

Beyond the Binary: A Multinomial Logit and Mixed-Methods Analysis of the Determinants of Integrated Conservation Agriculture–Agroforestry Adoption among Smallholder Farmers in East Wollega Zone, Ethiopia

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Abstract

Conservation agriculture (CA) and agroforestry (AF) are widely promoted as complementary pathways to sustainable land management in smallholder Africa, yet most adoption studies treat uptake as a binary choice, obscuring the progressive way farmers actually combine practices. This study examined the determinants of integrated CA-AF adoption among 410 smallholder households in East Wollega Zone, Oromia Region, Ethiopia, using an explanatory sequential mixed-methods design. Households were classified into conventional non-adopters ($n = 118$), partial adopters ($n = 173$), and integrated CA-AF adopters ($n = 119$). A multinomial logistic regression model, complemented by average marginal effects (AMEs) and a Two-Stage Residual Inclusion (2SRI) robustness check, was estimated alongside thematic analysis of 16 focus group discussions and 64 key informant interviews ($n = 144$). Institutional factors exerted the strongest influence on integrated adoption: land tenure security ($\text{AME} = 0.112, p < 0.01$), training participation ($\text{AME} = 0.098, p < 0.01$), and extension contact ($\text{AME} = 0.030, p < 0.01$). Human capital (education, household size), resource endowments (landholding, livestock), and biophysical stressors (severe erosion, steep slopes) were also significant. Female-headed households showed higher unconditional integrated-adoption propensity but derived significantly smaller returns from extension contact ($\text{Gender} \times \text{Extension } \beta = -0.184, p < 0.05$), pointing to service-delivery rather than motivational barriers. Qualitative narratives corroborated and enriched these findings, revealing labour, residue-livestock, and tenure-related trade-offs underlying the statistical patterns. The study contributes a three-stage adoption-pathway framework, evidence for institutional complementarity over isolated interventions, and gender-responsive extension design implications for accelerating sustainable land management in smallholder farming systems.

Highlights

- Household adoption of conservation agriculture–agroforestry (CA-AF) follows a three-stage pathway – conventional, partial, and integrated – rather than a binary decision.
- Institutional variables (tenure security, training, extension, credit, cooperative membership) exert the largest marginal effects on integrated adoption.
- Gender shapes adoption both directly and through a significant negative $\text{Gender} \times \text{Extension}$ interaction, indicating unequal service delivery rather than lower willingness among women.
- Severe soil erosion and steep slopes act as environmental thresholds that catalyse integrated adoption, while moderate slopes do not.
- A 2SRI robustness check finds no evidence of endogeneity in extension contact, supporting the stability of the multinomial logit estimates.

1. Introduction

Land degradation, declining soil fertility, and increasingly variable rainfall continue to undermine smallholder productivity across sub-Saharan Africa, prompting sustained policy interest in conservation agriculture (CA) and agroforestry (AF) as complementary land management responses (Lee & Gambiza, 2022). CA – built on minimum soil disturbance, permanent soil cover, and crop diversification – and AF – the deliberate integration of trees into cropping and livestock systems – are conceptually distinct but agronomically synergistic: residue retention under CA improves the microclimate for tree establishment, while AF supplies the biomass, shade, and nutrient cycling that CA systems depend on over time. Despite this complementarity, most empirical adoption research still analyses CA and AF as separate, single-practice decisions (Mohammed & Yimam, 2025; Lejissa et al., 2023), and even fewer studies model the joint, integrated adoption of both systems using a framework that distinguishes partial from full integration.

This gap matters because CA adoption in the smallholder tropics has persistently underperformed expectations. Two decades of promotion notwithstanding, CA uptake and retention in southern and eastern Africa remain low and geographically patchy, and a substantial critical literature has emerged questioning whether the technology package, as promoted, is agronomically and economically compatible with smallholder resource constraints (Giller et al., 2009; Corbeels et al., 2020; Descheemaeker et al., 2020). Corbeels et al. (2020), for instance, showed that the yield benefits of CA in sub-Saharan Africa are frequently overstated in the short to medium term, particularly where residue retention conflicts with livestock feed requirements – a tension this study's qualitative evidence independently reproduces. Lee and Gambiza's (2022) scoping review of CA adoption barriers in the Southern African Development Community similarly concludes that smallholder farmers are not a homogenous population and that uniform CA packages routinely fail to accommodate heterogeneous labour, tenure, and livestock circumstances. Risk and time preferences add a further behavioural layer: using panel data from Zambia, recent work finds that impatience and risk aversion independently suppress the extent and intensity of CA adoption, even after controlling for standard socioeconomic covariates (Chapoto et al., 2024, as reported in PMC evidence syntheses of Zambian smallholder CA panels). These critiques imply that adoption should be modelled not as a single yes/no decision but as a graded, multi-stage process shaped by the interaction of household capacity and institutional support – the premise this study adopts.

Ethiopia offers a particularly instructive setting for this question. National and regional extension systems have promoted CA and AF components – often as separate packages – for over a decade, and recent Ethiopian evidence continues to report highly heterogeneous adoption outcomes depending on how each package intersects with household assets and institutions. In Oromia's Welmera district, Hailu and Abate (2023) found that livestock ownership strongly promotes CA adoption while financial-service access is the stronger predictor for AF and crop diversification specifically – an early empirical signal that CA and AF may respond to different determinants when modelled separately. In the Sidaama Region, Lankamo et al. (2025) similarly report that climate-smart agriculture uptake, including AF, is shaped jointly by education, extension contact, and household asset endowments, but note persistent inconsistencies in effect sizes across studies (echoing Diro et al., 2022; Sisay et al., 2023). In

southwestern Ethiopia, Lejissa et al. (2023) modelled the binary CA adoption decision using nine household covariates and found extension access and livestock ownership dominant, while a companion study of the same zone linked CA adoption to tangible livelihood gains (Gebeyehu, 2023). Parallel agroforestry-specific research finds that socio-economic drivers of AF adoption diverge sharply by context: Mohammed and Yimam (2025) report that livestock ownership promotes AF adoption in Legambo district while larger landholdings and higher education paradoxically depress it, a finding that appears to contradict the resource-endowment logic more commonly reported for CA. This divergence across the CA and AF literatures — where the same variable (e.g., livestock or education) can carry opposite signs depending on which single practice is modelled — is precisely the ambiguity that an integrated, multinomial adoption-pathway framework is positioned to resolve, since it allows the same household characteristics to be evaluated simultaneously against partial and fully integrated adoption outcomes.

A second, cross-cutting gap concerns institutional access, and specifically gender. Ethiopian and broader African evidence consistently documents that women-headed households receive systematically less extension contact and lower-quality technical support than male-headed households, independent of their underlying interest in improved practices (Ragasa et al., as summarised in ESSP Working Paper 49; Ambler et al., 2022, in the North Shewa gender-technology-adoption evidence). FAO's (2023) global synthesis on gender and agrifood systems similarly finds that closing the extension and asset gap — rather than simply increasing aggregate extension volume — is the binding constraint on women's technology adoption. Yet most quantitative CA-AF adoption models in Ethiopia include gender only as an additive control, foreclosing analysis of whether institutional returns themselves are gendered. Finally, land tenure security is repeatedly identified as a first-order determinant of long-term conservation investment across the wider sustainable-land-management literature (Byamugisha & Dubosse, 2023), yet cross-sectional adoption studies rarely test whether this relationship is robust to the potential endogeneity of institutional variables such as extension contact.

This study addresses these three gaps by (i) modelling adoption as a three-category outcome — conventional non-adoption, partial adoption, and integrated CA-AF adoption — using multinomial logistic regression with average marginal effects; (ii) explicitly testing gender-differentiated returns to institutional support through interaction terms and likelihood ratio tests; and (iii) triangulating the econometric results with thematic analysis of 144 qualitative participants and a Two-Stage Residual Inclusion (2SRI) robustness check for potential endogeneity in extension contact. In doing so, the study contributes a replicable three-stage adoption-pathway framework and gender-responsive institutional evidence relevant to CA-AF scaling efforts across the Ethiopian highlands and comparable smallholder settings in sub-Saharan Africa.

1.1 Objectives and hypotheses

The specific objective was to identify and explain the determinants of partial and integrated CA-AF adoption relative to conventional farming among smallholder households in East Wollega Zone. Guided

by the literature reviewed above, the study tested the following expectations: (H1) human capital and resource endowments are positively associated with integrated adoption; (H2) institutional support variables – tenure security, training, extension, credit, and cooperative membership – exert the largest marginal effects among all covariate groups; (H3) gender moderates the returns to institutional support, such that female-headed households benefit less from a given unit of extension contact than male-headed households; and (H4) biophysical stress (severe erosion, steep slopes) is positively associated with integrated adoption, consistent with a threshold-response model of farmer behaviour.

2. Materials and Methods

2.1 Study area and research design

The study was conducted in East Wollega Zone, Oromia Region, Ethiopia, an area characterised by smallholder mixed crop-livestock production under heterogeneous socioeconomic and biophysical conditions. An explanatory sequential mixed-methods design was employed (Creswell & Plano Clark, 2018): a cross-sectional household survey and multinomial logit analysis were conducted first, followed by qualitative data collection designed to explain and contextualise the statistical results. Because the design is cross-sectional, findings are interpreted as robust statistical associations rather than as direct evidence of causal effects.

2.2 Sampling and adoption classification

A total of 410 households were surveyed and classified into three mutually exclusive adoption categories based on a structured adoption-scoring protocol: conventional non-adopters, practising neither CA nor AF components ($n = 118$); partial adopters, practising one or more CA or AF components without full integration ($n = 173$); and integrated CA-AF adopters, combining CA principles with AF components ($n = 119$). This categorisation formed the trichotomous dependent variable for the multinomial logistic regression (MNL) model.

2.3 Econometric specification

The MNL model was specified with conventional non-adopters as the reference category ($j = 0$), partial adopters as $j = 1$, and integrated adopters as $j = 2$. Explanatory variables spanned four domains – demographic/human capital, resource endowments, institutional access, and biophysical conditions – plus five gender interaction terms (Gender $\times$ Age, $\times$ Landholding, $\times$ Training, $\times$ Tenure Security, $\times$ Extension), selected on conceptual grounds and prior empirical evidence. Variables with high missingness, conceptual overlap, or that represented adoption-practice components rather than independent determinants (e.g., plough frequency, cropping pattern) were excluded a priori. Multicollinearity was assessed via variance inflation factors (VIF) and contingency coefficients; all VIFs fell below 1.5 (mean = 1.24, maximum = 1.42), well under the conservative threshold of 5.0. Average marginal effects (AMEs) were computed to express coefficients as probability changes. A likelihood

ratio test compared the restricted model (no gender interactions) against the full model to assess whether gender-differentiated effects improved model fit.

2.4 Robustness: Two-Stage Residual Inclusion (2SRI)

Because extension contact is plausibly endogenous to unobserved farmer motivation, a 2SRI instrumental-variable procedure was applied, using distance to the nearest Development Agent office (kilometres) as the excluded instrument. Relevance was assessed via the first-stage F-statistic (Staiger & Stock, 1997 criterion of $F > 10$); exogeneity rests on the assumption that, conditional on observed covariates, distance to the extension office affects adoption only through its effect on contact frequency, and not directly.

2.5 Qualitative data collection and analysis

Thematic content analysis was conducted on transcripts from 144 purposively sampled participants, comprising 16 focus group discussions (80 participants) and 64 key informant interviews, stratified across male- and female-headed households and adoption categories. Coding followed an inductive-deductive hybrid approach, with themes cross-validated against the quantitative results in a joint display (Table 8) following the integration procedures recommended by Creswell and Plano Clark (2018).

2.6 Ethical considerations

Informed consent

was obtained from all participants prior to data collection; participation was voluntary, and confidentiality was maintained through anonymised household and participant identifiers throughout data processing and reporting.

3. Results

3.1 Descriptive characteristics of the adoption categories

Table 1 summarises household characteristics across the three adoption categories. Integrated CA-AF adopters were significantly younger (45.9 ± 10.2 years) than conventional non-adopters (55.4 ± 11.8 years; $F = 18.42$, $p < 0.001$), had larger households (6.1 vs. 4.4 members), larger landholdings (4.72 vs. 2.85 ha), and substantially greater institutional access – more than three times the extension contact frequency (5.6 vs. 1.8 visits/year) and nearly double the cooperative membership rate (89.1% vs. 45.8%) of conventional non-adopters. Insecure land tenure was most prevalent among conventional non-adopters (61.9%) and least prevalent among integrated adopters (26.1%).

Table 1

Descriptive summary of household characteristics by adoption category (N = 410). Values are mean $\pm$ SD or %. Continuous variables tested by one-way ANOVA (F); categorical variables tested by Pearson's χ^2 . *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$. Full variable list (19 items) available in the online supplementary material.

Variable	Full Sample (N = 410)	Conventional (n = 118)	Partial (n = 173)	Integrated (n = 119)	Test stat.	p-value
Age of head (yrs)	50.9 $\pm$ 12.3	55.4 $\pm$ 11.8	51.2 $\pm$ 11.5	45.9 $\pm$ 10.2	F = 18.42	< 0.001
Male-headed (%)	79.5	68.6	81.5	87.4	$\chi^2=14.82$	0.001
Primary education (%)	57.1	38.1	61.3	69.7	$\chi^2=26.14$	< 0.001
Household size	5.3 $\pm$ 1.2	4.4 $\pm$ 1.1	5.4 $\pm$ 1.2	6.1 $\pm$ 1.3	F = 14.22	< 0.001
Landholding (ha)	3.75 $\pm$ 1.52	2.85 $\pm$ 1.15	3.68 $\pm$ 1.42	4.72 $\pm$ 1.64	F = 28.14	< 0.001
Livestock (TLU)	7.53 $\pm$ 1.60	6.42 $\pm$ 1.35	7.65 $\pm$ 1.52	8.45 $\pm$ 1.72	F = 16.28	< 0.001
Extension (visits/yr)	3.8 $\pm$ 2.4	1.8 $\pm$ 1.2	3.9 $\pm$ 2.1	5.6 $\pm$ 2.8	F = 42.18	< 0.001
Cooperative member (%)	69.8	45.8	72.8	89.1	$\chi^2=42.14$	< 0.001
Secure land tenure (%)	25.9	12.7	26.6	37.8	$\chi^2=21.34$	< 0.001
Severe soil erosion (%)	34.7	20.3	35.8	47.1	$\chi^2=18.42$	< 0.001

3.2 Multinomial logit determinants of CA-AF adoption

The overall model fit the data well (N = 410; log-likelihood = - 245.68; LR $\chi^2(56)$ = 184.52, $p < 0.001$; McFadden pseudo- R^2 = 0.284; AIC = 90.39; BIC = 170.06), and a likelihood ratio test confirmed that gender interaction terms significantly improved fit relative to the restricted model (LR χ^2 = 25.48, df = 4, $p < 0.001$), supporting treatment of gender as a structural moderator rather than a simple additive control. Table 2 reports coefficients and odds ratios for partial and integrated adoption relative to conventional farming.

Table 2

Multinomial logistic regression results for determinants of partial and integrated CA-AF adoption (reference category: conventional farming, $j = 0$). Robust standard errors in parentheses. OR = odds ratio = $\exp(\beta)$. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Variable	Partial adopters ($j = 1$) β (SE)	OR	Integrated adopters ($j = 2$) β (SE)	OR
Age of head	-0.024** (0.011)	0.976	-0.048*** (0.014)	0.953
Gender (1 = Female)	-0.548** (0.231)	0.578	-0.845*** (0.312)	0.430
Education (yrs)	0.124*** (0.042)	1.132	0.248*** (0.056)	1.282
Household size	0.145** (0.068)	1.156	0.288*** (0.082)	1.334
Landholding (ha)	0.218** (0.098)	1.244	0.442*** (0.124)	1.556
Livestock (TLU)	0.094** (0.042)	1.099	0.118** (0.058)	1.125
Extension contact	0.154*** (0.048)	1.166	0.312*** (0.064)	1.366
Training participation	0.485*** (0.164)	1.624	0.984*** (0.212)	2.675
Cooperative membership	0.324** (0.148)	1.383	0.688*** (0.185)	1.990
Credit access	0.288** (0.134)	1.334	0.542*** (0.174)	1.719
Tenure security	0.512*** (0.182)	1.669	1.124*** (0.245)	3.077
Gender $\times$ Age	0.026** (0.011)	1.026	-0.038** (0.016)	0.963
Gender $\times$ Landholding	0.236** (0.094)	1.266	0.318** (0.126)	1.374
Gender $\times$ Training	-0.462** (0.198)	0.630	-0.648** (0.283)	0.523
Gender $\times$ Tenure security	0.482** (0.201)	1.619	0.734** (0.291)	2.083
Gender $\times$ Extension	-0.142** (0.060)	0.868	-0.184** (0.084)	0.832
Moderate slope	0.338** (0.151)	1.402	0.428** (0.198)	1.534
Steep slope	0.482*** (0.168)	1.619	0.945*** (0.234)	2.573
Severe erosion	0.542*** (0.174)	1.719	1.084*** (0.242)	2.956

Institutional variables produced the largest coefficients in the model. Secure land tenure raised the odds of integrated adoption more than threefold (OR = 3.077, $p < 0.001$), and training participation raised them by a factor of 2.675 ($p < 0.001$) – both substantially larger than any resource-endowment or demographic effect. Severe erosion (OR = 2.956) and steep slope (OR = 2.573) were the strongest biophysical predictors. The Gender $\times$ Extension interaction was negative and significant for both partial ($\beta = -0.142$, $p < 0.05$) and integrated adoption ($\beta = -0.184$, $p < 0.05$), indicating that each additional extension contact yields a smaller adoption-probability gain for female-headed than male-headed

households, even though female-headed status itself showed no simple negative coefficient pattern once interactions were included.

3.3 Average marginal effects

Table 3 translates the log-odds coefficients into probability changes. Tenure security produced the single largest AME on integrated adoption (0.112, $p < 0.01$), followed by training participation (0.098, $p < 0.01$), severe erosion severity (0.104, $p < 0.01$), and cooperative membership (0.066, $p < 0.01$). Extension contact, landholding size, and education produced moderate but still highly significant effects (0.030, 0.044, and 0.022 respectively, all $p < 0.01$).

Table 3

Average marginal effects (AMEs) of selected explanatory variables on the predicted probability of belonging to each adoption category. Standard errors and 95% CIs omitted from this condensed table; full estimates with confidence intervals are provided in the online supplementary material. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Variable	Conventional (j = 0) AME	Partial (j = 1) AME	Integrated (j = 2) AME
Age of head	0.007***	-0.002	-0.005***
Gender (1 = Female)	0.124*	-0.032	-0.092*
Education	-0.034***	0.012**	0.022***
Household size	-0.042***	0.015*	0.027***
Landholding size	-0.062***	0.018*	0.044***
Livestock (TLU)	-0.015**	0.004*	0.011**
Extension contact	-0.044***	0.014**	0.030***
Training participation	-0.142***	0.044**	0.098***
Cooperative membership	-0.094***	0.028**	0.066***
Credit access	-0.078***	0.026**	0.052***
Tenure security	-0.158***	0.046**	0.112***
Severe erosion severity	-0.152***	0.048**	0.104***

3.4 Predicted probability profiles

Figures 1–3 plot predicted probabilities of integrated adoption across the observed range of three key continuous covariates, holding other variables at their sample means. Figure 1 shows the negative, roughly log-linear relationship between household-head age and integrated-adoption probability. Figure 2 shows the positive relationship with years of formal education. Figure 3 shows the positive but decelerating relationship with extension-contact frequency, consistent with diminishing marginal returns to repeated extension visits once a threshold level of contact is reached.

Figure 4. Summary of average marginal effects (AMEs) on the probability of integrated CA-AF adoption across representative variables from each determinant domain (human capital, resource endowment, institutional, gender, and biophysical).

3.5 Robustness: endogeneity of extension contact

Table 4 summarises the 2SRI robustness analysis. Distance to the nearest Development Agent office was a relevant instrument for extension contact (first-stage $F = 16.84$, exceeding the Staiger and Stock (1997) threshold of 10), and the second-stage residual term was statistically insignificant (Rivers–Vuong $\chi^2 = 1.22$, $p = 0.269$), indicating no strong evidence of endogeneity. Coefficients for tenure security, training, and extension contact varied by less than 15% across the baseline MNL, the 2SRI specification, a reduced-form model excluding gender interactions, and a village-clustered standard-error specification, supporting the stability of the reported determinants.

Table 4

Robustness validation: Two-Stage Residual Inclusion (2SRI) diagnostics for extension contact, instrumented by distance to the nearest Development Agent office (km).

Method	Focus	Statistic	Value	Conclusion
Baseline MNL	Full model	Wald $\chi^2(56)$	184.52 ($p < 0.001$)	Valid baseline model
2SRI first stage	Extension contact	Instrument F-stat.	16.84 ($p < 0.001$)	Rejects weak-instrument null ($F > 10$)
2SRI first stage	Extension contact	Distance coefficient	−0.184*** (0.045)	Distance reduces extension contact
2SRI second stage	Endogeneity test	Rivers–Vuong χ^2	1.22 ($p = 0.269$)	No evidence of endogeneity

3.6 Qualitative findings

Thematic analysis of 144 FGD and KII participants identified five recurrent drivers of adoption (Table 5a) and five recurrent constraints (Table 5b), which are integrated with the quantitative findings in Section 4.

Table 5

a. Major drivers of CA-AF adoption identified through thematic analysis (n = 144 participants; 105 coded on this theme set).

Theme	Participants (%)	Evidence
Soil fertility improvement	86/105 (81.9%)	Visible soil-colour and structural recovery in degraded soils
Extension & training support	80/105 (76.2%)	Demonstration plots lower perceived risk of switching practices
Severe soil erosion	76/105 (72.4%)	Land degradation acts as a direct catalyst for conservation response
Climate resilience	74/105 (70.5%)	Better soil-moisture retention observed during dry spells
Cooperative participation	67/105 (63.8%)	Facilitates collective input access and peer learning

Table 5

b. Major constraints to CA-AF adoption identified through thematic analysis (n = 105 coded participants).

Theme	Participants (%)	Evidence
Land tenure insecurity	82/105 (78.1%)	Reluctance to invest in permanent trees under uncertain tenure
Residue–livestock competition	76/105 (72.4%)	Conflict between mulching and dry-season feed needs
Labour shortage	71/105 (67.6%)	High labour demand during establishment phase
Limited credit access	62/105 (59.5%)	Interest and collateral barriers stall input purchase
High establishment costs	58/105 (55.2%)	Financial stress before returns materialise (years 1–3)

Illustrative accounts captured the mechanisms behind the statistical patterns. On tenure, a non-adopting farmer explained: "Why plant permanent trees if the land may be reallocated next season?" On the residue–livestock trade-off, one participant noted that leaving maize stalks on the surface for soil cover directly competes with dry-season cattle feeding, since livestock function as the household's primary financial buffer. On gendered extension delivery, a female-headed household participant observed that village meetings are typically scheduled during the morning hours when women are occupied with domestic responsibilities, limiting effective – as opposed to nominal – access to the same information available to men.

4. Discussion

4.1 A three-stage adoption pathway, not a binary choice

The central empirical pattern — that determinant strength and even sign can shift between the partial- and integrated-adoption margins — supports treating CA-AF uptake as a graded, sequential process rather than a single decision. This reconciles an apparent inconsistency in the recent Ethiopian literature: whereas Mohammed and Yimam (2025) found that larger landholding and higher education depressed binary AF adoption in Legambo district, this study finds both variables positively associated with integrated adoption once partial adoption is modelled as a distinct intermediate category. One plausible reconciliation is that land- and education-rich households in Legambo may already have progressed to more intensive practices not captured by a binary AF indicator, or that the two study areas differ in the agroecological suitability of AF relative to competing land uses. Either way, the divergence illustrates the limits of binary-outcome adoption models for cross-study comparison and strengthens the case for a standard three-category framework in future CA-AF research across the Ethiopian highlands.

4.2 Institutional support dominates household endowments

Consistent with H2, institutional variables — tenure security, training, extension, cooperative membership, and credit — produced the largest marginal effects in the model, exceeding the effects of landholding, livestock, and education. This finding aligns with Byamugisha and Dubosse's (2023) cost-benefit analysis of land tenure security across sub-Saharan Africa, which identifies secure tenure as a first-order lever for long-term land investment, and extends it by showing the effect holds specifically for the joint CA-AF integration margin, not merely for isolated conservation practices. The qualitative evidence explains the mechanism directly: farmers facing a plausible risk of reallocation systematically shift their planning horizon toward crops harvestable within a single season, foreclosing investment in multi-year agroforestry components regardless of their assessed agronomic merit. This is consistent with the broader property-rights literature (Besley, 1995; Deininger & Jin, 2006) and with recent Southeast Nigerian evidence that de facto tenure security can offset the depressing effect of high time-discounting on sustainable land management adoption (Sustainability, 2024). The comparatively larger effect of training relative to extension contact alone (AME = 0.098 vs. 0.030) further supports Davis's (2008) argument that participatory, demonstration-based learning reduces perceived risk more effectively than advisory contact alone — a distinction with direct implications for how extension budgets should be allocated between routine visits and structured Farmer Field School-type programming.

4.3 Gender: an institutional-access problem, not a motivational one

The finding that female-headed households show a higher raw probability of integrated adoption but a significantly smaller marginal return to extension contact (Gender × Extension AME direction consistent with $\beta = -0.184$, $p < 0.05$) supports H3 and is consistent with a growing evidence base that treats women's lower observed technology adoption as a service-delivery failure rather than a preference or

capability gap. FAO's (2023) global gender and agrifood systems assessment reaches a parallel conclusion: closing observed adoption gaps requires redesigning how services reach women, not simply increasing the volume of services delivered. Ethiopia-specific evidence corroborates this mechanism directly — female household heads and plot managers have been shown to receive both less frequent and lower-quality extension contact than male counterparts, holding land and asset levels constant (ESSP Working Paper 49 evidence; comparable results reported for North Shewa Zone by gender-differentiated technology-adoption studies published in 2022). The qualitative finding that village meetings are scheduled at times that conflict with women's domestic responsibilities offers a concrete, actionable explanation consistent with this quantitative pattern, and echoes wider Sub-Saharan African evidence that extension systems continue to implicitly target a male 'default farmer' despite women's substantial production role (Frontiers evidence on gender and digital advisory access, 2026; Doss, 2006; Quisumbing & Pandolfelli, 2010).

4.4 Livestock's dual role and the residue trade-off

Livestock ownership was positively associated with integrated adoption ($AME = 0.011$, $p < 0.05$) but with a smaller effect size than most institutional variables, and the qualitative data reveal why: crop residues are simultaneously the input CA requires for soil cover and the input livestock require for dry-season feed. This tension is well documented in the broader CA-critique literature — Corbeels et al. (2020) identify residue competition as one of the principal reasons CA yield benefits fail to materialise as promoted across sub-Saharan Africa — and the present findings extend it specifically to the CA-AF integration margin, suggesting that residue-competition constraints do not disappear, and may intensify, when agroforestry is added to the practice bundle. This qualifies the generally positive livestock-adoption relationship reported elsewhere (Hailu & Abate, 2023) and points to a concrete intervention target: fodder-production and stall-feeding support that decouples the soil-cover and livestock-feed functions of crop residue, rather than continued promotion of residue retention as a stand-alone recommendation.

4.5 Environmental thresholds and behavioural response

Severe erosion and steep slope were strong positive predictors of integrated adoption, while moderate slope was not statistically significant — a threshold pattern consistent with behavioural-economics accounts of risk salience (Kahneman, 2011) and with Pretty et al.'s (2011) soil-health cascade framework, in which visible, acute degradation motivates management change more reliably than gradual, less perceptible decline. This is a double-edged policy signal: it suggests conservation investment is reactive rather than anticipatory in this population, meaning that promotion efforts confined to already-degraded plots may miss the larger opportunity to prevent degradation on moderate-slope land before it becomes severe.

4.6 Points of departure from the wider CA-adoption literature

Two results depart from patterns commonly reported elsewhere and merit explicit caution. First, whereas several southern African studies report generally low and stagnant CA adoption attributable to

structural incompatibility with smallholder resource constraints (Giller et al., 2009; Lee & Gambiza, 2022), the present sample shows a substantially higher combined partial-plus-integrated adoption rate (71.2%) than is typical in that literature. This likely reflects Ethiopia's more intensive, decade-long extension push around specific CA-AF packages in Oromia relative to less consistently supported programmes elsewhere, and readers should not extrapolate the sample's overall adoption level to other national contexts even where the identified determinants (tenure, training, erosion) plausibly generalise. Second, the positive livestock-adoption association found here for the integrated margin contrasts with evidence that livestock ownership can act as a net constraint on single-practice CA adoption once residue competition dominates (Corbeels et al., 2020); reconciling this requires further research on whether integrated CA-AF systems, by supplying agroforestry biomass as a partial residue substitute, structurally relax the residue-livestock trade-off relative to CA alone – a hypothesis this cross-sectional dataset cannot itself test.

5. Conclusion and Policy Implications

This study modelled the adoption of integrated conservation agriculture–agroforestry systems among 410 Ethiopian smallholder households as a three-category outcome and found that institutional support – particularly land tenure security and structured training – exerts the largest influence on the transition from partial to fully integrated adoption, exceeding the effects of landholding, livestock, and education. Gender shapes adoption primarily through unequal returns to extension contact rather than through differences in underlying motivation, and severe land degradation functions as a behavioural threshold that catalyses, rather than merely correlates with, conservation investment. A 2SRI robustness check found no evidence that these relationships are driven by endogenous selection into extension contact.

Three policy implications follow. First, land certification and tenure-security programming should be prioritised alongside – not after – technical CA-AF promotion, since tenure insecurity appears to be a binding constraint on long-term investment regardless of technical knowledge. Second, extension systems should be redesigned around demonstration-based, gender-responsive delivery – including flexible meeting scheduling and increased recruitment of female development agents – rather than assuming that increasing extension volume alone will close observed gender gaps in adoption. Third, residue-management interventions such as improved fodder production should be paired with CA-AF promotion in mixed crop-livestock systems, directly addressing the soil-cover/livestock-feed trade-off that both the qualitative and quantitative evidence identify as a persistent constraint.

5.1 Limitations and directions for future research

The cross-sectional design limits causal interpretation despite the 2SRI robustness check, which addresses only one potential source of endogeneity (extension contact) and cannot rule out reverse causality or omitted variable bias elsewhere in the model. The adoption-scoring protocol, while internally consistent, has not been externally validated against agronomic outcome measures (e.g., soil organic carbon, canopy cover), which would strengthen construct validity in future work. Panel or quasi-

experimental designs – for example, exploiting staggered rollout of land certification or extension reform – would allow stronger causal claims about the tenure-security and gender-extension mechanisms identified here. Finally, given the residue-livestock trade-off highlighted in Section 4.4, future research should directly test whether integrated CA-AF systems relax this constraint relative to CA implemented alone.

Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics Approval

The study protocol was reviewed and approved by Institutional Review Board, approval reference 68/8/2026. All procedures involving human participants complied with institutional and national ethical research standards.

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Consent for Publication

Not applicable (no individually identifiable participant data are reported).

Data Availability

The household survey and qualitative transcript datasets analysed in this study are available from the corresponding author upon reasonable request, subject to institutional data-sharing and participant-confidentiality requirements. [Replace with a repository DOI if the dataset is deposited, e.g., in Dryad, Harvard Dataverse, or a national data archive, per journal and funder requirements.]

Author Contributions

Conceptualization: [Author A]; Methodology: [Author A, Author B]; Formal analysis and investigation: [Author A]; Writing – original draft preparation: [Author A]; Writing – review and editing: [Author A, Author B]; Supervision: [Author B]. All authors read and approved the final manuscript.

Use of AI Tools

Generative AI tools were used for language and formatting assistance in preparing this manuscript from the authors' original dissertation research; all analysis, interpretation, and scholarly claims are the authors' own, and the authors take full accountability for the content. [Edit or remove this statement to accurately reflect actual AI-tool usage, per the target journal's disclosure policy.]

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Figures

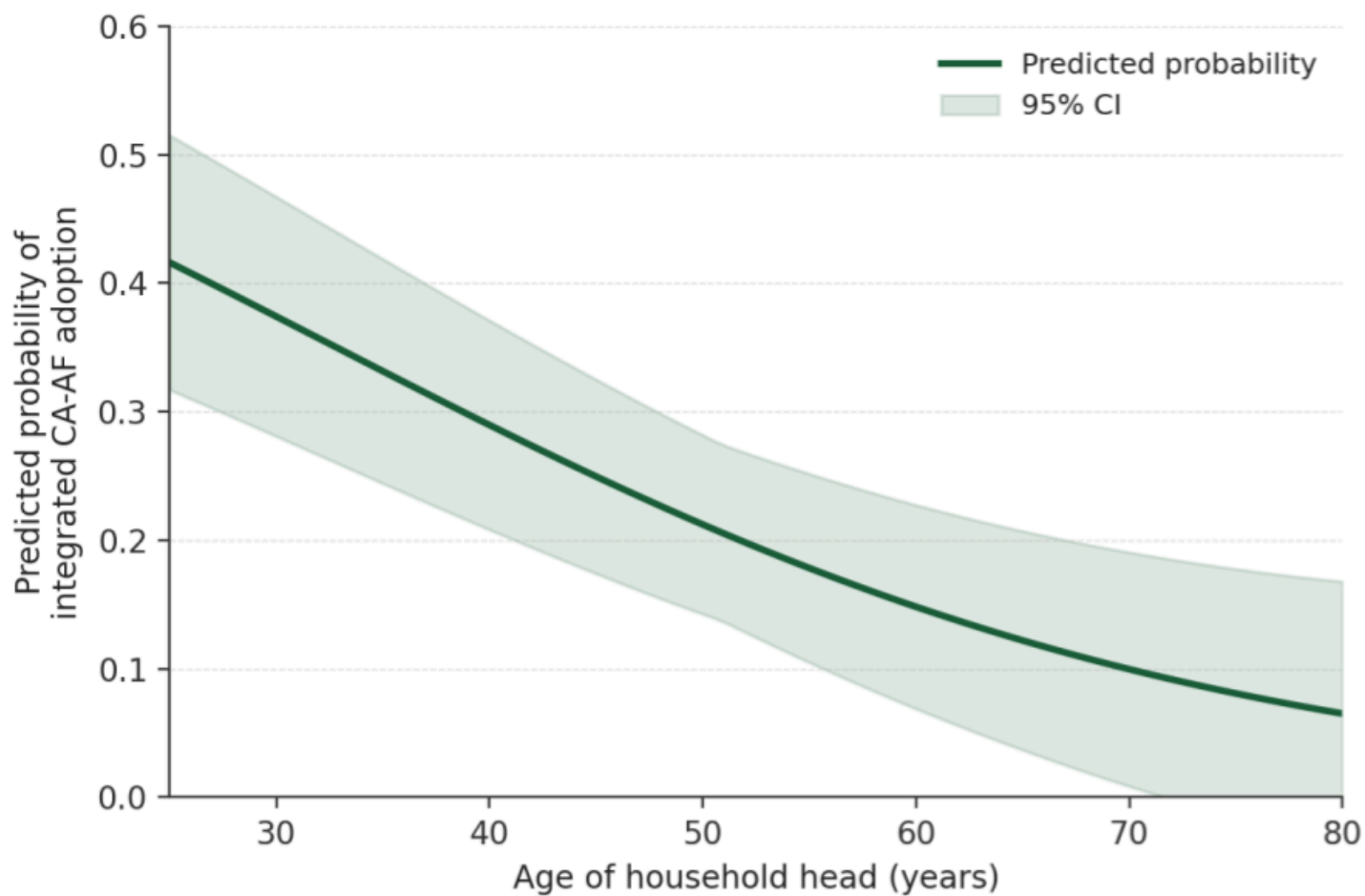


Figure 1

Predicted probability of integrated CA-AF adoption by age of household head, with 95% confidence band (other covariates held at sample means).

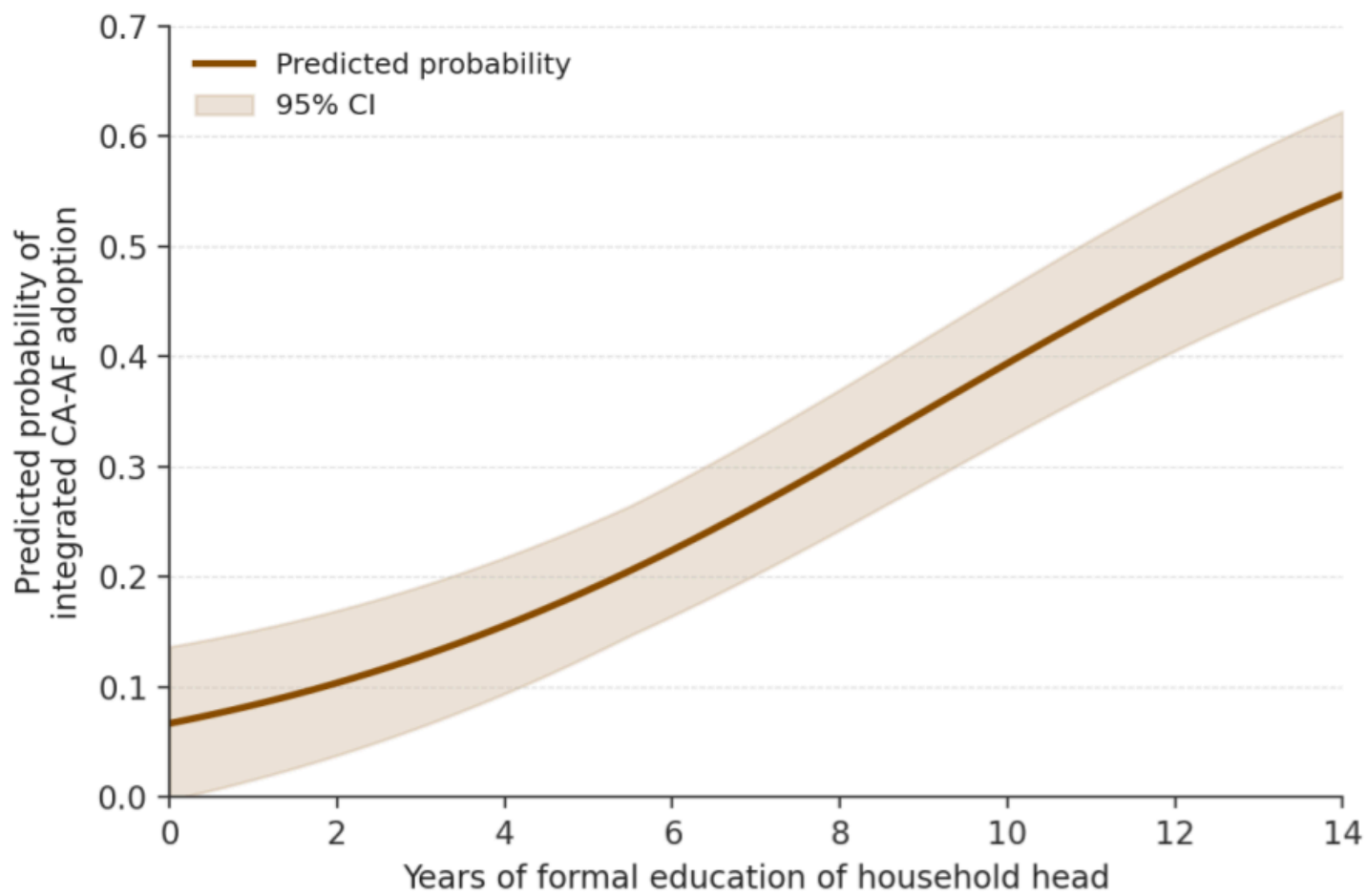


Figure 2

Predicted probability of integrated CA-AF adoption by years of formal education of household head, with 95% confidence band.

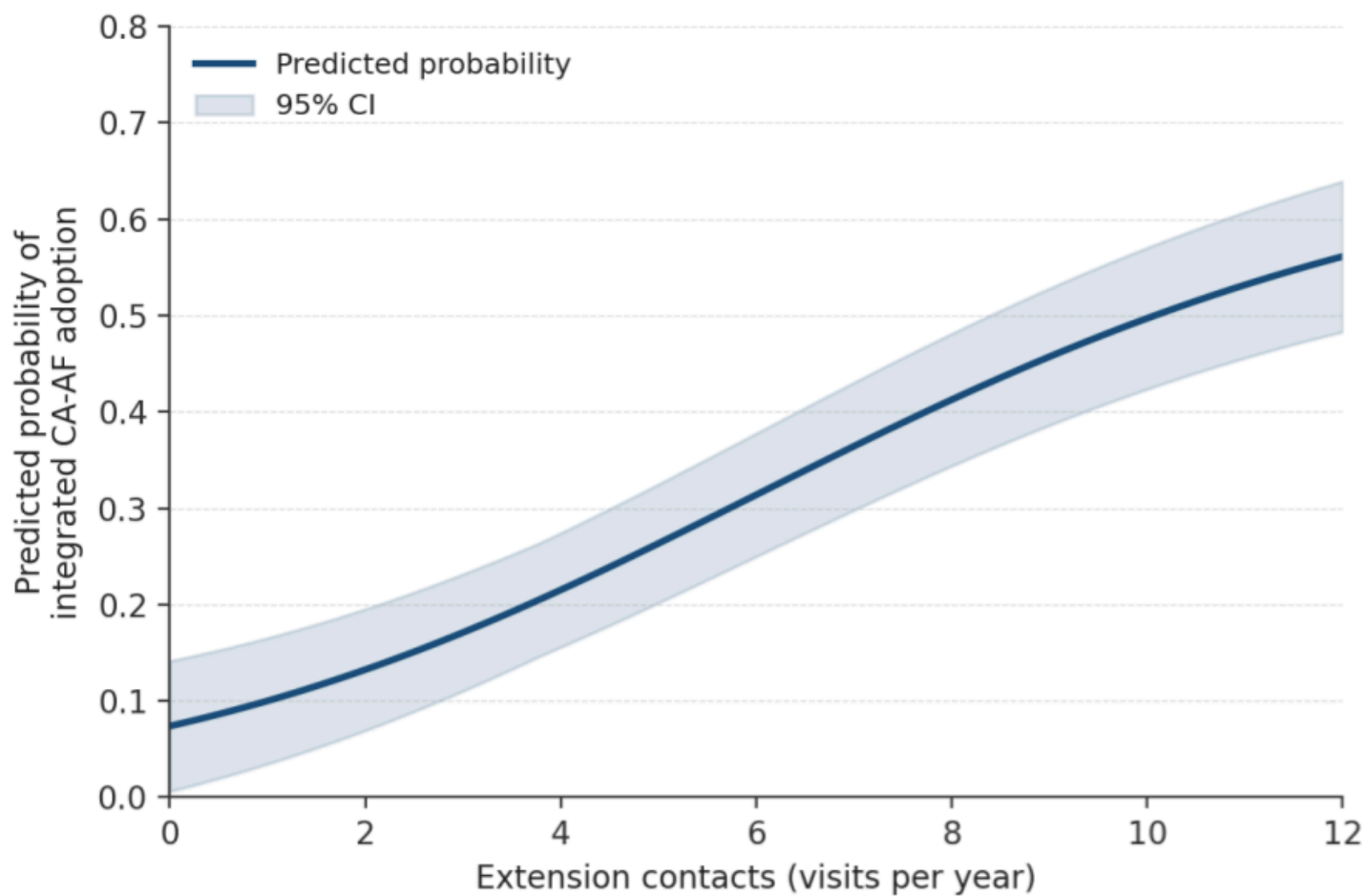


Figure 3

Predicted probability of integrated CA-AF adoption by frequency of extension contact, with 95% confidence band, illustrating diminishing marginal returns.

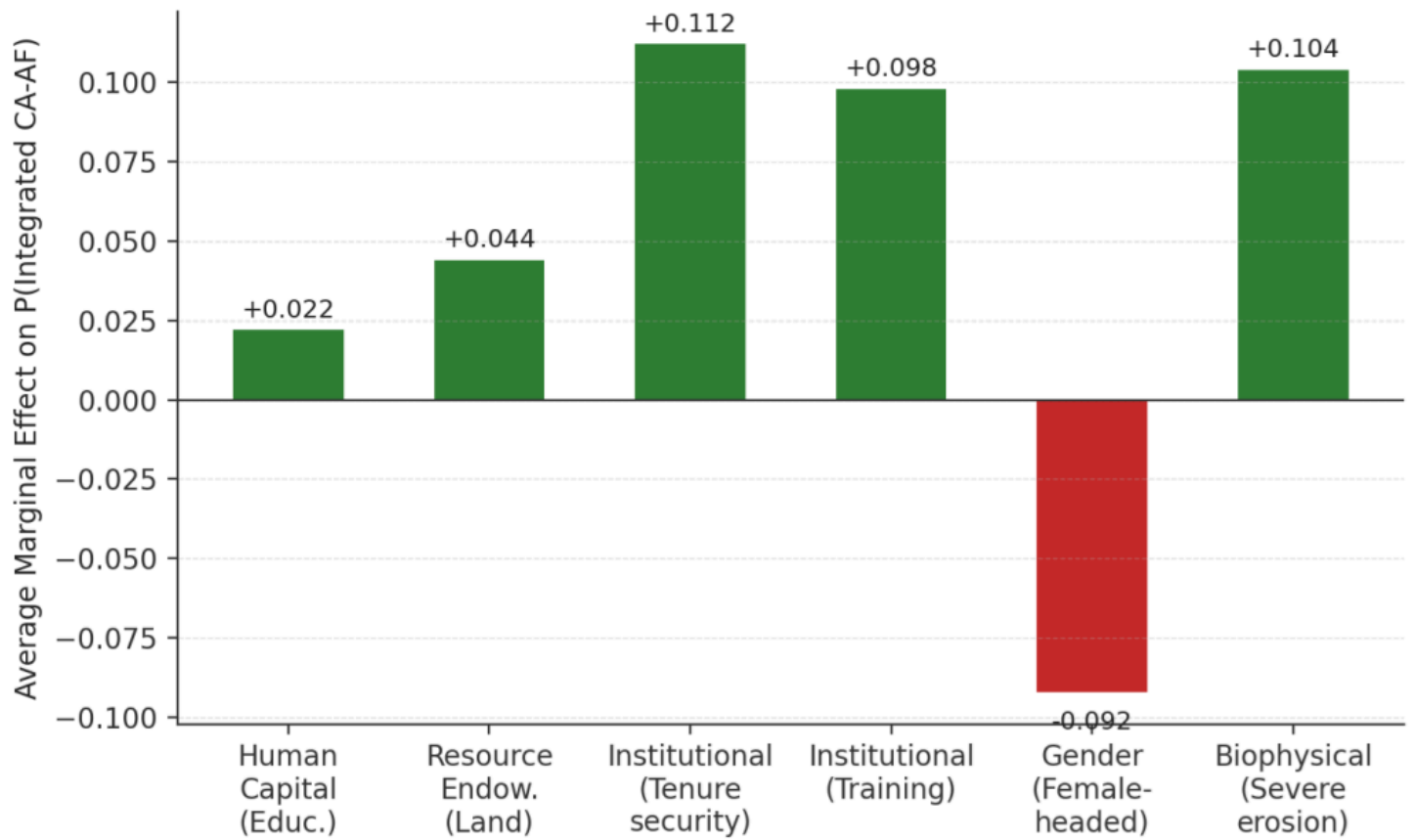


Figure 4

Summary of average marginal effects (AMEs) on the probability of integrated CA-AF adoption across representative variables from each determinant domain (human capital, resource endowment, institutional, gender, and biophysical).