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Bundled sustainable agricultural practices and fertiliser-use intensity in contrasting agroecological contexts of Zambia

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ABSTRACT

Bundled Sustainable Agricultural Practices (SAPs) are promoted alongside inorganic fertiliser to strengthen soil management, productivity and resilience, yet the two may function as complements, substitutes or unrelated inputs depending on the production environment. This study examined the association between high bundled SAP adoption and fertiliser-use intensity among smallholder maize-producing households in Mungwi and Senanga districts, Zambia, and assessed whether the relationship differed by district and household farm decision-making. High adoption was defined as using at least two of crop rotation, crop-residue retention and minimum or zero tillage. Agricultural Household Theory provides the principal economic foundation for the study. Cross-sectional data were obtained from 582 households. The benchmark fertiliser models used 517 complete observations after excluding two designated outliers, while multiple imputation retained 580 non-outlier households. Robust logit models estimated adoption correlates, and heteroskedasticity-robust ordinary least squares models estimated pooled and district-interaction associations with ln(fertiliser kg/ha + 1). Observation weighting, upper-tail sensitivity tests, Poisson pseudo-maximum-likelihood estimation, inverse-probability-weighted regression adjustment, multiple imputation under missing at random and delta-adjusted missing-not-at-random analyses were used for robustness. High bundled adoption was observed among 26.3% of surveyed households. In the complete-case interaction model, the association was negative in Mungwi (estimate = -0.610; $p = 0.018$) and positive in Senanga (estimate = 3.331; $p < 0.001$). Under multiple imputation, the Mungwi estimate remained negative but was not statistically distinguishable from zero (estimate = -0.323; $p = 0.162$), whereas the Senanga association (estimate = 3.320; $p < 0.001$) and district interaction (estimate = 3.643; $p < 0.001$) remained robust to the evaluated missing-not-at-random departures. Female/joint farm decision participation did not significantly moderate the relationship (interaction $p = 0.458$). The findings demonstrate robust agroecological heterogeneity and support locally adapted fertiliser-SAP recommendations, with particularly strong evidence of complementarity in Senanga and greater uncertainty in Mungwi.

Keywords: Agroecological Heterogeneity; Bundled Sustainable Agricultural Practices; Conservation Agriculture; Fertiliser-Use Intensity; Integrated Soil Fertility Management; Zambia

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I. INTRODUCTION

Agriculture remains central to rural livelihoods, employment and food security in Zambia, where smallholder households account for a substantial share of maize production (Jayne et al., 2003; Mason & Myers, 2013; Sitko & Jayne, 2014) . The country used an estimated 77.3 kg of fertiliser nutrients per hectare of arable land in 2023, although this national indicator conceals substantial differences across crops, farms and agroecological settings (World Bank, 2026). Zambia's Second National Agricultural Policy identifies low productivity, rainfed production risk, weak extension and unsustainable natural-resource management as persistent constraints, while the Comprehensive Agriculture Transformation Support Programme 2024-2033 prioritises productivity, sustainability and resilience (Government of the Republic of Zambia, 2016, 2024).

These challenges have encouraged the promotion of Sustainable Agricultural Practices (SAPs), including minimum or zero tillage, crop rotation and crop-residue retention, as components of conservation agriculture and sustainable intensification. Rather than operating as isolated technologies, these practices influence soil cover, water infiltration, crop diversification, biological nutrient cycling and labour requirements. Their agronomic and economic performance therefore depends on how they are combined, the length and quality of implementation, and the biophysical and institutional environment in which farmers use them (Andersson & D'Souza, 2014; Pretty et al., 2018). Zambia-specific evidence similarly shows that conservation practices are adopted incrementally and in combinations, with extension exposure, rainfall variability, labour constraints and household resources shaping both adoption and dis-adoption (Arslan et al., 2014; Chikopela et al., 2024).

The fertiliser implications of bundled SAP adoption are theoretically ambiguous. SAPs may complement inorganic fertiliser when residue retention, rotation, and reduced soil disturbance improve soil moisture, organic matter,

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or nutrient-use efficiency, thereby increasing the expected return to fertiliser. Conversely, improved nutrient cycling, legume rotations or lower production intensity may partly substitute for purchased nutrients. The debate is especially relevant in sub-Saharan Africa, where conservation agriculture often requires appropriate nutrient management to generate sufficient biomass and sustain productivity, but blanket fertiliser recommendations can perform poorly where soil constraints and crop responsiveness vary sharply (Kihara et al., 2016; Vanlauwe et al., 2014). Integrated soil fertility management consequently emphasises the locally adapted combination of mineral fertiliser, organic resources and improved agronomic practices rather than presuming universal complementarity (Stewart et al., 2020; Vanlauwe et al., 2010; Vanlauwe et al., 2015).

Existing evidence has concentrated more heavily on the determinants of SAP adoption and their effects on yields, income and resilience than on how bundled adoption relates to fertiliser-use intensity. Studies from Zambia show that SAP combinations can improve maize yields and household income, but they also reveal substantial differences across practices and farmer groups (Manda et al., 2016). More broadly, long-term and multi-site evidence indicates that conservation-agriculture outcomes vary with rainfall, soil texture, nitrogen input, residue management and implementation duration (Mhlanga et al., 2025; Siatwiinda et al., 2021; Wijk et al., 2011). An average pooled estimate may therefore mask relationships that differ across production environments.

Household governance adds another potential source of heterogeneity. Farm decision participation and control over crop revenue can shape technology choice, labour allocation and the capacity to finance inputs, but participation in a decision does not necessarily imply control over the resources needed to implement it (Doss, 2013). These variables may therefore be associated differently with SAP adoption and fertiliser use. Whether household decision arrangements actually modify the SAP-fertiliser relationship, however, is an empirical question rather than an assumption.

This study addresses these gaps using harmonised household data from Mungwi and Senanga, two contrasting maize-producing contexts in Zambia. It first identifies correlates of high bundled SAP adoption and then estimates the pooled association between high adoption and fertiliser-use intensity. Its principal contribution is a formal test of district heterogeneity, supported by adjusted margins and robustness analyses addressing differential outcome observation, upper-tail fertiliser values, the non-negative outcome distribution and observable selection. Household decision-making moderation is examined as a secondary hypothesis. By separating a robust district contrast from the less precise Mungwi estimate, the study provides a more cautious and policy-relevant account of how SAP bundles and fertiliser use relate under differing production conditions.

1.1 Statement of the Problem

SAP promotion and fertiliser-support programmes are frequently implemented in parallel, yet extension messages commonly imply that conservation-oriented practices and inorganic fertiliser should be promoted as a uniform package. This assumption is not self-evident. A bundle may raise fertiliser demand by improving moisture retention and the expected productivity of nutrients, or it may reduce fertiliser demand through enhanced nutrient cycling, legume rotations or changes in production intensity. The direction of the relationship is therefore an empirical matter with direct implications for input-support programmes, extension advice and the design of sustainable-intensification interventions.

The evidence gap is particularly important in Zambia. Existing studies have generated valuable evidence on conservation-farming adoption, crop productivity and household welfare, but much of the literature examines individual practices, defines adoption broadly, or estimates average effects without directly analysing fertiliser-use intensity (Arslan et al., 2014; Manda et al., 2016). The literature also shows that conservation-agriculture performance depends on rainfall, soils, nutrient inputs and implementation history, suggesting that pooled estimates may conceal meaningful agroecological differences (Thierfelder et al., 2013; Wijk et al., 2011). At the household level, resource control and decision participation may affect adoption and input allocation, but evidence that they moderate the SAP-fertiliser relationship remains limited.

Without context-specific evidence, programmes may recommend the same SAP-fertiliser combination in environments where farmers face different moisture constraints, soil responsiveness, input access and household resource-allocation conditions. This study therefore asks whether high bundled SAP adoption is associated with fertiliser-use intensity, whether the association differs between Mungwi and Senanga, and whether female/joint farm decision participation modifies it. The analysis also explicitly evaluates the sensitivity of the district findings to concentrated outcome missingness in Mungwi.

1.2 Research Objectives

i. determine the factors associated with high bundled SAP adoption;
ii. estimate the pooled association between high bundled SAP adoption and fertiliser-use intensity;
iii. assess whether the association differs between Mungwi and Senanga; and
iv. test, as a secondary objective, whether female/joint farm decision participation moderates the association.

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II. LITERATURE REVIEW

2.1 Theoretical Review

Agricultural Household Theory provides the principal economic foundation for the study. It treats the farm household as a joint production and consumption unit that allocates land, labour, cash and other resources to maximise household welfare. When labour, credit, insurance, land and input markets are incomplete, production choices cannot be separated cleanly from household endowments, consumption needs and liquidity constraints (De Janvry et al., 1991; Singh et al., 1986). SAP adoption and fertiliser allocation are therefore linked decisions: both depend on expected profitability, cash availability, labour requirements, information, assets and the household's capacity to absorb risk.

Risk and uncertainty reinforce this non-separability. Fertiliser is a cash-intensive input whose return depends on rainfall, soil conditions and crop management, while several SAPs require labour, residue retention or delayed benefits. In moisture-constrained environments, practices that reduce runoff or conserve soil water may lower production risk and raise the expected return to fertiliser. In wetter or poorly drained environments, the same practices may generate smaller or delayed gains. Long-term evidence confirms that conservation-agriculture responses depend on rainfall regime, soil texture, nitrogen input, rotation and the duration of implementation (Wijk et al., 2011).

Integrated soil fertility management provides the agronomic counterpart to the household model. It proposes that mineral fertiliser, organic resources and improved agronomic practices should be combined according to site-specific soil and crop conditions (Vanlauwe et al., 2010; Vanlauwe et al., 2015). The SAP-fertiliser relationship may consequently be complementary, substitutive or statistically imprecise. Vanlauwe et al. (2014) argue that appropriate fertiliser use is often essential for productive conservation agriculture in sub-Saharan Africa, whereas field evidence also demonstrates that responsiveness to nutrients varies widely within and between locations (Kihara et al., 2016).

Intra-household bargaining further extends the framework by recognising that household members may differ in preferences, information, labour responsibilities and control over income. Farm decision participation may improve information sharing or coordination, while control over maize revenue can determine whether cash is available for fertiliser or labour-intensive practices. These dimensions should not be treated as interchangeable (Doss, 2013; Doss & Quisumbing, 2021; Meinzen-Dick et al., 2011). They justify including both decision participation and revenue control in the empirical models, while leaving the direction and significance of moderation to be determined by the data.

2.2 Empirical Review

2.2.1 Determinants of bundled SAP adoption

Adoption studies consistently identify education, assets, labour availability, farming experience, access to information, credit and agroecological conditions as correlates of conservation-oriented technologies. Adoption is frequently sequential or partial because the value of one practice can depend on the presence of another, while benefits and costs differ across farms (Feder et al., 1985; Kassie et al., 2013; Knowler & Bradshaw, 2007; Teklewold et al., 2013). In Zambia, rainfall variability and extension support have been found to influence conservation-farming adoption, while labour constraints contribute to limited intensity and dis-adoption (Arslan et al., 2014). Reviews of southern African conservation agriculture caution that adoption cannot be understood solely from household covariates because project design, institutional support, markets and farmers' adaptation of promoted practices also matter (Andersson & D'Souza, 2014). Recent Zambian evidence similarly shows that soil-fertility-management practices are adopted in interconnected combinations and that information, groups, income, labour and farm characteristics shape adoption intensity (Chikopela et al., 2024).

2.2.2 SAP-fertiliser relationships

Evidence on the productive consequences of SAP bundles is generally favourable but heterogeneous. Manda et al. (2016) found that different combinations of sustainable agricultural practices produced different yield and income outcomes among rural Zambian households, confirming that bundles should not be treated as a single homogeneous technology. Crop rotations, residue retention and reduced tillage can generate agronomic synergies, yet their benefits often depend on adequate nutrient inputs, weed control and locally appropriate mechanisation or labour arrangements (Thierfelder et al., 2018). This distinction is important because a positive effect on productivity does not necessarily imply greater fertiliser use; the bundle may improve the return to fertiliser or reduce the amount required to achieve a given output.

Direct evidence on the SAP-fertiliser relationship remains limited. Vanlauwe et al. (2014) argue that fertiliser is a necessary complementary input where low soil fertility restricts biomass production and residue availability. Wijk et al. (2011), however, show that conservation-agriculture yield responses differ by rainfall, soil texture, rotation and nitrogen input, including weaker or adverse responses under some high-rainfall conditions. Kihara et al. (2016) further demonstrate that fertiliser response varies substantially even within sites because fields differ in nutrient limitations, soil

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carbon and responsiveness. Together, these studies indicate that the quantity of fertiliser used alongside SAPs should be expected to vary with local constraints rather than follow a universal pattern.

2.2.3 Sources of heterogeneity

Agroecological heterogeneity is therefore central. Rainfall amount and variability influence moisture stress and the risk attached to fertiliser expenditure, while soil texture, drainage and organic matter condition nutrient retention and crop response. Long-term Zambian evidence shows that conservation-agriculture effects on soil quality and maize productivity vary by location and management history (Thierfelder et al., 2013), and recent evidence from high-rainfall Northern Zambia indicates that productivity responses may emerge gradually over several seasons (Mhlanga et al., 2025). These findings justify a formal district interaction rather than relying only on separate or pooled regressions.

2.2.4 Household governance and resource allocation

Household governance may affect both adoption and input intensity through control over cash, labour and information. Doss (2013) emphasises that participation in decisions and control over productive resources are multidimensional and may not move together. This is relevant to the present study because female/joint participation in farm decisions and female/joint control over maize revenue capture different institutional positions within the household. Their coefficients should therefore be interpreted as conditional associations, not as direct measures of bargaining power or evidence that one household arrangement is intrinsically superior.

2.3 Synthesis and research gap

The reviewed literature establishes four points. First, SAP adoption is bundled, partial and context dependent. Second, conservation-oriented practices can create synergies with fertiliser, but adequate nutrient management and complementary practices are often required. Third, fertiliser response is heterogeneous across soils, rainfall regimes and management histories. Fourth, household resource control may influence adoption and input allocation, but evidence on moderation is limited. What remains insufficiently understood in Zambia is whether bundled SAP adoption is associated with fertiliser-use intensity, whether a pooled association masks contrasting agroecological relationships, and whether household decision participation alters that association. The present study addresses these linked gaps while explicitly assessing the consequences of differential outcome missingness.

III. METHODOLOGY

3.1 Study Area

The study was conducted in Mungwi District in Northern Province and Senanga District in Western Province. The two districts were selected because they represent contrasting maize-production environments in the study design. Senanga was treated as the drier Agroecological Region I context, whereas Mungwi represented the wetter Agroecological Region III context. Both districts are dominated by smallholder maize-based farming and have been exposed to sustainable-intensification promotion.

3.2 Data Source, Sampling and Analytical Sample

The study used cross-sectional household survey data. Face-to-face interviews captured household characteristics, maize production, fertiliser use, land allocation, institutional access, assets, household decision-making and adoption of crop rotation, residue retention and minimum or zero tillage. A multistage procedure selected agricultural camps and maize-producing households from camp-level registers.

District datasets were cleaned separately, including identity checks, unit harmonisation, harvest and fertiliser audits, recoding and missingness flags, before being appended into a pooled file. The cleaned survey contained 582 households: 311 in Mungwi and 271 in Senanga. Fertiliser-use intensity was originally observed for 520 households. Two Senanga records reporting 8,000 kg of fertiliser were retained in the audit data but designated as outliers and excluded from all fertiliser-outcome analyses. This produced 518 valid fertiliser outcomes and 517 complete cases for the benchmark outcome models. The multiple-imputation analysis retained all 580 non-outlier households and imputed 62 missing fertiliser outcomes together with two incomplete credit and cattle-ownership values. The high-SAP adoption model used 580 complete cases.

3.3 Measurement of Variables

The primary outcome was inorganic fertiliser applied per hectare. The principal regression outcome was ln(fertiliser kg/ha + 1), which retained zero-use observations and reduced the influence of the right-skewed distribution. High bundled SAP adoption equalled one when a household adopted at least two of crop rotation, residue retention and

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minimum or zero tillage. The continuous SAP breadth index was the number of practices adopted divided by three. The SAP variables measure adoption breadth; they do not measure duration, implementation quality or plot coverage.

Table 1
Variable definitions and measurement

Variable	Definition and measurement	Scale/coding	Role
Fertiliser-use intensity	Inorganic fertiliser quantity divided by maize area; two designated 8,000 kg records excluded from outcome analysis.	kg/ha	Raw outcome; PPML
Logged fertiliser-use intensity	Natural logarithm of fertiliser-use intensity plus one.	ln(kg/ha + 1)	Primary outcome
High bundled SAP adoption	Adoption of at least two of crop rotation, residue retention and minimum/zero tillage.	1 = high; 0 = low	Main explanatory variable
SAP adoption breadth	Number of the three SAP components adopted divided by three.	0-1 index	Continuous robustness
Female/joint farm decision participation	Spouse participates in farm decisions, or a female household head participates as head.	1 = participation; 0 = no identified female/joint participation	Control; secondary interaction
Female/joint maize-revenue control	Both male and female or a female household member controls maize revenue.	Binary	Control
Education	Completed years of formal schooling.	Years	Control
Credit access	Household reported access to credit.	Binary	Control
Maize-farming experience	Midpoint of reported maize-farming experience category.	Years	Control
Household size	Number of household members.	Count	Control
Cattle ownership	Household owns cattle.	Binary	Control
District	Mungwi or Senanga.	Mungwi reference; Senanga indicator	Heterogeneity variable

Notes: SAP = sustainable agricultural practice. The analysis is cross-sectional and all estimated relationships are interpreted as associations.

3.4 Empirical Strategy

The analysis began with a robust logit model of high bundled SAP adoption. Average marginal effects were reported for ease of interpretation. The fertiliser analysis then estimated a pooled ordinary least squares model with heteroskedasticity-robust standard errors:

$$ln(Fert\_i + 1) = \alpha + \beta_1 HighSAP\_i + \beta_2 Senanga\_i + \Sigma\gamma\_kX\_ki + \varepsilon\_i \quad \textbf{(1)}$$

where Fert_i is fertiliser-use intensity in kg/ha, HighSAP_i indicates adoption of at least two SAP components, Senanga_i is the district indicator and X_ki contains female/joint decision participation, female/joint revenue control, education, credit, maize experience, household size and cattle ownership. The preferred specification tested whether the high-SAP association differed between districts:

$$ln(Fert\_i + 1) = \alpha + \beta_1 HighSAP\_i + \beta_2 Senanga\_i + \beta_3(HighSAP\_i \times Senanga\_i) + \Sigma\gamma\_kX\_ki + \varepsilon\_i \quad \textbf{(2)}$$

The marginal high-SAP association was calculated separately for Mungwi and Senanga, and adjusted predictive margins were reported with robust 95% confidence intervals. A separate interaction replaced the district interaction with HighSAP_i × FemaleJoint_i to test the secondary decision-making hypothesis (Brambor et al., 2006).

3.5 Missingness, Extreme Values and Robustness

Fertiliser outcomes were originally missing for 62 households because fertiliser quantity was unavailable despite observed maize area; 61 of these households were in Mungwi. No missing outcome could be reconstructed from observed fertiliser quantity and maize area. Because missingness in Mungwi differed sharply by SAP status, a robust logit model estimated the probability that the fertiliser outcome was observed. Stabilised inverse-probability-of-observation weights, trimmed at the Mungwi 99th percentile, were then used in a weighted version of the preferred interaction model. Weight diagnostics included the distribution of observation probabilities, the number of trimmed observations and the effective weighted sample size.

Upper-tail robustness was assessed by winsorising fertiliser intensity at the 99th percentile and by excluding observations above that threshold. A Poisson pseudo-maximum-likelihood model estimated the relationship on the

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original non-negative kg/ha scale, and inverse-probability-weighted regression adjustment was used to adjust for observable differences between high and low adopters. Missing fertiliser outcomes were additionally imputed under a missing-at-random assumption using chained equations with predictive mean matching, 10 nearest neighbours and 50 imputations; the imputation model included the district interaction, all outcome-model covariates and auxiliary farm, production, cost and income variables (White et al., 2011). Delta-adjusted pattern-mixture analyses then shifted the imputed Mungwi outcomes to assess sensitivity to plausible missing-not-at-random departures (Leacy et al., 2017). All specifications were interpreted as associational and implemented using standard robust-inference principles (Wooldridge, 2016).

IV. FINDINGS & DISCUSSION

4.1 Sample Characteristics and Fertiliser Distribution

Table 2 presents the sample flow and descriptive statistics. High bundled SAP adoption was observed for 153 of the 582 surveyed households (26.29%). Female-headed households represented 57.22% of the survey sample; this is reported as a characteristic of the sampled communities and should not be interpreted as a national prevalence estimate. Female/joint participation in farm decision-making was identified for 70.62% of households, while 74.74% reported female/joint control over maize revenue. These two measures represent distinct dimensions of household governance.

After the two designated outliers were excluded, mean fertiliser-use intensity was 264.47 kg/ha, the median was 129.17 kg/ha and the maximum was 2,400 kg/ha. The raw distribution remained right-skewed, supporting the logged outcome and PPML robustness specification. In the final complete-case sample, mean logged fertiliser-use intensity was 3.756 among low adopters and 5.275 among high adopters; this unadjusted difference does not account for district composition or other covariates.

Table 2

Sample flow and descriptive statistics

Panel A. Sample flow		**Pooled**	**Mungwi**		**Senanga**
Cleaned survey sample		582	311		271
Originally observed fertiliser outcome		520	250		270
Designated 8,000 kg records excluded		2	0		2
Valid fertiliser outcome		518	250		268
Main outcome-model complete cases		517	249		268
High-SAP adoption-model complete cases		580	309		271
Panel B. Main analytical variables	**N**	**Mean**	**SD**	**Minimum**	**Maximum**
Logged fertiliser-use intensity	517	4.088	2.368	0.000	7.784
SAP adoption breadth index	517	0.360	0.309	0.000	1.000
High bundled SAP adoption	517	0.219	0.414	0.000	1.000
Female/joint decision participation	517	0.677	0.468	0.000	1.000
Female/joint maize-revenue control	517	0.754	0.431	0.000	1.000
Years of formal education	517	6.698	3.316	0.000	14.000
Credit access	517	0.273	0.446	0.000	1.000
Maize-farming experience	517	10.450	8.914	0.000	51.000
Household size	517	5.497	2.494	1.000	18.000
Cattle ownership	517	0.408	0.492	0.000	1.000

Notes: Binary-variable means are proportions. The raw fertiliser distribution among 518 valid outcomes had a mean of 264.47 kg/ha, median of 129.17 kg/ha and range of 0-2,400 kg/ha.

4.1.1 Correlates of High Bundled SAP Adoption

Table 3 reports average marginal effects from the pooled adoption model. Female/joint farm decision participation was associated with a 13.3 percentage-point lower probability of high bundled adoption. In contrast, female/joint control over maize revenue was associated with a 25.2 percentage-point higher probability. Each additional household member was associated with a 4.1 percentage-point higher probability, while cattle ownership was associated with a 15.2 percentage-point lower probability. Education, credit, experience and district were not statistically significant in the pooled model. District-specific adoption models are reported in Supplementary Table A1; credit is omitted from the Senanga model because it perfectly predicts adoption status in that subsample. These results identify conditional associations rather than the mechanisms through which household governance or assets influence adoption.

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Table 3

Correlates of high bundled SAP adoption: pooled average marginal effects

Variable	Average marginal effect	Robust SE	p-value
Female/joint farm decision participation	-0.133***	0.042	0.002
Female/joint control over maize revenue	0.252***	0.052	<0.001
Years of formal education	-0.009*	0.005	0.090
Credit access	0.044	0.046	0.335
Maize-farming experience	-0.000	0.002	0.998
Household size	0.041***	0.009	<0.001
Cattle ownership	-0.152***	0.040	<0.001
Senanga district	-0.066	0.053	0.211
Observations	580		
Pseudo R-squared	0.099		

Notes: Robust logit average marginal effects. *** p < 0.01; ** p < 0.05; * p < 0.10. District-specific adoption models are reported in Supplementary Table A1.

4.1.2 Adjusted Association with Fertiliser-Use Intensity

The pooled model in Table 4 shows a positive association between high bundled SAP adoption and logged fertiliser-use intensity (estimate = 1.302; p < 0.001). The continuous SAP breadth index was also positive. These pooled results should not be interpreted as evidence of a uniform complementary relationship because district-specific estimates point in opposite directions.

In the benchmark complete-case models, high adoption was negatively associated with logged fertiliser-use intensity in Mungwi (estimate = -0.551; p = 0.038) and positively associated with it in Senanga (estimate = 3.357; p < 0.001). Model fit was higher in Senanga (R-squared = 0.313) than in Mungwi (R-squared = 0.129), but this difference is descriptive and does not identify the mechanism underlying the district contrast. The complete-case interaction model formalised the contrast: with Mungwi as the reference category, the high-SAP coefficient was -0.610 (p = 0.018), and the high-SAP-by-Senanga interaction was 3.941 (p < 0.001). These estimates are treated as benchmark results and evaluated against the missing-data analyses in Section 4.6.

Table 4

Complete-case adjusted associations with logged fertiliser-use intensity

Variable	(1) Pooled	(2) SAP breadth	(3) Mungwi	(4) Senanga	(5) SAP × district
High bundled SAP adoption	1.302*** (0.247)		-0.551** (0.264)	3.357*** (0.409)	-0.610** (0.257)
SAP adoption breadth index		2.093*** (0.332)			
Senanga district	-2.091*** (0.271)	-2.288*** (0.274)			-2.916*** (0.291)
High SAP × Senanga					3.941*** (0.440)
Female/joint decision participation	-0.139 (0.218)	-0.146 (0.212)	0.134 (0.192)	-0.253 (0.408)	-0.007 (0.201)
Female/joint maize-revenue control	0.299 (0.255)	0.260 (0.250)	-0.188 (0.267)	0.228 (0.460)	-0.036 (0.241)
Education	-0.034 (0.027)	-0.041 (0.027)	0.077*** (0.024)	-0.121** (0.052)	-0.001 (0.027)
Credit access	-0.312 (0.210)	-0.378* (0.212)	-0.325* (0.182)	0.372 (0.511)	-0.184 (0.191)
Maize experience	0.017 (0.014)	0.019 (0.013)	-0.025 (0.028)	0.023 (0.017)	0.029** (0.014)
Household size	0.144*** (0.047)	0.122** (0.047)	0.144*** (0.036)	-0.044 (0.081)	0.061 (0.045)
Cattle ownership	-0.384* (0.213)	-0.346 (0.210)	-0.211 (0.235)	0.119 (0.316)	-0.170 (0.208)
Constant	4.265*** (0.358)	4.077*** (0.360)	4.319*** (0.400)	3.228*** (0.722)	4.789*** (0.337)
Observations	517	517	249	268	517
R-squared	0.221	0.239	0.129	0.313	0.326

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Notes: Dependent variable is ln(fertiliser kg/ha + 1). Robust standard errors are in parentheses. Mungwi is the reference district. *** p < 0.01; ** p < 0.05; * p < 0.10.

4.1.3 District Heterogeneity and Adjusted Margins

Complete-case adjusted predictions are reported in Table 5 and Figure 2. In Mungwi, predicted logged fertiliser-use intensity declined from 5.268 among low adopters to 4.658 among high adopters. In Senanga, it increased from 2.352 to 5.683. The corresponding complete-case high-SAP associations were -0.610 in Mungwi and 3.331 in Senanga. The formal interaction rejected H02 in the benchmark model; the missing-data analyses reported below confirm a strong district difference but show that the statistical precision of the Mungwi association is sensitive to how the missing fertiliser outcomes are handled.

Table 5

Complete-case adjusted fertiliser-use intensity by district and SAP status

Panel A. Adjusted margins	SAP status	Margin	Robust SE	95% CI
Mungwi	Low SAP	5.268	0.144	4.985 to 5.552
Mungwi	High SAP	4.658	0.242	4.183 to 5.133
Senanga	Low SAP	2.352	0.204	1.952 to 2.752
Senanga	High SAP	5.683	0.299	5.095 to 6.271
Panel B. Marginal association of high SAP	**Estimate**	**Robust SE**	**p-value**	**95% CI**
Mungwi	-0.610**	0.257	0.018	-1.115 to -0.106
Senanga	3.331***	0.349	<0.001	2.645 to 4.016

Notes: Margins are adjusted for household decision participation, maize-revenue control, education, credit, maize experience, household size and cattle ownership. Robust 95% confidence intervals; N = 517.

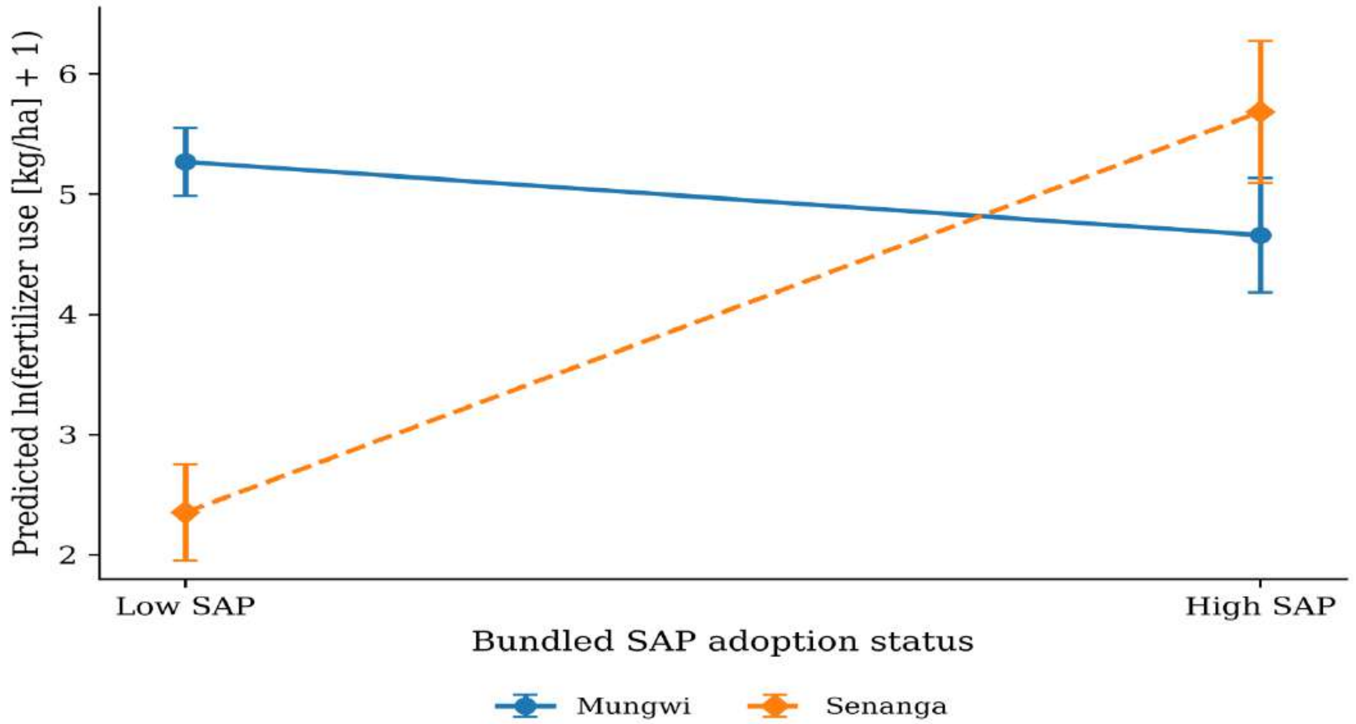

Figure 2

Complete-case adjusted predicted logged fertiliser-use intensity by bundled SAP adoption status and district.

Notes: Error bars are robust 95% confidence intervals. The dependent variable is ln(fertiliser kg/ha + 1); N = 517.

Figure 2 shows the benchmark complete-case pattern: adjusted fertiliser-use intensity declines between low and high adopters in Mungwi but rises sharply in Senanga. Because the Mungwi estimate is sensitive to missing-outcome treatment, this figure should be read together with Figure 3 and the missing-data results in Section 4.6.

4.1.4 Secondary Household Decision-Making Test

The high-SAP-by-female/joint decision-participation interaction was 0.368 (p = 0.458). The conditional high-SAP association was positive in households with no identified female/joint participation and in households with

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female/joint participation, but the difference between the two associations was not statistically significant. H03 is therefore not rejected. Household governance remains relevant to adoption and resource allocation, but the results do not support a claim that it moderates the SAP-fertiliser relationship in this sample. Full margins are reported in Supplementary Table A2 and Figure S2.

4.1.5 Missingness and Robustness

Fertiliser-use intensity was unavailable for 62 of the 582 surveyed households (10.65%) because fertiliser quantity was missing despite observed maize area. Missingness was concentrated in Mungwi, where the outcome was unavailable for 24 of 222 low-SAP households (10.81%) and 37 of 89 high-SAP households (41.57%). The pronounced difference by SAP status created a material risk of complete-case selection bias. Observation-weighted estimation retained a negative Mungwi association (estimate = -0.819; p = 0.005) and a positive high-SAP-by-Senanga interaction (estimate = 4.171; p < 0.001). The weights were not excessively unstable: the minimum estimated observation probability was 0.157, only two observations were trimmed at the 99th percentile, the maximum trimmed weight was 3.082 and the effective weighted Mungwi sample was approximately 212 compared with 249 observed cases.

Multiple imputation under a missing-at-random assumption produced a smaller negative Mungwi estimate that was not statistically distinguishable from zero (estimate = -0.323; p = 0.162). The Senanga association remained strongly positive (estimate = 3.320; p < 0.001), and the district interaction remained large and statistically significant (estimate = 3.643; p < 0.001). In the delta-adjusted missing-not-at-random analyses, the Mungwi estimate became positive only when the missing high-SAP outcomes were shifted upward by one log point relative to their missing-at-random predictions, approximately multiplying fertiliser plus one by 2.72. Under a symmetric scenario, the sign crossed zero at a relative delta of 1.25. The district interaction remained statistically significant throughout the evaluated range to delta 1.50. Upper-tail checks, PPML and IPWRA likewise retained the strong positive Senanga pattern. Figure 3 compares the district-specific estimates across the three principal missing-data analyses.

Table 6

Robustness and sensitivity analyses

Panel A. District-interaction robustness	**N**	**Mungwi high-SAP term**	**SE**	**p-value**	**High SAP × Senanga**	**SE**	**p-value**
Preferred robust OLS	517	-0.610**	0.257	0.018	3.941***	0.440	<0.001
Observation-weighted OLS	517	-0.819***	0.293	0.005	4.171***	0.467	<0.001
P99-winsorised outcome	517	-0.611**	0.257	0.018	3.933***	0.439	<0.001
Above-p99 excluded	514	-0.615**	0.257	0.017	3.856***	0.441	<0.001
PPML on kg/ha	517	-0.517***	0.166	0.002	2.639***	0.242	<0.001
Multiple imputation under MAR	580	-0.323	0.231	0.162	3.643***	0.414	<0.001

Panel B. IPWRA estimates	**N**	**ATET**	**Robust SE**	**p-value**	**95% CI**
Pooled	517	1.723***	0.318	<0.001	1.099 to 2.346
Mungwi	249	-0.546**	0.259	0.035	-1.054 to -0.039
Senanga (credit omitted)	268	4.254***	0.346	<0.001	3.576 to 4.932

Notes: OLS and PPML coefficients are on different scales. Multiple imputation used 50 chained-equation imputations and predictive mean matching. Detailed MNAR tipping-point results are reported in Supplementary Table A6 and Figures S5-S6. IPWRA and multiple imputation adjust for stated observed-data assumptions but do not establish causality.

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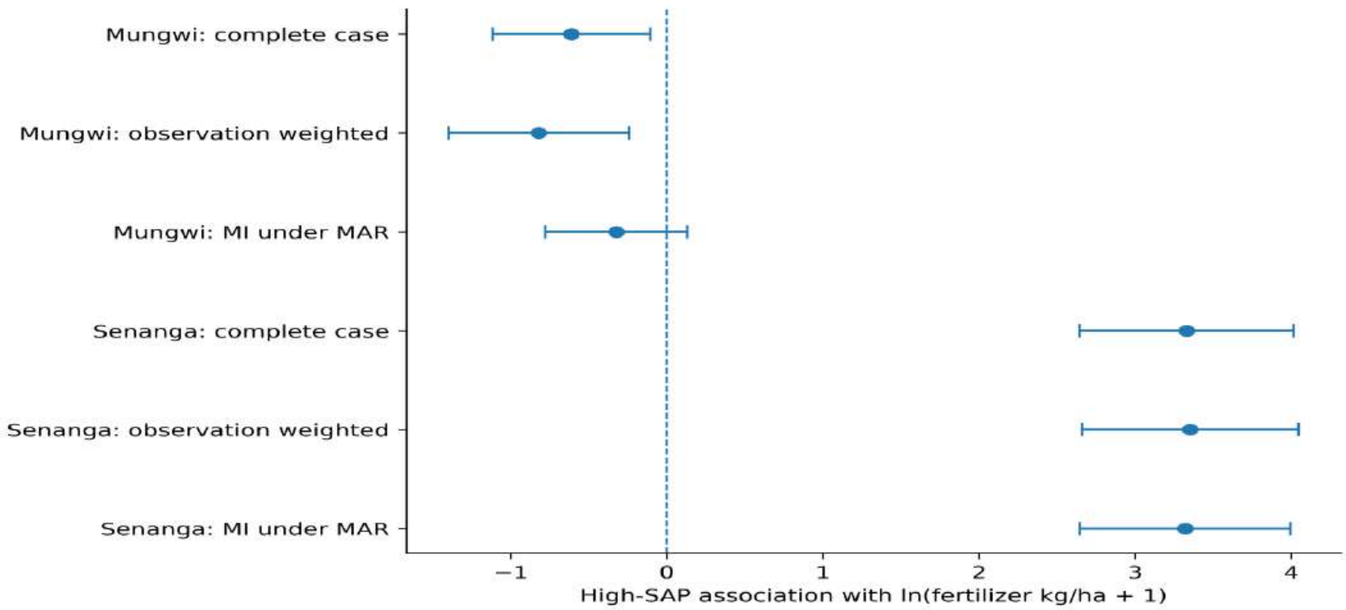

Figure 3
District-specific high-SAP associations across missing-data analyses.

Notes: Points show district-specific high-SAP associations; error bars are 95% confidence intervals. Complete-case and observation-weighted models use N = 517; multiple imputation uses N = 580.

Figure 3 demonstrates that the Senanga association remains large and positive under complete-case, observation-weighted and multiple-imputation analyses. The Mungwi point estimate remains negative across the three methods, but its multiple-imputation confidence interval crosses zero, supporting a cautious rather than definitive interpretation.

4.2 Discussion

4.2.1 Context-Dependent SAP-Fertiliser Relationships

The principal finding is the robust difference between districts rather than the positive pooled association. In Senanga, high bundled SAP adoption is associated with substantially greater fertiliser-use intensity across complete-case, observation-weighted and multiple-imputation models. This pattern is consistent with complementarity under a moisture-constrained production environment: practices that reduce soil disturbance, retain residues or diversify rotations may stabilise moisture availability and increase the expected return to fertiliser. A meta-analysis by Wijk et al. (2011) found that conservation-agriculture systems combining rotation and adequate inputs were more likely to generate yield gains in low-rainfall environments, while Vanlauwe et al. (2014) argue that appropriate fertiliser use is often necessary for conservation agriculture to sustain biomass and productivity in nutrient-constrained African smallholder systems.

The strong Senanga result should nevertheless be interpreted as an association rather than direct evidence of an agronomic mechanism. Soil fertility, fertiliser timing, input prices and realised rainfall were not modelled at plot level. Even so, the result is coherent with evidence that complementary practices, nutrient management and enabling conditions must be adapted to local agroecologies (Thierfelder et al., 2018). Kihara et al. (2016) show that crop responsiveness to fertiliser can vary markedly within and between sites because different soil constraints limit production. The Senanga estimate may therefore reflect a setting in which households adopting broader management bundles also find fertiliser more worthwhile or necessary.

The Mungwi relationship is less certain. Complete-case and observation-weighted estimates are significantly negative, but the multiple-imputation estimate is smaller and statistically imprecise. This pattern does not justify a firm conclusion that SAP bundles substitute for fertiliser in Mungwi. It does, however, suggest that the positive Senanga relationship is not transferable automatically to the wetter district. Long-term evidence from Zambia shows that conservation-agriculture responses depend on local soil and management history (Thierfelder et al., 2013), while high-rainfall benefits may emerge gradually rather than through an immediate increase in input intensity (Mhlanga et al., 2025). Wijk et al. (2011) also report that high-rainfall conditions can produce weaker outcomes under some residue-retention systems, reinforcing the need for a context-specific interpretation.

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4.2.2 Household Governance and Adoption

The adoption model also reveals that household governance variables capture distinct processes. Female/joint farm decision participation is negatively associated with high bundled adoption, whereas female/joint control over maize revenue is positively associated with it. The contrast is plausible because participation in a decision does not necessarily confer authority over the cash, labour or assets needed to implement a bundle. Doss (2013) cautions that decision-making indicators are multidimensional and should not be interpreted as direct measures of empowerment or bargaining power. The present estimates therefore describe conditional associations and should not be read as evidence that women's participation discourages sustainable practices.

The negative cattle-ownership association may reflect the competing demands that mixed crop-livestock systems place on residues, labour and land. Residues retained for soil cover can also be valued as livestock feed, creating a trade-off that affects the feasibility of conservation-oriented bundles (Valbuena et al., 2012). More generally, the importance of household size, revenue control and assets is consistent with Zambian and regional evidence that adoption depends on labour availability, extension, rainfall risk and household resources (Andersson & D'Souza, 2014; Arslan et al., 2014; Manda et al., 2016). These comparisons enrich the interpretation but do not establish the behavioural mechanisms behind the coefficients.

4.2.3 Household Decision-Making Moderation

The secondary interaction test does not support the earlier proposition that female/joint farm decision participation significantly moderates the SAP-fertiliser relationship. The conditional high-SAP association is positive in both decision categories, and the difference between the slopes is not statistically significant. This null finding is substantively important because it prevents the paper from converting descriptive household categories into unsupported claims about differential fertiliser responses.

The absence of moderation does not imply that household governance is irrelevant. Decision participation and revenue control remain associated with adoption and may affect access to information, labour coordination and input finance. Rather, the result indicates that the measured decision regime does not alter the high-SAP association with fertiliser intensity once the model covariates are controlled. This interpretation is consistent with the broader caution that household decision indicators capture different domains and should not be treated as a single hierarchy of influence (Doss, 2013).

4.2.4 Missing-Data Sensitivity and Strength of Evidence

The missing-data extension materially improves the credibility and precision of the study's claims. Fertiliser quantity was unavailable for 62 households, with missingness concentrated among high adopters in Mungwi. Observation weighting produced manageable weights and retained the negative complete-case pattern, while multiple imputation used all 580 non-outlier households. The multiple-imputation estimate reduced the magnitude and statistical precision of the Mungwi association but left the Senanga association and district interaction virtually unchanged. This comparison shows why the conclusion should focus on robust heterogeneity and Senanga rather than the complete-case significance of Mungwi.

The delta-adjusted analysis further shows that the district interaction remains significant across substantial departures from the missing-at-random assumption. The Mungwi coefficient becomes positive only after a large upward shift in the imputed outcomes of missing high adopters. These analyses do not prove that the missingness assumptions are correct, but they transparently identify which conclusions are stable and which are sensitive. This use of multiple imputation and delta adjustment follows established guidance for analysing and communicating sensitivity to incomplete outcomes (Leacy et al., 2017; White et al., 2011).

4.2.5 Policy and Extension Implications

Extension programmes should avoid treating bundled SAP adoption as a uniform signal for either higher or lower fertiliser demand. In Senanga, the robust positive association supports testing integrated packages in which moisture-conserving practices, rotation and site-appropriate fertiliser management are promoted together. In Mungwi, the uncertain relationship calls for diagnosis rather than prescriptive coupling: extension should assess soil condition, current fertiliser practice, drainage, organic-resource availability and the age and quality of SAP implementation before recommending changes in rates or timing. This approach is consistent with evidence that fertiliser responsiveness and conservation-agriculture performance are site-specific (Kihara et al., 2016; Thierfelder et al., 2018).

Programmes should also monitor implementation quality, duration and plot coverage because the study's SAP indicator measures breadth rather than agronomic fidelity. Demonstrations should compare locally relevant fertiliser rates, placement and timing under clearly documented SAP combinations and should record labour, residue and livestock trade-offs. Household engagement should include both women and men in information sharing and resource planning, but it should not be justified by a moderation effect that was not observed. The broader policy implication is

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to move from technology promotion based on adoption counts toward adaptive management that links soil and crop diagnosis, farmer resources and locally tested input combinations (Thierfelder et al., 2018; Vanlauwe et al., 2014).

V. CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

High bundled SAP adoption was positively associated with fertiliser-use intensity in the pooled complete-case model, but the average concealed substantial district heterogeneity. The Senanga association was strongly positive across complete-case, observation-weighted and multiple-imputation analyses. In Mungwi, the estimated association remained negative across the three approaches but was not statistically distinguishable from zero after multiple imputation. The difference between districts remained large and statistically significant under missing-at-random and the evaluated missing-not-at-random assumptions. Female/joint farm decision participation did not significantly moderate the relationship.

The evidence therefore supports a robust positive Senanga relationship and robust agroecological heterogeneity, but not a definitive negative Mungwi relationship. Bundled SAPs and inorganic fertiliser should not be assumed to be universally complementary or substitutable. Their observed relationship depends on production context, and the strength of inference also depends on how incomplete outcomes are handled.

5.2 Recommendations

Extension and input-support programmes should translate the district heterogeneity into locally differentiated advice. In Senanga, the evidence supports on-farm testing and promotion of packages that combine SAP bundles with balanced, site-appropriate fertiliser management, particularly where moisture conservation can protect the return to nutrient investment. In Mungwi, recommendations should be preceded by farm and plot diagnosis because the negative point estimate is not statistically precise after multiple imputation. Agricultural extension officers should therefore assess soil condition, drainage, organic-resource availability, existing fertiliser rates and the duration and quality of SAP implementation before recommending either higher or lower fertiliser use.

Demonstrations and monitoring systems should record more than whether a practice was adopted. They should document the specific combination used, plot coverage, duration, residue-management quality, labour requirements, fertiliser timing and placement, and crop-livestock trade-offs. Input-support and sustainable-intensification programmes should coordinate their messages so that fertiliser guidance reflects the practices being implemented and the local constraints affecting crop responsiveness. Inclusive household engagement should remain part of extension delivery to improve information sharing and resource planning, while avoiding unsupported claims that a particular decision regime necessarily changes the fertiliser response to SAP adoption.

Future research should use longitudinal, panel or experimental designs that follow plots and households across seasons. Combining household surveys with plot-level soil tests, weather data, fertiliser prices, application timing and verified measures of SAP quality would make it possible to identify the biophysical and behavioural mechanisms underlying the district contrast. Research designs should also plan prospectively for fertiliser-quantity nonresponse and incorporate qualitative evidence on why farmers adopt particular bundles and how household members negotiate input and revenue decisions.

Declaration of Interest

The authors declare that they do not have any known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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