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Gender-patterned adoption of bundled sustainable agricultural practices among smallholder maize farmers in Zambia: Headship and economic agency

Musowe Nsakilwa*
Department of Agricultural Economics and Extension Studies, the University of Zambia, Lusaka, Zambia. E-mail: mnsakilwa@gmail.com

Elias Kuntashula
Department of Agricultural Economics and Extension Studies, the University of Zambia, Lusaka, Zambia. E-mail: ekuntashula@unza.zm

* Corresponding author

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Abstract

Gender-responsive programmes often use household headship as a proxy for women's position, although it may not capture economic agency. This study examines the adoption of a bundle comprising crop rotation, minimum/zero tillage and residue retention among 582 maize-producing households in Mungwi and Senanga, Zambia. A nonlinear logit model estimated average marginal effects for 578 complete cases, with robust and camp-clustered inference, and Fairlie decomposition accounted for the female-headed–male-headed gap. The raw gap was positive but statistically insignificant. Female headship was negatively associated with adoption under robust inference (AME = -0.077; p = 0.043) but not after clustering (p = 0.103). Female/joint control over maize revenue was positively associated with adoption (AME = 0.234; clustered p = 0.002) and dominated the explained gap. Programmes should distinguish headship from control over agricultural benefits and tailor support to practice-specific and local constraints.

Key words: bundled adoption, economic agency, Fairlie decomposition, gender, household headship

1. Introduction

Sustainable agricultural practices (SAPs) are promoted in smallholder maize systems to maintain soil functions, manage production risk and sustain output under climatic and resource constraints. Crop rotation, minimum or zero tillage and crop residue retention are often presented as a package because diversification, reduced soil disturbance and soil cover may reinforce one another. Farmers nevertheless select, adapt and combine components according to labour, land, livestock feed requirements, information, expected returns and local production conditions (Andersson & D'Souza

2014; Arslan *et al*. 2014; Jones-Garcia & Krishna 2021). Adoption is therefore better understood as a portfolio decision, while component-specific evidence remains important because each practice imposes different opportunity costs (Teklewold *et al*. 2013; Kassie *et al*. 2015).

Gendered institutions may shape these choices through unequal access to land, labour, finance, extension, assets and agricultural income. Empirical measurement is difficult, however, because the sex of the household head is not equivalent to plot management, participation in production decisions or control over revenue. Female-headed households may also differ from male-headed households in marital status, household composition and labour availability. Consequently, an observed headship difference may combine gendered constraints with demographic, resource and household life-cycle differences (Doss 2018; Fischer *et al*. 2021).

African evidence does not support a universal female adoption disadvantage. Ndiritu *et al*. (2014) show that gender differences among Kenyan plot managers vary across sustainable-intensification practices. Tufa *et al*. (2022) similarly find technology-specific differences in Malawi and show that an adjustment for unequal productive resources changes the apparent gender pattern. In Zambia, the adoption of conservation farming responds to rainfall, labour, extension and household resources (Arslan *et al*. 2014), while qualitative evidence indicates that gendered labour roles and programme implementation shape farmers' experiences of conservation agriculture (Umar 2021). These studies establish that gender, technology and context interact, but they do not resolve how household headship, economic agency and observed characteristics jointly account for a binary bundled-adoption gap.

The research problem has four dimensions. First, analysing only a single practice or an undifferentiated index can conceal whether an apparent gender pattern is concentrated in one component of a bundle (Ndiritu *et al*. 2014; Kassie *et al*. 2015). Second, headship alone may misclassify women's role because it does not identify who controls agricultural benefits (Alkire *et al*. 2013; Doss 2018). Third, constant linear effects for household size and farming experience may overlook capacity thresholds and household life-cycle relationships. Fourth, a regression coefficient describes a conditional association but does not show how differences in observed characteristics account for the total female-headed–male-headed probability gap; a nonlinear decomposition is required for that purpose (Fairlie 2005). Without this evidence, extension programmes risk using headship as a crude targeting rule and treating diverse SAP components as a homogeneous technology.

This study therefore examines the gender-patterned adoption of a bundle comprising crop rotation, minimum/zero tillage and residue retention among maize-producing households in Mungwi and Senanga districts in Zambia. It contributes by combining practice-specific and bundled adoption analysis, distinguishing household headship from female/joint control over maize revenue, allowing nonlinear household-size and farming-experience relationships, and applying Fairlie decomposition to the female-headed–male-headed adoption difference. The contribution is empirical rather than a claim that logit or decomposition methods are new. The study asks whether raw adoption differs by headship, whether female headship is conditionally associated with high adoption, whether the relationship varies nonlinearly and across districts, and how measured characteristics account for the observed gap. The null hypothesis is that female household headship has no conditional association with high SAP adoption. The preview of the results is deliberately cautious: the raw gap is modest and statistically uncertain, the adjusted headship association is inference-sensitive, and economic agency is more consistently associated with adoption than headship alone.

2. Literature review and conceptual framework

2.1 Household resources, agency and technology choice

The study is anchored in agricultural household theory, which treats production and consumption decisions as interdependent when labour, land, credit or output markets are incomplete (De Janvry *et al*. 1991). Under such conditions, a household's resource endowment and internal allocation rules can influence whether it can meet the labour, management and liquidity demands of a technology portfolio. Reviews of sustainable intensification consistently identify human capital, farm resources, institutions, risk and technology attributes as important correlates, while emphasising that their signs and magnitudes vary across settings (Guo *et al*. 2020; Jones-Garcia & Krishna 2021).

Agency is analytically distinct from resource ownership or headship. The Women's Empowerment in Agriculture Index (WEAI) separates production decisions, access to resources and control over income into related but distinct domains (Alkire *et al*. 2013). Evidence from maize households in Kenya links women's empowerment to productivity and input allocation (Diiro *et al*. 2018), while research in Eastern Zambia shows that land, donor interventions and intra-household relations shape empowerment in ways that formal participation categories may not capture (Umar *et al*. 2020). For this reason, the present analysis treats female/joint control over maize revenue as an economic-agency variable rather than as another label for female headship.

2.2 Multiple-practice adoption and gender heterogeneity

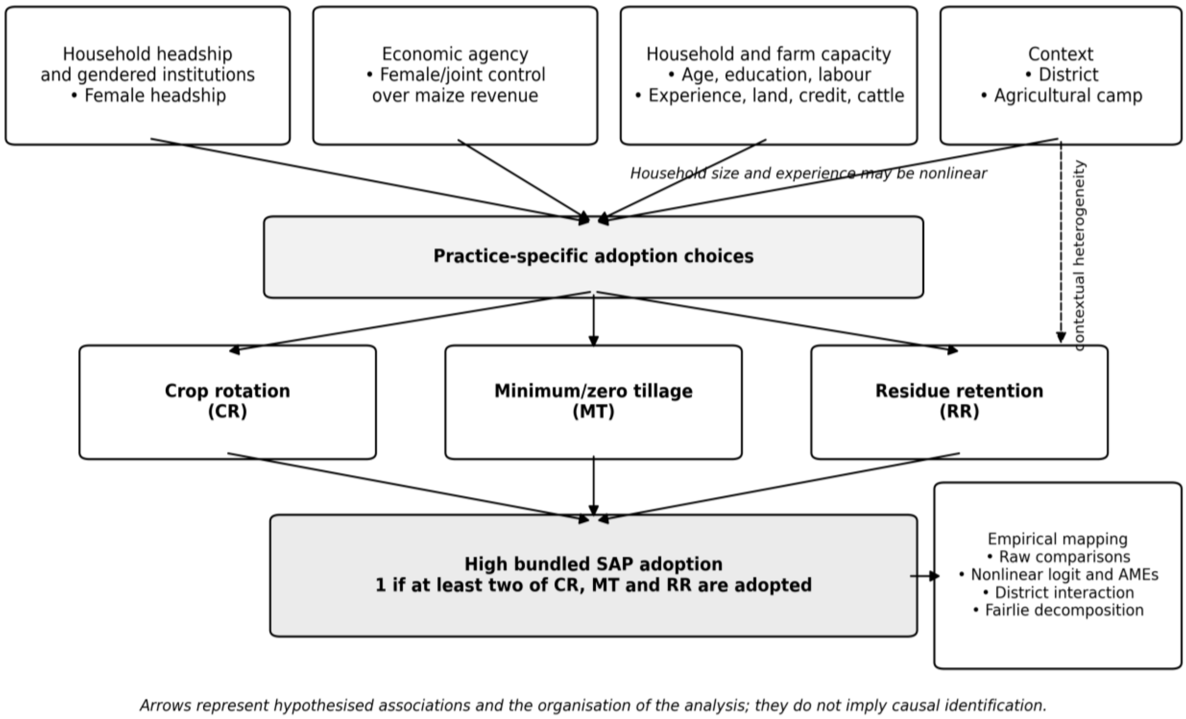
Multiple-practice adoption is economically relevant because practices may share fixed costs, compete for labour or biomass, or affect one another's returns. Studies from Ethiopia and eastern and southern Africa show that adoption choices are interrelated and that household resources, information and location affect the composition of the adopted portfolios (Teklewold *et al*. 2013; Kassie *et al*. 2015). In Zambia, SAP combinations have heterogeneous associations with maize yield and income (Manda *et al*. 2016), and the intensity of conservation-farming adoption varies with rainfall, extension and household resources (Arslan *et al*. 2014).

Gendered adoption evidence is equally heterogeneous. Female plot managers in Kenya were less likely to use some practices but not others (Ndiritu *et al*. 2014). In Malawi, women managers were more likely to adopt certain technologies and less likely to adopt others, and unequal access to productive factors explained only part of the pattern (Tufa *et al*. 2022). Cross-country evidence also indicates that gender gaps in climate-smart agriculture reflect institutions, information and assets rather than sex alone (Hailemariam *et al*. 2024). Agency-focused studies further suggest that women's participation and empowerment may support adoption, although the relevant domain and mechanism differ by technology and setting (Oyawole *et al*. 2021; Shahbaz *et al*. 2022).

The closest literature therefore establishes portfolio interdependence, technology-specific gender patterns and the limitations of headship as a gender measure. The unresolved contribution is to integrate these insights within one Zambian analysis that reports component outcomes, estimates a nonlinear bundled-adoption model, distinguishes headship from revenue control, tests district heterogeneity and decomposes the observed binary gap. Fairlie decomposition is suited to the last objective because it preserves the nonlinear probability structure of a logit model (Fairlie 2005).

2.3 Conceptual framework

Figure 1 links household headship and gendered institutions, economic agency, household and farm capacity, and local context to practice-specific adoption choices. Crop rotation, minimum/zero tillage and residue retention then combine to form the high-adoption outcome. Household size and farming experience are allowed to be nonlinear, while district captures broad contextual heterogeneity. The framework maps directly to the descriptive comparisons, logit model, district interaction and Fairlie decomposition. Its arrows represent hypothesised associations and analytical organisation, not causal identification.



Note: CR = crop rotation; MT = minimum/zero tillage; RR = residue retention; AMEs = average marginal effects

Figure 1: Conceptual framework for gender-patterned bundled SAP adoption
Source: Authors' conceptualisation based on the agricultural household, gender-agency and multiple-practice adoption literature

3. Methodology

3.1 Study area, design and sampling

The study used cross-sectional household survey data from Mungwi District in Northern Province and Senanga District in Western Province, Zambia. Mungwi represents a relatively higher-rainfall Agroecological Region III setting, whereas Senanga represents the more drought-prone Agroecological Region I. The comparison permits an assessment of contextual heterogeneity but does not identify the particular biophysical or institutional mechanism responsible for a district difference. A multistage procedure selected agricultural camps and maize-producing households from camp registers within the two purposively selected districts. The harmonised survey contained 582 households: 311 in Mungwi and 271 in Senanga. The sample comprised 249 male-headed and 333 female-headed households. Because the districts and camps were purposively selected, inference is limited to comparable surveyed maize-producing households and should not be interpreted as nationally representative.

3.2 Data harmonisation, analytical samples and variables

District datasets were cleaned separately before harmonisation. Checks covered identifiers, variable coding, the SAP count and a reconstruction of agency indicators. The agency information merged to all 582 households using district and household identifiers, and headship classifications agreed across source files. Descriptive statistics use the available sample for each variable. The preferred logit and Fairlie analyses use the same 578 complete cases: 308 in Mungwi and 270 in Senanga, comprising 249 male-headed and 329 female-headed households and all 153 high adopters. Four female-headed low adopters were excluded because of missing age or missing credit and cattle information. Clustered inference uses 13 non-empty district-by-camp clusters.

Female/joint participation in farm decisions is reported descriptively but excluded from the preferred model because every female-headed household was coded as participating, leaving no common support with headship. Female/joint control over maize revenue occurs in both headship groups and districts and is retained as a contemporaneous indicator of economic agency. Because revenue-control status and SAP adoption were measured in the same survey round, revenue control is not treated as an exogenous determinant: adoption-related production outcomes, bargaining processes and unobserved household organisation may jointly shape both variables. The robustness analysis therefore re-estimates the preferred specification without revenue control. Farming experience was recorded categorically in Mungwi and in exact years in Senanga; the Mungwi categories were assigned representative values of 0.5, 3, 8 and 12.5 years, making the pooled measure coarser in Mungwi. Contemporaneous input-use variables are excluded because of selected missingness and possible joint determination with SAP adoption.

For household i, the binary outcome is defined by Equation (1), where CR, MT and RR indicate the adoption of crop rotation, minimum/zero tillage and residue retention, respectively.

$$Y_i = \mathbf{1}(CR_i + MT_i + RR_i \geq 2) \tag{1}$$

Female household headship is the focal explanatory variable. Controls are age, household size, education, maize-farming experience, maize area, credit access, cattle ownership, female/joint control over maize revenue and a Senanga indicator. Household size and experience enter in linear and squared form. Group membership is reserved for sensitivity analysis.

3.3 Empirical specification and estimand

Welch t-tests compare continuous characteristics and Pearson chi-square tests compare binary outcomes. The preferred binary logit model is shown in Equation (2), where H_i denotes female household headship, S_i denotes household size, E_i denotes maize-farming experience and Z_i contains the linear demographic, farm, agency and district controls, including the linear S_i and E_i terms. The logistic cumulative distribution function is denoted by $\Lambda(\cdot)$. The specification follows standard binary-response modelling, while interpretation is based on average marginal effects rather than odds ratios (Williams 2012).

$$\Pr(Y_i = 1 \mid Z_i) = \Lambda(\alpha + \delta H_i + Z_i'\boldsymbol{\beta} + \gamma_1 S_i^2 + \gamma_2 E_i^2) \tag{2}$$

For the binary female-headship indicator, the reported average marginal effect is the sample-average discrete change in predicted probability in Equation (3), holding each household's other observed characteristics at their recorded values (Williams 2012).

$$\mathrm{AME}_H = \frac{1}{N}\sum_{i=1}^{N}\left[\hat{P}(Y_i = 1 \mid H_i = 1, X_i) - \hat{P}(Y_i = 1 \mid H_i = 0, X_i)\right] \quad (3)$$

The estimand is associational. Female headship is not randomly assigned, and covariate adjustment cannot remove unmeasured confounding. The results therefore describe conditional probability differences within the observed sample rather than a causal effect of headship. Heteroskedasticity-robust standard errors provide the primary household-level inference. The model is also estimated with standard errors clustered by agricultural camp because households may share extension, infrastructure or local norms. With only 13 clusters, cluster-based inference is treated as a conservative sensitivity check (Cameron & Miller 2015).

3.4 Model selection, decomposition and robustness

Three admissible specifications were compared: a linear model, Q1, with quadratic experience, and Q2, with quadratic experience and household size. Q2 retained the full preferred sample, had the lowest Akaike and Bayesian information criteria, and produced the best receiver-operating-characteristic area and Brier score. Likelihood-ratio tests supported both nonlinear additions. Model assessment also considered the Hosmer–Lemeshow test, a squared-prediction functional-form test, calibration, classification, separation and influence diagnostics. No single statistic was treated as proof of correct specification.

The female-headed minus male-headed adoption difference was decomposed using Fairlie's nonlinear extension of the Blinder–Oaxaca approach (Fairlie 2005). Equation (4) separates the observed gap into an explained component generated by group differences in measured characteristics evaluated at pooled coefficients, and a residual component R. The implementation uses 1 000 replications, randomised covariate order and a fixed seed. Linear and squared terms for household size are grouped, as are the experience terms. The decomposition is an accounting exercise based on fitted associations: neither individual contributions nor the residual identify causal pathways, mediation or discrimination.

$$\bar{Y}_F - \bar{Y}_M = \left[\frac{1}{N_F}\sum_{i=1}^{N_F}\Lambda\left(X_{Fi}\hat{\boldsymbol{\beta}}^*\right) - \frac{1}{N_M}\sum_{i=1}^{N_M}\Lambda\left(X_{Mi}\hat{\boldsymbol{\beta}}^*\right)\right] + R \quad (4)$$

Robustness checks used the parsimonious nonlinear specification, re-estimated Q2 without revenue control, added group membership, changed the adoption outcome, excluded influential observations, restricted household-size tails and interacted headship with district. The specification excluding revenue control is particularly relevant for assessing how the headship estimate depends on conditioning on this contemporaneous agency measure.

4. Results

4.1 Household and agency characteristics

Female-headed households represented 57.2% of the pooled sample. They were, on average, younger, smaller, less educated and operated smaller farms than male-headed households, but reported more access to credit and substantially more female/joint control over maize revenue. These differences were not uniformly favourable or unfavourable and motivate multivariable adjustment and decomposition. These differences are summarised in Table 1.

Table 1: Selected characteristics by sex of household head

Characteristic	Male-headed	Female-headed	Female–male	p-value
Age of household head (years)	46.43 (13.50)	44.09 (13.45)	-2.34	0.039
Household size (persons)	5.77 (2.56)	5.33 (2.36)	-0.44	0.036
Education (years)	7.73 (3.02)	6.05 (3.23)	-1.68	< 0.001
Maize-farming experience (years)	10.76 (8.65)	9.86 (8.39)	-0.90	0.209
Maize area cultivated (ha)	1.59 (1.34)	1.44 (1.10)	-0.15	0.141
Total farms size (ha)	5.97 (6.42)	4.32 (4.72)	-1.65	0.001
Access to credit (%)	25.70	37.76	+12.06	0.003
Cattle ownership (%)	40.56	34.44	-6.12	0.154
Female-joint maize-revenue control (%)	52.61	91.29	+38.68	< 0.001

Notes: Continuous variables are means with standard deviations in parentheses; binary variables are percentages. Differences are female-headed minus male-headed. Welch t-tests and Pearson chi-square tests are used.

4.2 Practice-specific and bundled adoption

The pooled high-adoption rate was 28.23% among female-headed households and 23.69% among male-headed households. The 4.53 percentage-point difference was not statistically significant. Crop rotation rates were almost identical and residue-retention rates differed little. The clearest component difference was minimum/zero tillage, which was 10.42 percentage points higher among female-headed households. The adoption of all three practices was also higher in the female-headed group, but that alternative outcome is not the paper's principal estimand. Table 2 presents the corresponding practice-specific and bundled adoption rates.

Table 2: SAP adoption rates by sex of household head

Outcome	Male-headed (%)	Female-headed (%)	Female–male (pp)	p-value
Crop rotation	49.40	49.25	-0.15	0.972
Minimum/zero tillage	30.12	40.54	+10.42	0.010
Residue retention	28.11	30.33	+2.22	0.561
High SAP adoption (at least two)	23.69	28.23	+4.53	0.219
All three SAPs	11.24	17.42	+6.17	0.038

Notes: Pearson chi-square tests compare proportions; pp = percentage points. Adoption of all three practices is an alternative breadth outcome.

4.3 Preferred model and adjusted associations

Q2 improved fit materially relative to the linear model: the Akaiki information criterion (AIC) fell from 624.85 to 571.83, the area under the receiver operating characteristic (ROC) curve rose from 0.725 to 0.781 and the Brier score declined from 0.174 to 0.154. Adding quadratic household size to Q1 improved fit (likelihood-ratio $\chi^2 = 18.04$; $p < 0.001$). The Q2 Hosmer–Lemeshow p-value was 0.070 and the squared-prediction p-value was 0.095. One outcome pattern was determined completely, but all 578 preferred observations were retained. The average marginal effects from the preferred Q2 model are reported in Table 3.

Female headship had an average marginal effect (AME) of -0.0770 under household-level robust inference ($p = 0.043$), but the p-value rose to 0.103 under camp clustering. The evidence therefore does not establish a robust independent headship association across the two inference approaches. Female/joint revenue control had the largest positive AME and remained statistically significant after clustering. Cattle ownership and age were negatively associated under both approaches, while evidence for education, maize area and the district indicator weakened after clustering.

Table 3: Average marginal effects from the preferred high-SAP adoption model

Variable	AME	Robust SE	Robust p	Cluster SE	Cluster p
Female-headed household	-0.0770	0.0380	0.043	0.0472	0.103
Age of household head	-0.0044	0.0015	0.002	0.0018	0.012
Household size	0.0444	0.0078	< 0.001	0.0178	0.013
Education years	-0.0136	0.0051	0.008	0.0100	0.175
Maize-farming experience	0.0192	0.0036	< 0.001	0.0037	< 0.001
Maize area cultivated	0.0262	0.0144	0.068	0.0278	0.346
Access to credit	-0.0049	0.0433	0.909	0.0702	0.944
Cattle ownership	-0.0935	0.0377	0.013	0.0360	0.009
Female-joint revenue control	0.2340	0.0333	< 0.001	0.0768	0.002
Senanga District	-0.1670	0.0476	< 0.001	0.1070	0.119

Notes: N = 578; AME = average marginal effect; SE = standard error. Clustered standard errors use 13 district-by-camp clusters. Household size and farming experience enter with squared terms; displayed AMEs are average derivatives and not constant effects.

4.4 Nonlinear relationships and district heterogeneity

The fitted turning points were 8.37 persons for household size and 14.87 years for maize-farming experience. Predicted probabilities rose toward these intermediate values and declined thereafter. Because experience was measured more coarsely in Mungwi and observations were sparse at the tails, the turning points describe the fitted pooled relationship rather than precise behavioural thresholds. Figure 2 shows these fitted nonlinear relationships.

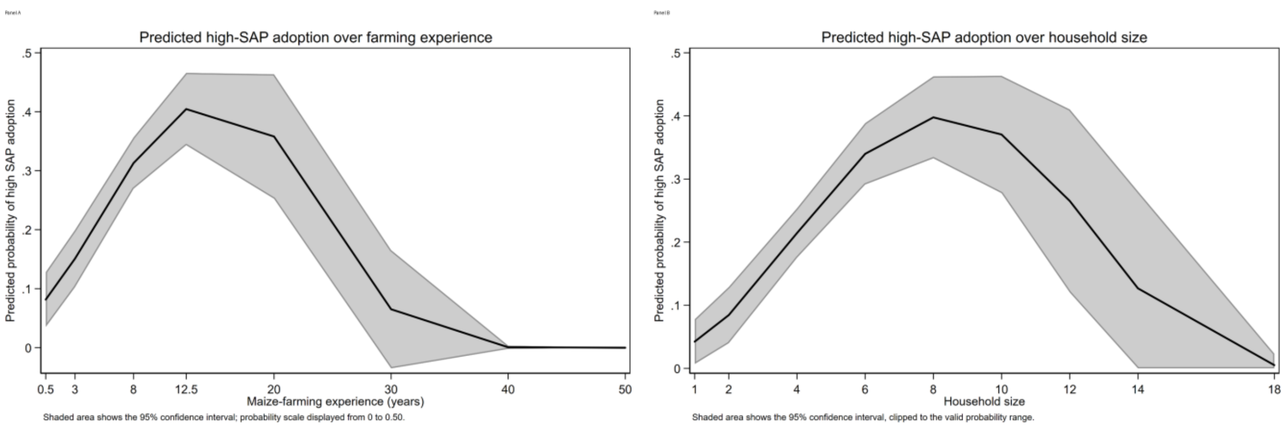


Figure 2: Predicted high-SAP adoption over farming experience and household size

Notes: Panel A shows maize-farming experience and Panel B household size; shaded areas are 95% confidence intervals clipped to the valid probability range; tail predictions should be interpreted cautiously.

The district interaction yielded a female-headship AME of -0.0229 in Mungwi ($p = 0.659$) and -0.1283 in Senanga ($p = 0.003$); the interaction test gave $p = 0.040$. The model reported two completely determined failures, so the contrast is treated as qualified evidence of heterogeneity rather than a causal district mechanism. The district-specific average marginal effects are displayed in Figure 3.

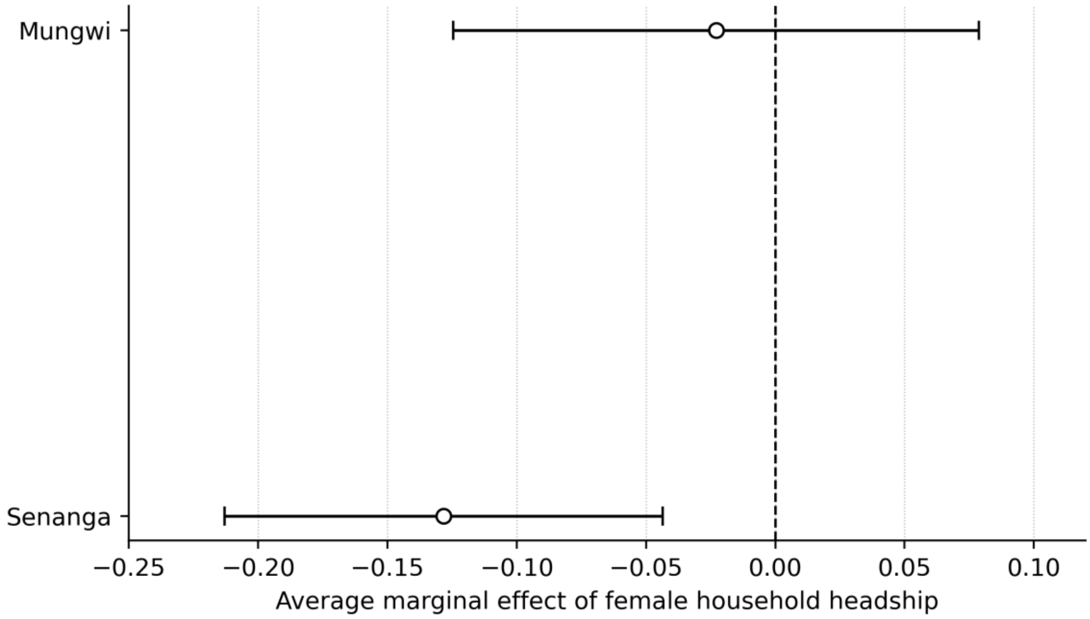


Figure 3: District-specific adjusted association between female headship and high SAP adoption

Notes: Points are district-specific AMEs and capped lines are robust 95% confidence intervals; The interaction model produced limited separation warnings.

4.5 Fairlie decomposition and robustness

In the preferred analytical sample, the female-headed adoption rate was 0.2857 and the male-headed rate was 0.2369. The observed gap of 0.04877 was smaller than the explained component of 0.11452, leaving an unexplained component of -0.06575. Measured characteristics therefore over-explained the observed female-headed advantage. Female/joint revenue control contributed 0.06774, or 59.2%, of the explained component. Detailed variable-level contributions and the full contribution plot are reported in Appendix Table A1 and Figure A1. The principal decomposition results are summarised in Table 4.

Table 4: Summary of Fairlie decomposition of the female-headed minus male-headed adoption difference

Quantity or factor	Contribution	Interpretation (%)
Female-headed adoption rate	0.2857	–
Male-head adoption rate	0.2369	–
Observed gap	0.04877	100.00
Explained component	0.11452	234.8
Unexplained component	-0.06575	-134.8
Female/joint revenue control	+0.06774	59.2 of explained

Notes: N = 578; 1 000 replications; pooled coefficients; randomised variable order. Percentages exceed 100 because observed characteristics over-explain the gap and the negative residual offsets them. Detailed variable-level contributions are reported in Appendix Table A1.

Table 5: Adoption-focused robustness results

Analysis or outcome	Female-head AME	p-value
Q1: quadratic experience only	-0.0643	0.101
Q2: without revenue control	+0.0267	0.151
Q3: plus group members	-0.0805	0.032
Crop rotation outcome	-0.0736	0.107
Minimum/zero tillage outcome	+0.0984	0.012
Residue-retention outcome	-0.1162	0.004
All-three-SAP outcome	-0.0380	0.181

Notes: The preferred estimate is the Q2 high-SAP model in Table 3. The alternatives show specification and outcome sensitivity; p-values use household-level robust inference.

These specification and outcome-sensitivity checks are summarised in Table 5. The headship association was sensitive to specification and outcome definition. It was imprecise in Q1, when revenue control was omitted, the female-headship AME became +0.0267 and was statistically insignificant (p = 0.454); and it remained negative when group membership was added. This sensitivity shows that the conditional headship estimate depends partly on the covariate set, but it does not identify revenue control as a causal mediator. Alternative outcomes confirm that no single gender pattern applies across the components: minimum/zero tillage was positively associated with female headship, residue retention negatively associated, and crop rotation and the adoption of all three was not statistically distinguishable at 5%.

5. Discussion

5.1 Practice-specific gender patterns

The absence of a statistically established pooled raw headship gap cautions against claiming a general female advantage or disadvantage in bundled SAP adoption. The component results are more informative: minimum/zero tillage displayed a female-headed advantage, whereas crop rotation and residue retention showed little difference. This technology specificity accords with evidence that gender patterns vary across practices (Ndiritu *et al*. 2014; Tufa *et al*. 2022). The minimum-tillage direction differs from Kenyan evidence for female plot managers, but headship and plot management are different analytical units and local labour and programme conditions also differ (Ndiritu *et al*. 2014; Umar 2021). Moreover, the binary indicator cannot distinguish deliberate conservation adoption from constrained reduced tillage caused by limited access to animal traction, machinery or ploughing labour. The observed female-headed advantage therefore does not establish stronger environmental preference or higher-quality implementation.

5.2 Raw and adjusted headship patterns

The negative adjusted headship AME alongside a positive raw gap reflects compositional differences rather than an arithmetical inconsistency. Female-headed households had smaller members, less education and smaller farms, but were much more likely to report female/joint revenue control. Holding these measured characteristics constant changed the conditional comparison. Similar evidence from Malawi shows that apparent gender patterns can change after adjustment for unequal productive resources, while work in Uganda and Tanzania also cautions against interpreting sex or management status without considering resources and bargaining position (Teklewold *et al*. 2020; Tufa *et al*. 2022). The loss of conventional significance after camp clustering is substantively important. Households within a camp may share extension exposure, markets and local norms, so household-level standard errors can overstate precision. At the same time, inference with only 13 clusters is itself imprecise (Cameron & Miller 2015). The defensible interpretation is therefore narrow: female headship is negatively associated under household-level robust inference, but the evidence does not establish a robust independent headship association across inference approaches. This statistical fragility precludes using the coefficient as a stand-alone targeting rule.

5.3 Economic agency and the decomposition

Female/joint control over maize revenue was the strongest positive correlate and the largest Fairlie contribution. This supports the conceptual distinction between household headship and control over agricultural benefits. The WEAI treats control over income as a separate empowerment domain (Alkire *et al*. 2013), while empirical work links women's empowerment to agricultural investment and productivity and shows that empowerment also depends on land and intra-household relations (Diiro *et al*. 2018; Umar *et al*. 2020).

Revenue control was measured contemporaneously with SAP adoption and is not treated as exogenous. Reverse causality or joint determination is plausible because adoption can affect production outcomes, while both variables may respond to bargaining power, commercial orientation or unobserved household organisation. Omitting revenue control changes the female-headship AME to +0.0267 ($p = 0.454$). This sensitivity does not establish mediation; it shows that the headship comparison depends on whether the agency measure is included. Revenue control is therefore interpreted as a correlate and decomposition contribution, not a causal policy lever.

The Fairlie decomposition clarifies how measured compositional differences account for the raw gap. Observed characteristics predict a larger female-headed advantage than the one actually observed, producing an explained component above 100% and a negative residual. Fairlie decomposition remains an accounting method based on fitted correlations (Fairlie 2005): the explained contributions do not identify causal pathways or mediation, and the residual should not be labelled discrimination because it can reflect coefficient differences, omitted variables, measurement error and functional-form limitations.

5.4 Household capacity, livestock and district context

The inverted-U relationships suggest that household capacity is not monotonic. Moderate household size may supply labour for land preparation, weeding and residue management, while very large households may face greater dependency and consumption demands. Experience may initially improve knowledge of soils, seasons and practice combinations, but long farming histories correlate with older age and established routines. Reviews that find mixed effects for labour, age and experience are compatible with nonlinear and context-dependent relationships (Guo *et al*. 2020; Jones-Garcia & Krishna 2021). Because the Mungwi experience measure is categorical, the estimated turning point should be treated as approximate.

Cattle ownership was negatively associated with high SAP adoption under both household-level robust and camp-clustered inference. This result is consistent with the possibility that livestock ownership affects the opportunity cost of retaining crop residues in mixed crop–livestock systems, where residues may also be required for feed (Valbuena *et al*. 2012). Because cattle ownership is included primarily as a farm-resource control in the present analysis, this association is not interpreted as a central mechanism of the observed headship gap.

The district interaction suggests a more negative conditional headship association in Senanga, consistent with wider evidence that conservation-practice adoption varies with agroecology, extension, labour and local implementation conditions (Andersson & D'Souza 2014; Arslan *et al*.

2014; Manda *et al*. 2016). The present data cannot isolate rainfall, soils, markets or institutions, and separation warnings reduce confidence. The result identifies Senanga as a setting for deeper qualitative and longitudinal investigation, rather than establishing an intrinsic district-specific female disadvantage.

6. Conclusions, recommendations and limitations

The study finds no statistically established pooled raw headship gap in high-bundled SAP adoption but identifies clear practice-specific differences. Minimum/zero tillage is more common among female-headed households, while crop rotation and residue retention show little raw difference. Female headship is negatively associated with adoption under household-level robust inference but not under camp-clustered inference; accordingly, the evidence does not support a robust independent headship association across inference approaches. Female/joint control over maize revenue is a large, cluster-robust positive correlate and the dominant contribution to the explained gap, while household size and farming experience are nonlinear and cattle ownership is negatively associated. The Fairlie results should be interpreted strictly as model-based accounting of the observed probability gap: neither the explained contributions nor the unexplained component identify causal mechanisms, mediation or discrimination. Overall, household headship alone is an incomplete indicator of gender-patterned adoption.

For Zambia's Ministry of Agriculture, district extension services and programmes promoting sustainable intensification, the findings support improving programme diagnostics and monitoring so that household headship is recorded separately from the person managing maize production and from control over agricultural proceeds. Component-specific constraints should also be diagnosed rather than assuming that a bundled SAP indicator represents a uniform technology. Because revenue control is contemporaneous and potentially jointly determined with adoption, the present results do not justify assuming that reallocating income-control rights would cause SAP uptake. Interventions intended to strengthen women's economic agency are better treated as testable programme hypotheses that should be piloted and evaluated prospectively.

The findings also motivate context-specific diagnostic work on household capacity and crop-livestock trade-offs. Labour-saving services may merit testing where labour constraints are documented, and residue-retention advice should account for competing feed uses in cattle-owning households. The qualified Senanga interaction warrants local qualitative investigation before intervention design is generalised. Future surveys should identify the actual plot manager, measure the duration, quality, motivation and area coverage of each practice, use comparable experience measures across sites, follow households over time and include enough camps to strengthen cluster-based inference.

Important limitations qualify these interpretations. The cross-sectional design supports associations rather than causal effects, and female/joint revenue control may be endogenous or jointly determined with adoption. Fairlie decomposition is an accounting procedure based on the fitted model and cannot establish causal mediation, discrimination or the mechanisms underlying the residual component. Purposive district and camp selection limits national generalisation, and headship remains an imperfect proxy for gendered farm management. Clustered inference relies on only 13 camps, while limited separation affects the preferred and interaction models. Farming experience is measured more coarsely in Mungwi. Finally, the high-adoption threshold measures breadth rather than duration, field coverage, agronomic quality or motivation; minimum/zero tillage, for example, may sometimes reflect constrained access to ploughing resources rather than a deliberate sustainability strategy.

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Appendix: Detailed contributions of Fairlie decomposition

Appendix Table A1: Detailed contributions to the explained high-SAP adoption difference

Factor	Contribution	Share of explained component (%)
Female/joint revenue control	+0.06774	59.2
Education	+0.01530	13.4
Age	+0.01128	9.9
Household size: combined terms	+0.01086	9.5
Farming experience: combined terms	+0.01070	9
Cattle ownership	+0.00539	4.7
Maize area, credit and district combined	-0.00660	-5.8

Notes: N = 578; 1 000 replications; pooled coefficients; randomised variable order. Household-size and experience terms are combined. Percentages exceed 100 because positive observed characteristics over-explain the gap and the negative residual offsets them.

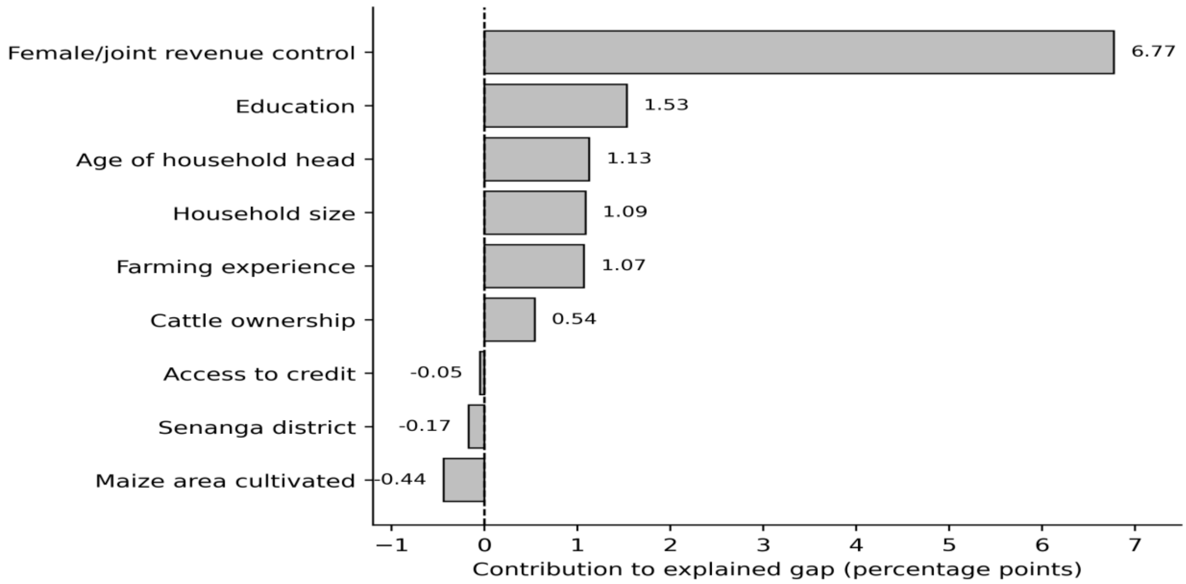

Figure A1: Contributions to the explained high-SAP adoption difference

Notes: Positive values reinforce the observed female-headed advantage; negative values offset it. Values are percentage points. The plot is descriptive, not causal.