpreted cautiously. In interpreting the results we regarded synergy as supported for an outcome only when the unadjusted contrast and the adjusted β_3 agreed in sign.

2.4.3 Model Validation, Diagnostic Testing, and Statistical Precision

Data are presented as mean $\pm$ standard deviation (SD) unless stated otherwise. Model assumptions were checked with Shapiro–Wilk and Levene’s tests. Multicollinearity was assessed with variance inflation factors (VIF; retention threshold < 5). Marginal R^2 (fixed effects) and conditional R^2 (fixed plus random effects) were calculated following Nakagawa and Schielzeth (2013). Tukey’s honestly significant difference (HSD) test was used for pairwise comparisons among systems in Tables 1–6 and 8.

3 Results

3.1 Descriptive characteristics of sample plots

Farming systems were balanced for key biophysical covariates (Online Resource 2): plot area (0.64–0.76 ha), elevation (1845–1912 m), slope (11.8–13.2%) and Nitisol share (56.9–62.1%) did not differ significantly among systems ($p > 0.05$ for all). The only significant difference was years under the current system: Conventional (18.6 ± 12.4 years) $>$ AF-only (6.8 ± 3.4) $>$ CA-AF (5.3 ± 2.6) $>$ CA-only (4.2 ± 2.1) ($F = 78.45$, $p < 0.001$). This difference was included as the ‘Time’ covariate in all LMMs and is treated as a limitation in Section 4.5.

3.2 Soil health

3.2.1 Soil organic carbon

SOC differed significantly among farming systems ($F = 32.67$, $p < 0.001$). Integrated CA-AF had the highest SOC (41.2 ± 4.5 Mg C ha $^{-1}$), followed by AF-only (31.2 ± 4.1), CA-only (29.7 ± 3.8) and Conventional (22.3 ± 3.5) (Table 1, Fig. 2). SOC under CA-AF was 84.8% higher than Conventional, 38.7% higher than CA-only and 32.1% higher than AF-only. CA-only and AF-only did not differ significantly ($p = 0.089$), but both exceeded Conventional ($p = 0.001$). The CV was lowest for CA-AF (10.9%).

Table 1 Soil organic carbon (SOC) by farming system (0–20 cm depth)

Farming system	<i>n</i>	SOC (Mg C ha $^{-1}$)	Range	CV (%)	vs. Conventional
Conventional	102	22.3 ± 3.5^a	15.2–31.8	15.7	—
CA-only	102	29.7 ± 3.8^b	21.4–39.2	12.8	+33.2%
AF-only	103	31.2 ± 4.1^b	22.8–42.6	13.1	+39.9%
Integrated CA-AF	103	41.2 ± 4.5^c	31.4–51.8	10.9	+84.8%

Values are mean $\pm$ SD. Different superscript letters indicate significant differences at $p < 0.05$ (Tukey HSD). CA, conservation agriculture; AF, agroforestry; CV, coefficient of variation

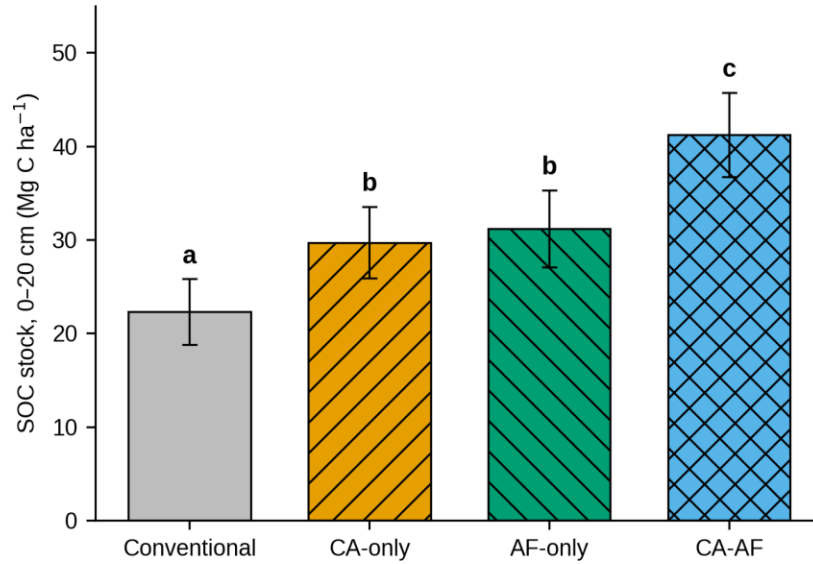


Fig. 2 Soil organic carbon (SOC) stock (0–20 cm) by farming system. Bars are means and error bars are SD; different letters indicate significant differences (Tukey HSD, $p < 0.05$). CA, conservation agriculture; AF, agroforestry

3.2.2 Aggregate stability (MWD)

MWD showed the strongest differentiation among systems ($F = 52.34$, $p < 0.001$): CA-AF (1.96 ± 0.22 mm) > CA-only (1.42 ± 0.18) > AF-only (1.18 ± 0.15) > Conventional (0.71 ± 0.12) (Table 2, Fig. 3). All pairwise differences were significant ($p < 0.01$). MWD in CA-AF was about 2.8-fold that of Conventional, 38% higher than CA-only and 66% higher than AF-only. MWD was strongly correlated with SOC across plots (Pearson's $r = 0.82$, $p < 0.001$); each 1 Mg C ha⁻¹ increase in SOC was associated with a 0.023 mm increase in MWD (95% CI 0.020–0.026).

Table 2 Aggregate stability (mean weight diameter, MWD) by farming system

Farming system	<i>n</i>	MWD (mm)	Range	CV (%)	vs. Conventional
Conventional	102	0.71 ± 0.12^a	0.48–1.02	16.9	—
CA-only	102	1.42 ± 0.18^b	1.05–1.88	12.7	+100%
AF-only	103	1.18 ± 0.15^c	0.85–1.56	12.7	+66.2%
Integrated CA-AF	103	1.96 ± 0.22^d	1.52–2.48	11.2	+176%

Values are mean $\pm$ SD. Different superscript letters indicate significant differences at $p < 0.01$ (Tukey HSD)

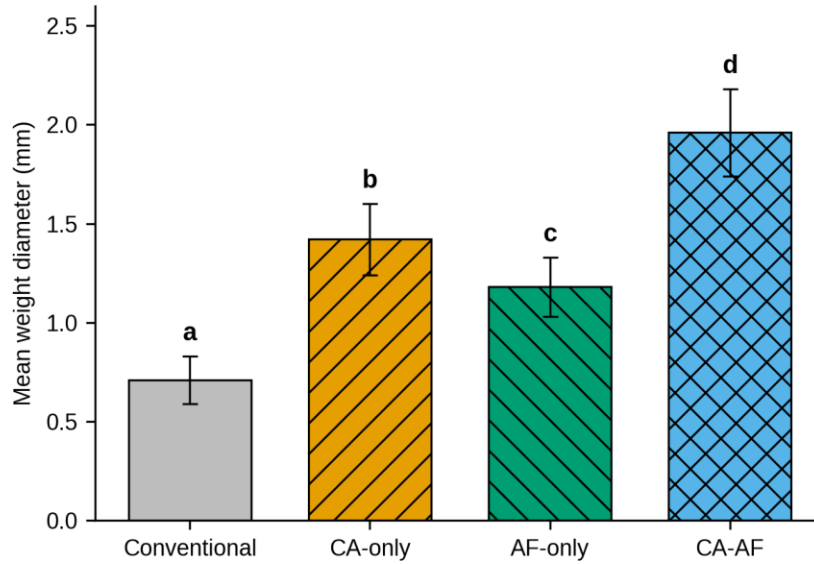


Fig. 3 Aggregate stability (mean weight diameter) by farming system. Bars are means and error bars are SD; different letters indicate significant differences (Tukey HSD, $p < 0.01$)

3.2.3 Microbial biomass carbon

MBC varied significantly among systems ($F = 48.67$, $p < 0.001$): CA-AF ($412 \pm 45 \mu\text{g g}^{-1}$) > CA-only (298 ± 41) > AF-only (267 ± 38) > Conventional (161 ± 34) (Table 3, Fig. 4). MBC under CA-AF was 156% higher than Conventional, 38% higher than CA-only and 54% higher than AF-only. MBC was strongly correlated with SOC ($r = 0.78$, $p < 0.001$) and MWD ($r = 0.74$, $p < 0.001$).

Table 3 Microbial biomass carbon (MBC) by farming system

Farming system	<i>n</i>	MBC ($\mu\text{g g}^{-1}$)	Range	CV (%)	vs. Conventional
Conventional	102	161 ± 34^a	98–242	21.1	—
CA-only	102	298 ± 41^b	215–398	13.8	+85.1%
AF-only	103	267 ± 38^c	185–356	14.2	+65.8%
Integrated CA-AF	103	412 ± 45^d	325–512	10.9	+156%

Values are mean $\pm$ SD. Different superscript letters indicate significant differences at $p < 0.001$ (Tukey HSD)

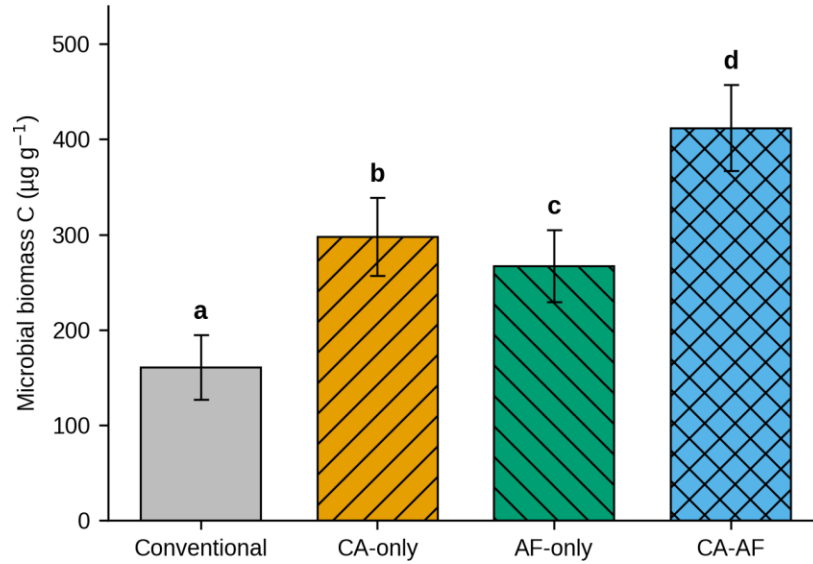


Fig. 4 Microbial biomass carbon by farming system. Bars are means and error bars are SD; different letters indicate significant differences (Tukey HSD, $p < 0.001$)

3.3 Ecosystem carbon storage

Total ecosystem carbon differed significantly among systems ($F = 38.92$, $p < 0.001$; Table 4, Fig. 5). CA-AF stored 2.56 times as much total ecosystem carbon as Conventional (199.0 vs. 77.6 Mg C ha^{-1}), 1.53 times as much as CA-only (130.3) and 1.32 times as much as AF-only (150.9). Crop biomass carbon contributed 34.4% of total ecosystem carbon in CA-AF, compared with 40.5% (Conventional), 53.8% (CA-only) and 34.3% (AF-only). Annual crop biomass is a seasonal pool, so total ecosystem carbon is best read together with the tree and soil pools.

Table 4 Ecosystem carbon pools by farming system (Mg C ha^{-1})

Carbon pool	Conventional	CA-only	AF-only	Integrated CA-AF
Above-ground tree biomass C	18.3 ± 4.2^a	22.5 ± 4.8^a	52.7 ± 8.9^b	68.9 ± 10.2^c
Below-ground tree biomass C	4.8 ± 1.2^a	5.9 ± 1.4^a	13.8 ± 2.5^b	18.1 ± 2.8^c
Soil organic C (0–20 cm)	22.3 ± 3.5^a	29.7 ± 3.8^b	31.2 ± 4.1^b	41.2 ± 4.5^c
Litter C	0.8 ± 0.3^a	2.1 ± 0.6^b	1.4 ± 0.5^c	2.3 ± 0.7^b
Crop biomass C (shoots + roots)	31.4 ± 5.6^a	70.1 ± 8.9^b	51.8 ± 7.2^c	68.5 ± 8.4^b
Total ecosystem C	77.6 ± 10.5^a	130.3 ± 12.8^b	150.9 ± 14.2^c	199.0 ± 15.6^d

Values are mean $\pm$ SD. Different superscript letters within a row indicate significant differences at $p < 0.05$ (Tukey HSD)

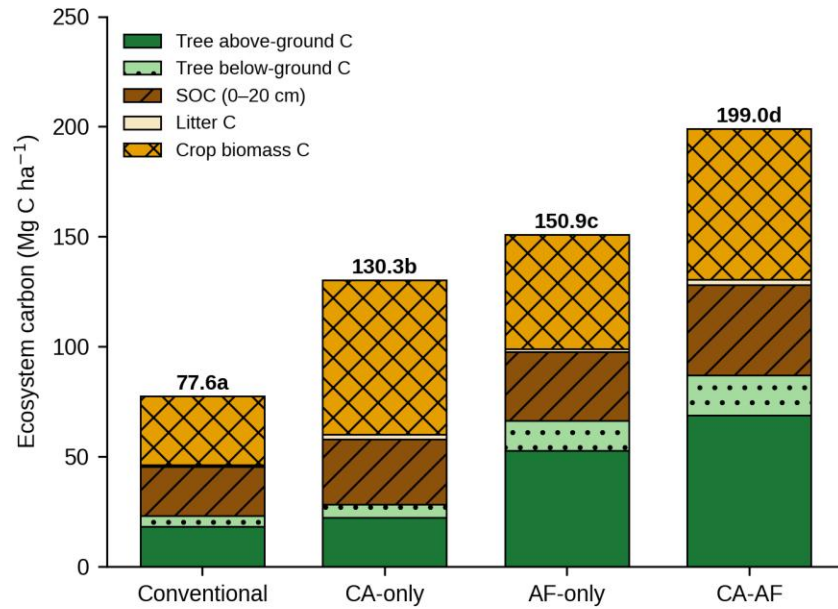


Fig. 5 Ecosystem carbon pools by farming system. Stacked segments show mean pool sizes; numbers above bars give total ecosystem carbon with Tukey letters ($p < 0.05$)

3.4 Hydraulic conductivity and bulk density: soil-physical evidence related to drainage

We measured Ksat and BD to examine soil-physical properties potentially relevant to waterlogging (Table 5). Ksat differed markedly among systems, with the highest values in CA-AF (34.6 mm h⁻¹), 2.8-fold that of CA-only (12.4 mm h⁻¹), 2.2-fold that of AF-only (15.8 mm h⁻¹) and 4.2-fold that of Conventional (8.2 mm h⁻¹). BD was lowest in CA-AF (1.18 g cm⁻³). Macroporosity in CA-AF (22.4%) was more than twice that under CA-only (10.2%). The observed CA-AF Ksat also exceeded the additive expectation ($12.4 + 15.8 - 8.2 = 20.0$ mm h⁻¹), although this interaction was not formally tested. These patterns are consistent with deep-rooted woody perennials in CA systems promoting stable structural macropores. However, water-table depth, redox potential and crop performance were not measured, so we cannot confirm that this mechanism operates or that waterlogging is alleviated (Sections 4.2 and 4.6).

Table 5 Soil physical properties potentially related to waterlogging, by farming system

Property	Conventional	CA-only	AF-only	Integrated CA-AF
Ksat (mm h ⁻¹)	8.2 ± 2.4 ^a	12.4 ± 3.1 ^b	15.8 ± 3.6 ^c	34.6 ± 5.2 ^d
Bulk density (g cm ⁻³)	1.34 ± 0.08 ^a	1.28 ± 0.07 ^b	1.31 ± 0.08 ^{ab}	1.18 ± 0.06 ^c
Macroporosity (%)	8.4 ± 2.1 ^a	10.2 ± 2.4 ^a	12.6 ± 2.8 ^b	22.4 ± 3.4 ^c

Values are mean ± SD. Different superscript letters within a row indicate significant differences at $p < 0.01$ (Tukey HSD). Ksat, saturated hydraulic conductivity

3.5 Greenhouse gas emissions

Modeled net GHG emissions differed significantly among systems ($F = 22.45$, $p < 0.001$; Table 6, Fig. 6). When sequestration was included, CA-AF was the only system with a modeled net sink (-8.64 ± 2.3 Mg CO₂-eq ha⁻¹ yr⁻¹; CFT estimate, see Section 2.3.6 for the chamber check). This is within the broad range of values summarized for

tropical agroforestry (Kim et al. 2016; Mutuo et al. 2005; Nair et al. 2009), although system boundaries differ among studies. AF-only was a weak modeled sink (-1.32 ± 1.1), whereas CA-only ($+2.19 \pm 0.8$) and Conventional ($+5.67 \pm 1.2$) remained modeled net sources.

Table 6 Modelled net GHG emissions by farming system ($\text{Mg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$; Cool Farm Tool estimates)

GHG component	Conventional	CA-only	AF-only	Integrated CA-AF
Gross total	5.67 ± 1.2^a	3.89 ± 0.9^b	4.68 ± 1.1^c	2.84 ± 0.7^d
Sequestration total	0	-1.7 ± 0.5	-6.0 ± 1.4	-11.48 ± 2.5
Net emissions	$+5.67 \pm 1.2^a$	$+2.19 \pm 0.8^b$	-1.32 ± 1.1^c	-8.64 ± 2.3^d

Values are mean $\pm$ SD. Different superscript letters within a row indicate significant differences at $p < 0.001$. Negative values indicate a modelled net carbon sink

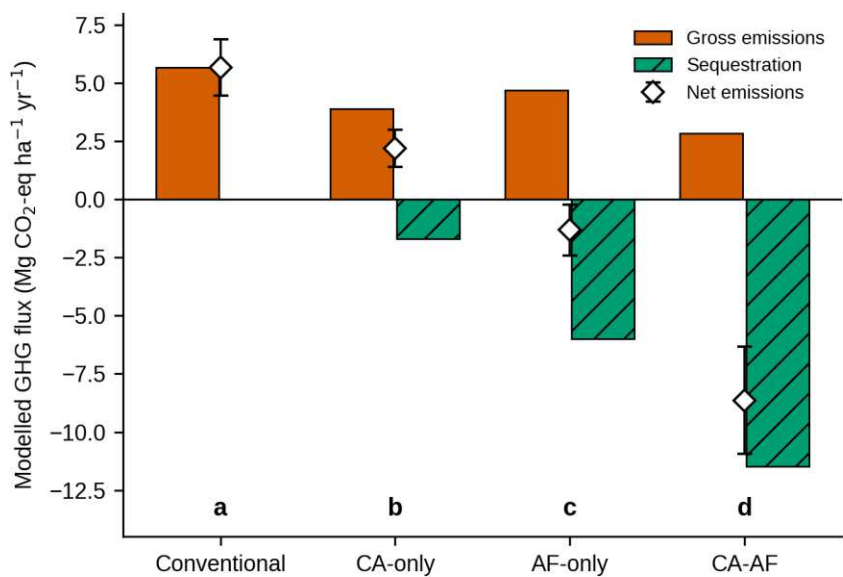


Fig. 6 Modelled gross emissions, sequestration and net GHG balance by farming system (Cool Farm Tool). Diamonds show net emissions (mean $\pm$ SD); letters refer to net emissions (Tukey HSD, $p < 0.001$). CO₂-eq, carbon dioxide equivalent

3.6 Synergy analysis

LMMs tested CA $\times$ AF interactions while controlling for soil type, slope, elevation, time since adoption and land-holding size (Table 7). The model-adjusted interaction coefficient (β_3) was positive and significant for SOC ($p < 0.001$), MWD ($p < 0.001$) and MBC ($p < 0.01$). For total ecosystem carbon β_3 was positive but only marginally significant ($p < 0.05$), and for modeled net GHG balance it was negative (that is, a larger sink than additive; $p < 0.001$). The adjusted β_3 estimates for SOC, MWD and MBC were larger than the unadjusted contrasts calculated from group means (Table 7), so the magnitude of the interaction depends on model specification; we therefore regard its direction as more reliable than its size. For total ecosystem carbon the unadjusted contrast was negative ($-4.6 \text{ Mg C ha}^{-1}$), disagreeing in sign with the adjusted estimate, and we do not consider synergy supported for this outcome. Modeled GHG results are treated as descriptive because they depend on the inputs supplied to the CFT.

Table 7 Linear mixed-effects model results for CA × AF interaction effects

Outcome	CA	AF	CA × AF (adjusted β_3)	Unadjusted contrast	R ² (marg./co nd.)	Interpretation
SOC (Mg C ha ⁻¹)	7.42*** (1.28)	8.93*** (1.35)	7.84*** (1.88)	2.6	0.45/0.69	Overyielding (+6.7%); positive β_3
MWD (mm)	0.71*** (0.08)	0.47*** (0.09)	0.54*** (0.12)	0.07	0.52/0.74	Overyielding (+3.7%); positive β_3
MBC ($\mu\text{g g}^{-1}$)	137*** (18.2)	106*** (19.4)	78.3** (26.8)	8.0	0.48/0.70	Overyielding (+2.0%); positive β_3
Total ecosystem C (Mg C ha ⁻¹)	46.2*** (6.8)	69.9*** (7.2)	22.4* (9.8)	-4.6	0.51/0.72	Not supported (unadjusted contrast negative)
Net GHG (Mg CO ₂ -eq ha ⁻¹ yr ⁻¹)	-1.78*** (0.52)	-2.22*** (0.56)	-1.34*** (0.38)	-3.84	0.42/0.61	Larger modelled sink than additive (descriptive)

Values are coefficients with standard errors in parentheses. Significance from Wald tests on coefficient/standard error: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Unadjusted contrast = (CA-AF - CA-only) - (AF-only - Conventional), from Tables 1–4 and 6. Models controlled for time since adoption, soil type, elevation, slope and land-holding size

Under H3, CV of SOC was lowest in CA-AF (10.9%, versus 12.8–15.7% in the other systems; Table 1), although this partly reflects its higher mean. The MBC: SOC ratio was reported as highest in CA-AF (1.00%), compared with CA-only (0.92%), AF-only (0.86%) and Conventional (0.72%), indicating a larger share of SOC in the living microbial pool

3.7 Quantitative overyielding

The additive expectation for SOC ($29.7 + 31.2 - 22.3 = 38.6$ Mg C ha⁻¹) was exceeded by the observed CA-AF value (41.2 Mg C ha⁻¹), a 6.7% overyielding (+2.6 Mg C ha⁻¹). For MWD the additive expectation ($1.42 + 1.18 - 0.71 = 1.89$ mm) was exceeded by the observed 1.96 mm (+3.7%), and for MBC the expectation ($298 + 267 - 161 = 404$ $\mu\text{g g}^{-1}$) was exceeded by the observed 412 $\mu\text{g g}^{-1}$ (+2.0%). For total ecosystem carbon the additive expectation ($130.3 + 150.9 - 77.6 = 203.6$ Mg C ha⁻¹) was not reached by CA-AF (199.0 Mg C ha⁻¹; -2.3%), mainly because crop biomass carbon was lower in CA-AF than in CA-only (68.5 vs. 70.1 Mg C ha⁻¹). Thus H1 was supported for SOC but not for total ecosystem carbon. The overyielding was small relative to the differences among systems: most of the SOC difference between CA-AF and Conventional reflects the additive contributions of CA and AF rather than their interaction.

3.8 Robustness checks

PSM was used to address potential selection bias. After matching CA-AF plots ($n = 103$) with matched controls ($n = 103$), covariates were balanced (standardized mean differences < 0.10). LMMs re-estimated on the matched sample gave interaction coefficients consistent with the full sample: SOC $\beta = 6.54$ ($p < 0.001$), MWD $\beta = 0.49$ ($p < 0.001$)

and MBC $\beta = 72.1$ ($p < 0.001$). Observed selection on measured covariates therefore does not fully account for the associations, but selection on unmeasured factors is not ruled out, and balance on time since adoption is constrained by the lack of short-duration Conventional plots (Section 4.5). Sensitivity analyses using winsorization (values above the 95th percentile) and removal of extreme outliers changed coefficients by less than 5%, and Kruskal–Wallis tests agreed with the ANOVA results (e.g. $\chi^2 = 52.3$, $p < 0.001$ for MBC).

3.9 Vegetation diversity

Vegetation diversity differed significantly among farming systems ($p < 0.001$), with tree-integrated systems (AF-only and CA-AF) showing the greatest complexity (Table 8, Fig. 7). CA-AF had a Shannon index (H') of 2.34, 163% higher than Conventional and 65% higher than CA-only. Species richness and Shannon diversity did not differ significantly between AF-only and CA-AF ($p > 0.05$), so adding CA practices did not reduce the diversity of agroforestry plots. Woody species richness was nine times higher in CA-AF (10.8 ± 2.8) than in Conventional plots (1.2 ± 0.8). Nitrogen-fixing taxa (Fabaceae) made up 38.2% of taxa in CA-AF. Taxa tentatively identified as potential nitrogen fixers included *Acacia abyssinica* Hochst. ex Benth., *Albizia gummifera* (J.F.Gmel.) C.A.Sm., *Leucaena leucocephala* (Lam.) de Wit (where planted) and *Sesbania sesban* (L.) Merr. Because active nitrogen fixation was not confirmed (e.g. nodule scoring or $\delta^{15}\text{N}$), the 38.2% figure represents taxonomic potential rather than functional nitrogen fixation.

Table 8 Vegetation diversity indicators by farming system

Indicator	Conventional	CA-only	AF-only	Integrated CA-AF
Species richness	5.6 ± 1.8^a	9.3 ± 2.4^b	17.8 ± 3.1^c	18.4 ± 3.2^c
Shannon index (H')	0.89 ± 0.18^a	1.42 ± 0.21^b	2.28 ± 0.26^c	2.34 ± 0.28^c
Evenness (J')	0.53 ± 0.12^a	0.72 ± 0.15^b	0.89 ± 0.18^c	0.91 ± 0.19^c
Woody species richness	1.2 ± 0.8^a	1.8 ± 1.1^a	9.6 ± 2.4^b	10.8 ± 2.8^b
Nitrogen-fixing taxa (%)	8.2 ± 3.1^a	12.4 ± 4.2^b	34.6 ± 6.8^c	38.2 ± 7.1^c
Deep-rooted species (%)	3.4 ± 1.5^a	6.7 ± 2.3^b	28.4 ± 5.6^c	32.1 ± 6.2^c

Values are mean $\pm$ SD. Different superscript letters within a row indicate significant differences at $p < 0.05$ (Tukey HSD)

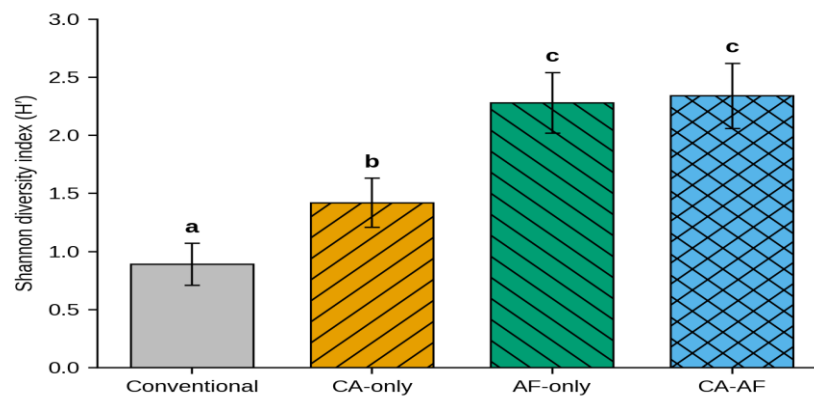


Fig. 7 Shannon diversity index (H') by farming system. Bars are means and error bars are SD; different letters indicate significant differences (Tukey HSD, $p < 0.05$)

4 Discussion

4.1 Associations between integrated CA-AF and soil health

This observational study from Ethiopian smallholder systems shows that integrated CA-AF is associated with higher SOC, aggregate stability and microbial biomass than either practice alone. The direction of the CA $\times$ AF interaction was positive for SOC, MWD and MBC, in agreement with our hypothesis, but the overyielding relative to the additive expectation was modest (2.0–6.7%; Section 3.7). Most of the 84.8% SOC difference between CA-AF and Conventional therefore reflects the individual associations of CA (+33.2%) and AF (+39.9%) added together. The SOC value in CA-AF (41.2 Mg C ha⁻¹) is above the 20–40% increases reported for AF alone in Ethiopian systems (Mekuria and Aynekulu 2021), but this cross-sectional comparison cannot establish a recovery trajectory.

MWD in CA-AF (1.96 mm) lies between the arable-land and grassland values reported for South African Highveld soils by Lobe et al. (2011), although differences in soil type and sieving protocol limit direct comparison. The strong SOC–MWD correlation ($r = 0.82$) is consistent with organic matter acting as a primary binding agent for aggregates (Six and Paustian 2014; Tisdall and Oades 1982). The higher MBC in CA-AF (+156% relative to Conventional) is consistent with greater organic-substrate supply and a more favorable habitat for soil biota, and MBC is widely used as an indicator of soil biological condition (Lehmann et al. 2020). The MBC: SOC ratio should be interpreted with caution (Section 3.6).

4.2 Potential mechanisms underlying the observed associations

Drainage and macropores. Ksat was 2.8-fold higher and macroporosity more than twice as high in CA-AF as in CA-only plots, and Ksat in CA-AF exceeded the additive expectation. Tree roots can create stable biopores and improve infiltration; for example, intermediate tree cover maximized groundwater recharge in seasonally dry West Africa (Ilstedt et al. 2016), and active plant biomass inputs influenced pore-system functioning in Brazilian no-till soils (Hernandez Gamboa et al. 2023). These studies are from different climates and soils, and none tests waterlogging in Ethiopian Nitisols, which are usually well drained. Our data are consistent with a root-mediated pathway to better drainage but do not demonstrate it.

Organic inputs and aggregation. Tree litter and root turnover add organic substrates that can increase aggregate-associated carbon and microbial activity (Six and Paustian 2014; Tisdall and Oades 1982). In Malawian maize systems, *Gliricidia sepium* (Jacq.) Walp. intercropping increased soil organic matter fractions (Beedy et al. 2010), which is consistent with the higher SOC, MWD and MBC in tree-integrated plots.

Microclimate and residue use. Canopy shading could moderate soil temperature and microbial respiration, and tree litter or pruning could reduce competition for crop residues under CA (Giller et al. 2015). We did not measure soil temperature, moisture, residue use or decomposition, so these pathways remain hypotheses.

Alternative explanations. Farmers who combine CA and trees may differ from others in land quality, land-use history, labor or management skill, and trees may have been retained on better soils. Tree canopies may also influence where soil samples were taken. These possibilities cannot be separated from the mechanisms above in a cross-sectional design.

Direct measurements of water-table depth, redox potential and root-zone oxygen were not collected, so the Ksat and macroporosity results do not by themselves show that waterlogging is alleviated. Future work should pair soil physical measurements with in situ hydrologic monitoring and yield data during high-rainfall periods.

4.3 Comparison with regional and global studies

SOC in CA-AF ($41.2 \text{ Mg C ha}^{-1}$ at 0–20 cm) is within the ranges reported for East African agroforestry ($30\text{--}60 \text{ Mg C ha}^{-1}$; Kuyah et al. 2019) and Ethiopian highland agroforestry ($30\text{--}94 \text{ Mg C ha}^{-1}$; Mekuria and Aynekulu 2021). Dividing the SOC difference between CA-AF and Conventional ($18.9 \text{ Mg C ha}^{-1}$) by the mean CA-AF duration (5.3 years) gives an apparent rate of about $3.6 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$. Comparable rates have been reported for the restoration of severely degraded land, such as grazing exclosures in northern Ethiopia (about $3 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ over 0–30 cm; Noulékoun et al. 2021), which is a much stronger intervention than the practices compared here. This apparent rate is therefore more plausibly explained, at least in part, by pre-existing differences among plots than by accumulation under CA-AF (Section 4.5). The modelled net GHG sink ($-8.64 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$) is comparable in magnitude to values summarized for tropical agroforestry (Kim et al. 2016; Mutuo et al. 2005; Nair et al. 2009), although it is driven largely by the tree sequestration term.

Evidence on CA–AF interactions from sub-Saharan Africa is scarce. Mulimbi et al. (2023) reported short-term benefits of CA in smallholder systems in the Democratic Republic of the Congo. Our study adds an observational comparison of four system types for SOC, aggregate stability, microbial biomass and hydraulic properties, with the design limitations stated in Section 4.6.

4.4 Implications for soil health and climate mitigation

Total ecosystem carbon in CA-AF exceeded that in Conventional by $121.4 \text{ Mg C ha}^{-1}$, although CA-AF plots averaged 5.3 years under the current system versus 18.6 years for Conventional plots. Because baseline carbon stocks at adoption were not measured, this difference cannot be attributed to accumulation under CA-AF; part probably reflects pre-existing variation in site conditions, for example higher initial soil carbon or tree cover on plots where farmers adopted CA-AF. Tree carbon in particular ($87.0 \text{ Mg C ha}^{-1}$ above and below ground in CA-AF) must pre-date the current management, and ‘years under the current system’ is not tree age. Longitudinal studies with baseline measurements are needed to quantify sequestration rates.

The modeled net sink in CA-AF ($-8.64 \pm 2.3 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$), compared with net sources under CA-only ($+2.19 \pm 0.8$) and Conventional ($+5.67 \pm 1.2$), suggests that tree integration, rather than CA alone, drives net climate benefits in these estimates. CA-only reduced gross emissions relative to Conventional, but its modeled sequestration (-1.7) did not offset them, whereas the larger tree-biomass term in CA-AF (-11.48) produced a net sink. Pending experimental confirmation, integrated CA-AF may merit consideration as a candidate carbon sequestration option within Ethiopia’s Climate Resilient Green Economy (CRGE) strategy. We stop short of a policy recommendation given the observational design and the modeled nature of the GHG estimates.

4.5 Duration confounding

A key limitation is the difference in management duration among groups: Conventional plots (18.6 ± 12.4 years) had markedly longer histories than CA-AF plots (5.3 ± 2.6 years). The cross-sectional design cannot fully separate

management effects from temporal or selection effects, for three reasons. First, no Conventional plots with short duration (< 8 years) exist in the sample, which prevents duration-matched comparisons. Second, time since adoption was included as a covariate in all LMMs, but this controls only for linear duration effects, not for non-linear trajectories or unmeasured history. Third, farmers who adopted CA-AF may have had systematically different baseline soil conditions. The PSM re-estimation (Section 3.8) shows that observed covariates do not explain the associations away, but it cannot rule out selection on unobserved factors. The magnitude of the carbon differences should therefore be read as suggestive of a strong association rather than as a demonstrated treatment effect, and the shorter duration of CA-AF plots should not be taken as evidence of rapid recovery.

4.6 Limitations

- *Observational design.* Models control for measured confounders, but farmer skill, land-use history and land quality could influence results. Causal inference requires long-term experimental trials, and all findings should be read as associations.
- *Duration confound and space-for-time inference.* Conventional plots averaged 18.6 years under management versus 5.3 years for CA-AF; reverse causality and selection cannot be excluded (Section 4.5).
- *Clustering and precision.* Plots were clustered in eight kebeles ($DEFF = 7.03$; $n(eff) \approx 58$). With so few clusters, variance among kebeles is imprecisely estimated, and confidence intervals for non-primary outcomes are not cluster-robust (Section 2.2).
- *Single time point and shallow SOC sampling.* One sampling occasion cannot capture seasonal dynamics or equilibrium SOC levels, and SOC was measured only to 20 cm at a fixed depth rather than on an equivalent-soil-mass basis (Ellert and Bettany 1995); lower BD in CA-AF may make this comparison conservative, but deeper carbon dynamics may differ.
- *Drainage mechanism not measured.* No water-table, redox, soil-moisture or waterlogging data, and no yield data, were collected, so the drainage interpretation rests on Ksat, BD and macroporosity alone. Crop yield was not systematically recorded, and the trade-off between soil improvement and productivity, which determines smallholder viability, should be a priority for future work.
- *GHG modeling.* CFT estimates correlated moderately with chamber CO_2 measurements ($r = 0.78$), but the chamber data cover one season and soil CO_2 only; CH_4 and N_2O were not measured, and modeled sequestration depends on tree inputs. Year-round direct flux measurements would strengthen conclusions.
- *Ecosystem carbon accounting.* Annual crop biomass carbon is a transient pool that contributes 34–54% of total ecosystem carbon; pool-specific results (SOC, tree carbon) are more informative than the total.
- *Generalizability.* The study covered two districts; replication in other agroecological zones is needed.

5 Conclusions

This observational study from Ethiopian smallholder systems shows that integrated CA-AF is associated with higher SOC, aggregate stability, microbial biomass and hydraulic conductivity than CA or AF alone. Quantitative overyielding relative to the additive expectation was small but positive for SOC (41.2 vs. 38.6 Mg C ha⁻¹, +6.7%),

MWD (1.96 vs. 1.89 mm, +3.7%) and MBC (412 vs. 404 $\mu\text{g g}^{-1}$, +2.0%), and adjusted CA $\times$ AF interactions were positive for these three outcomes. For total ecosystem carbon there was no overyielding (199.0 vs. 203.6 Mg C ha⁻¹, -2.3%), and synergy is not supported.

Ksat was 2.8-fold higher in CA-AF than in CA-only plots, which is consistent with, but not direct proof of, a mechanism by which deep-rooted trees and reduced tillage interact to improve drainage and aeration and possibly to offset the waterlogging limitation of CA-only systems in high-rainfall environments. CA-AF was also the only system classified as a modeled net carbon sink (-8.64 Mg CO₂-eq ha⁻¹ yr⁻¹), largely through the tree sequestration term.

Because Conventional plots had substantially longer management histories than CA-AF plots and the design is cross-sectional, these findings cannot demonstrate causality. Long-term experimental or longitudinal trials with baseline measurements, direct hydrologic monitoring and yield data are needed to confirm the associations, resolve the duration confound and establish whether integrated CA-AF should be prioritized over CA-only or AF-only interventions for soil restoration and climate mitigation in sub-Saharan African highlands.

Supplementary information

Online Resource 1 (ESM_1.pdf): Adherence protocol and scoring rubric used to classify households into Conventional, CA-only, AF-only and integrated CA-AF systems. Online Resource 2 (ESM_2.pdf): Descriptive characteristics and covariate balance among farming systems (plot area, elevation, slope, soil type, years under the current system).

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References

- Adugna A, Abegaz A (2016) Effects of land use changes on the dynamics of selected soil properties in northeast Wellega, Ethiopia. *SOIL* 2:63–70. <https://doi.org/10.5194/soil-2-63-2016>
- Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. *J Stat Softw* 67:1–48. <https://doi.org/10.18637/jss.v067.i01>
- Beedy TL, Snapp SS, Akinnifesi FK, Sileshi GW (2010) Impact of *Gliricidia sepium* intercropping on soil organic matter fractions in a maize-based cropping system. *Agric Ecosyst Environ* 138:139–146
- Bolinder MA, Janzen HH, Gregorich EG, Angers DA, VandenBygaart AJ (2007) An approach for estimating net primary productivity and annual carbon inputs to soil for common agricultural crops in Canada. *Agric Ecosyst Environ* 118:29–42
- Corbeels M, Naudin K, Whitbread AM, Kühne R, Letourmy P (2020) Limits of conservation agriculture to overcome low crop yields in sub-Saharan Africa. *Nat Food* 1:447–454. <https://doi.org/10.1038/s43016-020-0114-x>
- Ellert BH, Bettany JR (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Can J Soil Sci* 75:529–538
- FAO (2023) The state of food and agriculture 2023: revealing the true cost of food to transform agrifood systems. FAO, Rome
- Foley JA, DeFries R, Asner GP et al (2005) Global consequences of land use. *Science* 309:570–574. <https://doi.org/10.1126/science.1111772>
- Giller KE, Andersson JA, Corbeels M et al (2015) Beyond conservation agriculture. *Front Plant Sci* 6:870. <https://doi.org/10.3389/fpls.2015.00870>
- Hernandez Gamboa C, Coutinho Figueiredo G, Machado Vezzani F, Carenhatto Ferreira F, Bayer C (2023) Active plant biomass inputs influence pore system functioning in no-till soils. *Geoderma* 434:116477
- Ilstedt U, Bargués Tobella A, Bazié HR et al (2016) Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. *Sci Rep* 6:21930. <https://doi.org/10.1038/srep21930>
- IPCC (2019) 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. IPCC, Geneva
- IPCC (2022) Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
- Isaac ME, Sinclair F, Laroche G, Olivier A, Thapa A (2024) The ties that bind: how trees can enhance agroecological transitions. *Agrofor Syst* 98:2369–2383
- Kassam A, Friedrich T, Derpsch R (2019) Global spread of conservation agriculture. *Int J Environ Stud* 76:29–51
- Kemper WD, Rosenau RC (1986) Aggregate stability and size distribution. In: Klute A (ed) *Methods of soil analysis, part 1*, 2nd edn. American Society of Agronomy, Madison, pp 425–442
- Kim D-G, Kirschbaum MUF, Beedy TL (2016) Carbon sequestration and net emissions of CH₄ and N₂O under agroforestry: synthesizing available data and suggestions for future studies. *Agric Ecosyst Environ* 226:65–78
- Kuyah S, Dietz J, Muthuri C, Jamnadass R, Mwangi P, Coe R, Neufeldt H (2012a) Allometric equations for estimating biomass in agricultural landscapes: I. Aboveground biomass. *Agric Ecosyst Environ* 158:216–224

- Kuyah S, Dietz J, Muthuri C, Jamnadass R, Mwangi P, Coe R, Neufeldt H (2012b) Allometric equations for estimating biomass in agricultural landscapes: II. Belowground biomass. *Agric Ecosyst Environ* 158:225–234
- Kuyah S, Whitney CW, Jonsson M, Sileshi GW, Öborn I, Muthuri CW, Luedeling E (2019) Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. *Agron Sustain Dev* 39:47. <https://doi.org/10.1007/s13593-019-0589-8>
- Lehmann J, Bossio DA, Kögel-Knabner I, Rillig MC (2020) The concept and future prospects of soil health. *Nat Rev Earth Environ* 1:544–553. <https://doi.org/10.1038/s43017-020-0080-8>
- Lobe I, Sandhage-Hofmann A, Brodowski S, Du Preez CC, Amelung W (2011) Aggregate dynamics and associated soil organic matter contents as influenced by prolonged arable cropping in the South African Highveld. *Geoderma* 162:251–259
- Mekuria W, Aynekulu E (2021) Soil organic carbon stocks under agroforestry and exclosure lands in the highlands of Ethiopia. *Geoderma* 385:114–125
- Miller DC, Ordoñez PJ, Brown SE, Forrest S, Nava NJ, Hughes K, Baylis K (2020) The impacts of agroforestry on agricultural productivity, ecosystem services, and human well-being in low- and middle-income countries: an evidence and gap map. *Campbell Syst Rev* 16:e1066. <https://doi.org/10.1002/cl2.1066>
- Mulimbi W, Brye KR, Nalley LL, Birindwa DR (2023) Conservation agriculture assists smallholder farmers and their agroecosystem in the Democratic Republic of the Congo. *Agric Ecosyst Environ* 355:108597
- Muthuri CW, Kuyah S, Njenga M, Kuria A, Öborn I, Van Noordwijk M (2023) Agroforestry's contribution to livelihoods and carbon sequestration in East Africa: a systematic review. *Trees For People* 14:100432
- Mutuo PK, Cadisch G, Albrecht A, Palm CA, Verchot L (2005) Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. *Nutr Cycl Agroecosyst* 71:43–54. <https://doi.org/10.1007/s10705-004-5285-6>
- Nair PKR, Kumar BM, Nair VD (2009) Agroforestry as a strategy for carbon sequestration. *J Plant Nutr Soil Sci* 172:10–23
- Nakagawa S, Schielzeth H (2013) A general and simple method for obtaining R^2 from generalized linear mixed-effects models. *Methods Ecol Evol* 4:133–142. <https://doi.org/10.1111/j.2041-210x.2012.00261.x>
- Noulékoun F, Birhane E, Kassa H et al (2021) Grazing exclosures increase soil organic carbon stock at a rate greater than “4 per 1000” per year across agricultural landscapes in Northern Ethiopia. *Sci Total Environ* 782:146821. <https://doi.org/10.1016/j.scitotenv.2021.146821>
- Pittelkow CM, Liang X, Linquist BA et al (2015) Productivity limits and potentials of the principles of conservation agriculture. *Nature* 517:365–368. <https://doi.org/10.1038/nature13809>
- Rockström J, Williams J, Daily G et al (2017) Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio* 46:4–17. <https://doi.org/10.1007/s13280-016-0793-6>
- Seidel SJ, Ahmadi SH, Weihermüller L et al (2024) The overlooked effects of environmental impacts on root:shoot ratio in experiments and soil-crop models. *Sci Total Environ* 955:176738
- Six J, Paustian K (2014) Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. *Soil Biol Biochem* 68:A4–A9. <https://doi.org/10.1016/j.soilbio.2013.06.014>

- Tisdall JM, Oades JM (1982) Organic matter and water-stable aggregates in soils. *J Soil Sci* 33:141–163.
<https://doi.org/10.1111/j.1365-2389.1982.tb01755.x>
- Vance ED, Brookes PC, Jenkinson DS (1987) An extraction method for measuring soil microbial biomass C. *Soil Biol Biochem* 19:703–707. [https://doi.org/10.1016/0038-0717\(87\)90052-6](https://doi.org/10.1016/0038-0717(87)90052-6)
- Vanlauwe B, Descheemaeker K, Giller KE et al (2015) Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *SOIL* 1:491–508. <https://doi.org/10.5194/soil-1-491-2015>

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request. Household survey responses cannot be shared publicly because of confidentiality restrictions.

Use of AI tools A generative AI tool (Gemini, Google) was used only for language-clarity editing of author-drafted text. All content was reviewed by the authors, who take full responsibility for the final text.