

Adaptation Portfolios and Perceived Effectiveness of Food-System Resilience Strategies Among Smallholder Farmers in Southern Zambia's Agro-Ecological Region I

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Abstract

Climate change is increasingly reshaping agrifood systems in semi-arid regions. However, limited evidence exists on how smallholder farmers combine multiple adaptation strategies into portfolios and whether these combinations are perceived as effective. This study examines adaptation portfolios and the perceived effectiveness of food-system resilience strategies among smallholder farmers in Zambia's semi-arid Agro-ecological Region I of Southern Province. An explanatory sequential mixed methods research design was used to collect the data. A household survey was conducted with 202 smallholder farmers across Chirundu, Gwembe, Kazungula and Siavonga districts. Data were analysed using descriptive statistics, Mann-Whitney U tests, principal component analysis, hierarchical clustering, Poisson regression and binary logistic regression. Perceived effectiveness was measured on a 1–5 scale, with scores ≥ 4 classified as high effectiveness. The results showed that irrigation was the most widely adopted strategy (85.1%), followed by agroforestry (65.3%) and extension (59.9%). However, drought-tolerant crop varieties were the most effective among adopters (4.28/5). The comprehensive portfolio combining all five strategies achieved near-universal high effectiveness (97.5%, mean = 4.90/5). Each additional strategy adopted doubled the odds of reporting high effectiveness (OR = 2.18, $p < 0.001$). Land access emerged as the dominant structural constraint: medium landholders (6 to 10 ha) had 5-fold higher odds (OR = 4.95, $p < 0.001$) and larger landholders (10 to 15 ha) 20-fold higher odds (OR = 20.15, $p = 0.013$) of high effectiveness compared to land-constrained households (< 5 ha). Land-constrained farmers could not achieve high effectiveness regardless of portfolio breadth. Gender, household size, and district were not significant predictors after controlling for land access. In conclusion, adaptation portfolios substantially outperform single strategies, but land access remains the binding structural constraint limiting their effectiveness for vulnerable households. By shifting attention from single practices to portfolios and from adoption to effectiveness, the study shows that policy must move toward portfolio-based adaptation and address land governance to enable equitable, climate-resilient food-system transformation.

INTRODUCTION

Climate change is increasingly reshaping agrifood systems through interacting biophysical, economic and social pathways. In semi-arid regions, rainfall variability, drought, heat stress and land degradation directly affect production, but household resources, market conditions, institutional support and access to adaptation options often mediate their impacts (Bezner Kerr et al., 2022, 2022; Musa et al., 2025). This complexity has shifted climate–food systems research away from single-risk explanations towards systems-based approaches that recognise the combined effects of climate stress, structural vulnerability and livelihood constraints. (Arslan et al., 2022; Hadley et al., 2023; Mwale, 2023). For smallholder farmers, resilience is therefore determined not only by exposure to climatic hazards but also by the range, suitability and effectiveness of strategies available to sustain food production, access, utilisation and livelihood stability. (Ballamingie et al., 2020; Mwale, 2023) Adaptation has become central to climate-resilient food-system transformation in Africa. Common strategies include crop diversification, irrigation, drought-tolerant varieties, agroforestry, extension support, climate-smart

agriculture and market-oriented livelihood adjustments. (Campbell et al., 2023; A. R. Dzvene et al., 2025; Zougmore et al., 2021). However, evidence increasingly shows that single adaptation practices are rarely sufficient in the face of compound climate and food-system risks. Households often combine several practices to manage different forms of uncertainty, creating adaptation portfolios that reflect available resources, perceived risks, knowledge systems and institutional access. Recent work on climate-smart agriculture and multiple-practice adoption suggests that bundled or portfolio-based strategies may offer stronger resilience benefits than isolated interventions by spreading risk across production, ecological and economic domains. (Reidsma et al., 2023; Tirado et al., 2022; Wassihun et al., 2026). An adaptation portfolio is defined here as the set of strategies that a household simultaneously employs to manage climate-related food-system risks.

Despite this growing recognition, important empirical gaps remain. First, many studies document whether farmers adopt specific practices. (Azadi et al., 2019; Mwale, 2023; Wassihun et al., 2026) However, pay less attention to how combinations of practices function as adaptation portfolios. This limits understanding of whether resilience is enhanced by individual strategies or by the cumulative effect of multiple, complementary practices. Second, adaptation studies often infer effectiveness from adoption, although adoption does not necessarily mean that farmers perceive a strategy as useful, affordable, reliable or sustainable. Farmers may adopt practices because of project exposure, extension messaging or short-term necessity, while still perceiving them as only partially effective under persistent drought, market instability or land pressure. (H. Azadi et al., 2022; Y. Azadi et al., 2019; Ndhlovu, 2023). Third, adaptation effectiveness is often analysed in relation to agricultural production, with limited attention to wider food-system resilience, including food availability, livelihood stability, ecosystem services and household capacity to respond to shocks (Fanzo & Davis, 2021; Galanakis et al., 2025; Meyer, 2020).

These gaps are particularly relevant to Zambia's semi-arid Agro-Ecological Region I, where smallholder food systems face low and variable rainfall (Chisengele & Nyanga, 2026; Makondo & Thomas, 2020), recurring droughts, heat stress, land constraints, and shifting market conditions. Climate-security analysis for Zambia highlights how climatic stress can interact with livelihood insecurity, resource pressures and local socio-economic vulnerabilities (Chisengele & Nyanga, n.d.; Ndhlovu, 2023). In such contexts, adaptation cannot be reduced to promoting a single climate-smart practice. Farmers may need diversified portfolios that combine water management, crop diversification, improved varieties, agroforestry, and extension-based knowledge support. However, there is limited empirical evidence on which adaptation strategies are most commonly combined, which households can adopt broader portfolios, and whether farmers perceive these portfolios as effective in enhancing food-system resilience.

This study addresses this gap by examining adaptation portfolios and the perceived effectiveness of food-system resilience strategies among smallholder farmers in Zambia's semi-arid Agro-Ecological Region I. Specifically, the study analyses the uptake and combination of selected adaptation strategies, including irrigation, crop diversification, drought-tolerant varieties, extension services and agroforestry.

(Chisengele & Nyanga, 2026; Karan et al., 2022). It further assesses how socio-demographic and structural factors, including district, gender, education, income, household size and farmland size, shape adaptation intensity and perceived effectiveness. By shifting attention from single practices to adaptation portfolios, the study contributes to climate food systems scholarship in three ways. First, it provides household-level evidence on how smallholder farmers combine resilience strategies under semi-arid conditions. Second, it distinguishes between adoption and perceived effectiveness, thereby avoiding the assumption that practice uptake automatically translates into resilience. Third, it generates policy-relevant evidence for designing integrated adaptation packages that are responsive to local constraints, rather than relying on fragmented climate-smart interventions.

RESEARCH METHODOLOGY

2.1 Study design

The study adopted an explanatory sequential mixed-methods design. This design was appropriate because the study first generated quantitative evidence on adaptation portfolios and the perceived effectiveness of food-system resilience strategies (Creswell & Plano Clark, 2023). The qualitative data were used to explain, contextualise, and enrich the interpretation of the survey results. While the quantitative phase revealed measurable patterns in strategy adoption, combinations of adaptation practices, and perceptions of effectiveness, the qualitative phase focused on understanding why farmers chose specific strategies, how they evaluated their usefulness, and which contextual factors influenced their adaptation decisions. The study was informed by a food-system resilience framework, which conceptualises resilience as the capacity of households and communities to anticipate, absorb, adapt to and recover from climate-related shocks while maintaining food security outcomes. The framework guided the selection of variables related to adaptation strategies, adaptation intensity, perceived effectiveness, and household characteristics, and informed the interpretation of resilience outcomes across different adaptation portfolios.

2.2 Study area

The study was conducted in Zambia's semi-arid Agro-Ecological Region I, focusing on four districts: Chirundu, Gwembe, Kazungula and Siavonga (Fig. 1). These districts were selected because they are located in a climate-stressed agro-ecological zone characterised by low and variable rainfall, recurrent droughts, high temperatures and strong dependence on rain-fed smallholder agriculture (Chisengele & Nyanga, 2026; Makondo & Thomas, 2020). The districts also represent diverse livelihood, market and ecological conditions, including riverine, lakeshore, border and dryland farming systems (Chisengele & Nyanga, 2025; Masasi, 2025). This made them suitable for examining adaptation portfolios and perceived effectiveness of resilience strategies among smallholder farmers.

2.3 Quantitative sampling and data collection

The quantitative phase involved a household survey of 202 smallholder farmers across the four study districts. The sample was distributed as follows: A multi-stage sampling procedure was employed. First, the four districts were purposively selected because of their high exposure to climate variability and recurrent droughts. Second, agricultural camps and villages were selected using probability-based procedures within each district. Third, eligible smallholder farming households were selected using systematic random sampling from village household registers. Only households actively engaged in crop and/or livestock production during the study period were included in the survey. Chirundu, 50 respondents; Gwembe, 50 respondents; Kazungula, 52 respondents; and Siavonga, 50 respondents. Respondents were selected from smallholder farming households because they are directly exposed to climate-related food-system risks and are primary users of household-level adaptation strategies. The minimum sample size was determined using Cochran's sample size formula at a 95% confidence level and a 5% margin of error. The final sample of 202 households exceeded the minimum threshold required for statistical analysis and regression modelling. A structured questionnaire was used to collect data on socio-demographic characteristics, household size, income, farmland size, perceived changes in the food system, adaptation strategies, barriers to adaptation, and the perceived effectiveness of resilience strategies. The adaptation strategies assessed included irrigation, crop diversification, the use of drought-tolerant varieties, extension services, and agroforestry. Perceived effectiveness was measured using a multi-item Likert scale assessing the extent to which adaptation strategies contributed to improved food availability, food access, production stability, income security and resilience to climate shocks. Responses were measured on a five-point scale ranging from strongly disagree (1) to agree (5) strongly. Composite effectiveness scores were generated by aggregating responses across the indicator items. The questionnaire was administered through face-to-face interviews. This approach was suitable because it allowed the researcher to reach respondents with different levels of literacy and to ensure that questions were clearly understood. Before full data collection, the tool was reviewed for clarity, relevance and consistency with the study objectives. The questionnaire was pre-tested with smallholder farmers outside the study sample to assess its clarity, comprehensibility, and contextual relevance. Feedback from the pilot exercise informed revisions to question wording, sequencing and response categories.

2.4 Qualitative sampling and data collection

The qualitative phase was conducted after the household survey to explain and enrich the quantitative results. Focus group discussions and key informant interviews were used to collect qualitative data. A total of 12 focus group discussions were conducted, with 3 in each district. Each FGD comprised 8 to 12 participants. In every district, one female-only focus group discussion, one male-only focus group discussion and one mixed male-and-female focus group discussion were conducted. This arrangement allowed the study to capture gender-specific and shared community perspectives on adaptation strategies, barriers and perceived effectiveness. The focus group discussions explored farmers' experiences with adaptation practices, reasons for adopting or not adopting specific strategies, perceived benefits and limitations, and the conditions under which strategies were considered effective. Key informant interviews were also conducted with local leaders and agricultural stakeholders. The key

informants included village headmen, agricultural extension officers and the provincial agriculture officer. Village headmen provided local historical and institutional perspectives on climate-related changes in the food system and community adaptation responses. Extension officers provided technical insights on promoted adaptation practices, farmer uptake, extension support and implementation constraints. The provincial agriculture officer provided a broader policy and programme-level perspective on climate resilience and food-system adaptation in the study area.

2.5 Data analysis

Quantitative data were analysed using descriptive and inferential statistical methods (Creswell & Plano Clark, 2023). Descriptive statistics, including frequencies and percentages, were used to summarise respondent characteristics, uptake of adaptation strategies, and perceived effectiveness. An adaptation portfolio approach was used to examine whether households relied on single strategies or combinations of strategies. An adaptation intensity index was constructed to measure the breadth of household adaptation portfolios. The index was calculated as the total number of adaptation strategies adopted by each household, with each adopted strategy assigned a value of 1 and non-adoption a value of 0. Higher scores indicated greater adaptation intensity and more diversified adaptation portfolios. To identify distinct adaptation portfolio typologies among farming households, cluster analysis was conducted using adopted adaptation strategies as classification variables. The resulting clusters represented groups of households exhibiting similar adaptation patterns and enabled comparison of adaptation behaviour across livelihood and socio-economic contexts. Bivariate analysis was conducted to examine associations between household characteristics and the uptake of adaptation strategies. Chi-square tests were used for categorical variables, while non-parametric tests were applied where assumptions for parametric tests were not met. Multivariate regression models were employed to identify factors associated with adaptation intensity and perceived effectiveness. For adaptation intensity, count-data models including Poisson and negative binomial regression were evaluated, while ordinal logistic regression was applied to perceived effectiveness outcomes. Predictor variables included district, gender, age, education, household size, income level, farmland size and access to extension services. Diagnostic tests were conducted to assess model assumptions, multicollinearity, and goodness of fit. Variance inflation factors (VIFs) below 10 were used as evidence of acceptable multicollinearity among explanatory variables. Depending on the distribution and coding of the outcome variables, binary logistic regression, ordinal logistic regression, or count models were applied. Predictor variables included district, gender, age, education, income, household size and farmland size. Qualitative data from focus group discussions and key informant interviews were analysed thematically. The analysis followed both deductive and inductive procedures. Deductive codes were informed by the study objectives and focused on adaptation strategies, perceived effectiveness, barriers, enabling factors and food-system resilience. Inductive codes were developed from recurring ideas emerging from participants' narratives. Data collection and analysis proceeded concurrently until thematic saturation was achieved, at which point no substantially new themes emerged from subsequent interviews and discussions. To enhance trustworthiness, several measures were employed, including triangulation across focus group discussions and key informant interviews, peer review of coding decisions, maintenance of an audit trail

and participant verification of key interpretations where feasible. Thematic findings were then used to explain and contextualise the quantitative results, particularly where statistical patterns required deeper interpretation.

2.6 Integration of quantitative and qualitative findings

Integration occurred at both the analysis and interpretation stages following the explanatory sequential mixed-methods design. Quantitative findings were first analysed to identify adaptation patterns, portfolio typologies, determinants of adaptation intensity and perceived effectiveness. These findings informed the qualitative inquiry by highlighting issues requiring deeper exploration. Subsequently, qualitative findings were integrated with quantitative results using joint display analysis, enabling direct comparison between statistical patterns and participants' explanations. Areas of convergence, complementarity and divergence were identified and interpreted to provide a more comprehensive understanding of food-system resilience and adaptation decision-making among smallholder farmers.

2.7 Validity and Reliability

Several procedures were implemented to enhance the study's validity and reliability. Content validity was established through expert review by specialists in climate change adaptation, agricultural development and food systems research. Construct validity was assessed using exploratory factor analysis of multi-item scales. Methodological triangulation was achieved by integrating quantitative survey data, focus group discussions and key informant interviews, thereby strengthening the robustness and credibility of the findings. The research tools (Questionnaire used is attached as supplementary file1)

2.7 Ethical considerations

The University of Zambia's Natural and Applied Sciences Research Ethics Committee approved this study (NASREC: 2025 APR-007). Permission was also granted by the Ministry of Agriculture and local traditional authorities. All participants were informed about the study's purpose and provided written consent before data collection. Participants were assured of confidentiality, and their participation was voluntary. Data were anonymised and securely stored. The study adhered to standard ethical procedures for research involving humans. Participants were briefed on the study's purpose, the voluntary nature of involvement, and their right to withdraw at any time. Informed consent was obtained prior to administering questionnaires, conducting focus groups, and interviewing key informants. Personal identifiers were not used in data analysis or reporting to maintain confidentiality. Qualitative responses were anonymised, and data were used solely for academic purposes.

RESULTS OF THE STUDY

Table 1 presents the socio-demographic characteristics and uptake of adaptation strategies across the four study districts. Across the full sample (N = 202), irrigation was the most widely adopted strategy (85.1%), followed by agroforestry (65.3%) and extension services (59.9%). Crop diversification (40.1%) and drought-tolerant varieties (34.2%) showed lower but substantial uptake. District-level variation revealed that Chirundu and Gwembe reported higher mean effectiveness scores (3.86 and 3.92 out of 5,

respectively) than Kazungula and Siavonga (3.46 and 3.52, respectively). Female-headed households constituted between 40% (Chirundu) and 73% (Kazungula) of respondents across districts.

Table 1
Socio-demographic characteristics and adaptation strategy uptake across the study areas

Characteristic	Kazungula	Siavonga	Chirundu	Gwembe	Total (N)
Total respondents (N = 202)	52.00	50.00	50.00	50.00	202.00
Female (%)	73.10	70.00	40.00	58.00	60.40
Mean household size	7.40	6.20	6.80	7.00	6.90
Mean adaptation intensity	3.00	3.00	2.60	2.70	2.85
Mean effectiveness (1–5)	3.50	3.50	3.90	3.90	3.69
High effectiveness (%)	57.70	60.00	64.00	68.00	62.40
Strategy uptake (%)					
Irrigation (%)	86.50	88.00	88.00	78.00	85.10
Diversification (%)	46.20	40.00	32.00	42.00	40.10
Drought-tolerant (%)	32.70	44.00	26.00	34.00	34.20
Extension (%)	67.30	52.00	66.00	54.00	59.90
Agroforestry (%)	71.20	72.00	52.00	66.00	65.30

Adaptation Portfolio Typologies

Figure 2(a) illustrates the distribution of adaptation portfolios across the sample. The majority of households (50.5%) employed bundled strategies combining 2–3 practices, while 32.2% adopted extensive portfolios of 4–5 strategies. Only 17.3% relied on single strategies. This distribution indicates that farmers predominantly adopt combinations of practices rather than isolated interventions. Figure 1b examines the relationship between individual strategy adoption and perceived effectiveness. Mann-Whitney U tests revealed significant differences in perceived effectiveness between adopters and non-adopters for irrigation ($p = 0.041$), diversification ($p = 0.0003$), and drought-tolerant varieties ($p = 0.0004$). However, no significant differences were observed for extension services ($p = 0.945$) or agroforestry ($p = 0.287$), suggesting that adoption alone does not guarantee perceived effectiveness.

Top Performing Portfolio Combinations

Table 2 and Fig. 2 below present the top-performing adaptation portfolios, ranked by mean perceived effectiveness. The portfolio combining all five strategies, irrigation, diversification, drought-tolerant

varieties, extension, and agroforestry, achieved the highest effectiveness score (4.90/5, n = 40). Notably, the combination of diversification and agroforestry without irrigation also performed well (4.33/5, n = 6). Interestingly, pairing irrigation with extension (3.29/5) was less effective than irrigation alone (3.86/5), suggesting potential negative interactions or diminishing returns in certain combinations.

Table 2
the top-performing adaptation portfolios based on mean perceived effectiveness

Rank	Portfolio combination	n	Mean effectiveness (1–5)	Interpretation/comments
1	IRR + DIV+DTV + EXT+AGR	40	4.90	Optimal bundle
2	DIV + AGR	6	4.33	Strong diversification-agroforestry synergy
3	IRR + DIV+DTV + AGR	8	4.00	Strong without extension
4	IRR (single)	35	3.86	Moderate effectiveness
5	IRR + DIV+AGR	12	3.67	Moderate effectiveness
6	IRR + EXT+AGR	13	3.23	Lower than single irrigation
7	IRR + EXT	35	3.29	Lower than single irrigation
8	EXT + AGR	13	2.62	Lowest among top portfolios
Note: IRR=Irrigation, DIV=Diversification, DTV=Drought-tolerant varieties, EXT=Extension, AGR=Agroforestry				

Boxplots show median, interquartile range, and means (dashed lines). Asterisks indicate significant differences from Mann-Whitney U tests (**p* < 0.05, ****p* < 0.001). Note that while irrigation has the highest adoption rate (85.1%), drought-tolerant varieties have the highest mean effectiveness among adopters (4.28/5).

Multivariate Space of Adaptation Strategies

Figure 3 presents a Principal Component Analysis (PCA) biplot of the five adaptation strategies, with households colored by perceived effectiveness. The first two principal components capture the dominant patterns of strategy co-adoption. Households reporting high effectiveness (green-yellow points) cluster in regions associated with multiple strategy vectors, while low-effectiveness households (red points) show weaker associations with strategy combinations. The loadings indicate that irrigation and agroforestry are strongly correlated, while diversification and drought-tolerant varieties form a distinct cluster.

N.B. Vectors show strategy loadings—high-effectiveness households (yellow-green) cluster in regions with multiple strategy vectors, indicating bundled adoption. Red points (low effectiveness) indicate weaker

Portfolio Clusters

Table 3 below shows the six distinct household clusters identified across the study areas.

Table 3
Key findings from clustering (k = 6, Silhouette = 0.805)

Cluster	n (%)	Primary strategies	Mean effectiveness	High effectiveness (%)	Characterization
5	40 (19.8%)	All 5 strategies	4.90	97.5	Comprehensive adopters (optimal)
1	35 (17.3%)	Irrigation only	3.86	62.9	Irrigation specialists
6	25 (12.4%)	All 5 (lower intensity)	3.40	60.0	Partial comprehensive
4	37 (18.3%)	IRR + AGR	3.32	51.4	Water-Forestry bundlers
2	35 (17.3%)	IRR + EXT	3.29	45.7	Water-extension bundlers
3	30 (14.9%)	EXT + AGR	3.03	46.7	Forestry-extension bundlers (lowest)

Hierarchical cluster analysis of the PCA coordinates identified six distinct adaptation strategy profiles (Table 3 and Fig. 4a&b, Silhouette score = 0.805 indicating strong cluster separation). Table 3 characterizes these six clusters. Cluster 5 (n = 40, 19.8%) represents the most successful group, adopting all five strategies and achieving near-universal high effectiveness (97.5%, mean = 4.90). This "comprehensive adopter" cluster serves as a benchmark for optimal portfolio design. Cluster 1 (n = 35, 17.3%) relies solely on irrigation. Despite being the most common single strategy, its effectiveness (3.86) is substantially lower than that of the comprehensive portfolio. Clusters 2–4 represent intermediate portfolios with varying combinations of irrigation, extension, and agroforestry, showing moderate effectiveness (3.29–3.32). Cluster 3 (n = 30) adopts extension and agroforestry without irrigation, showing the lowest effectiveness among non-zero portfolios (3.03). Cluster 6 (n = 25) nominally adopts all five strategies but with lower effectiveness (3.40), suggesting implementation quality or contextual constraints moderate outcomes.

Cluster 5 demonstrates near-universal adoption of all strategies and the highest effectiveness (Fig. 5).

Determinants of Portfolio Intensity

Table 4 below presents the Poisson regression results for factors associated with adaptation portfolio intensity (i.e., the number of strategies adopted). The model was statistically significant (LLR $p = 0.001$) with pseudo- $R^2=0.042$.

Table 4
Poisson regression analysis results

Constant	coefficient	Standard error	z	p> z 	[0.025	0.975]
	1.0206	0.261	3.906	0.000	0.508	1.533
Female	0.1112	0.092	1.211	0.226	-0.069	0.291
hh_size	0.0264	0.019	1.411	0.158	-0.010	0.063
dist_Kazungula	0.1261	0.124	1.017	0.309	-0.117	0.369
dist_Siavonga	0.1441	0.127	1.136	0.256	-0.104	0.393
dist_Gwembe	0.0380	0.125	0.304	0.761	-0.207	0.283
Farm_6–10 ha	-0.4422	0.092	-4.820	0.000	-0.622	-0.262
Farm_10–15 ha	-0.4037	0.227	-1.781	0.075	-0.848	0.041
edu_Secondary	-0.0751	0.251	-0.299	0.765	-0.568	0.418
edu_Primary	-0.1197	0.240	-0.498	0.619	-0.591	0.352
edu_Tertially	-0.1915	0.503	-0.381	0.703	-1.178	0.795

As shown in Table 5, the only significant predictor was medium landholding size (6–10 ha), which reduced adaptation intensity by 35.7% (IRR = 0.643, 95% CI: 0.537–0.769, $p < 0.001$) compared with very small landholdings (< 5 ha). Surprisingly, gender, household size, district, and education showed no statistically significant associations with the number of strategies adopted. This finding suggests that land-constrained households (< 5 ha) adopt more strategies, potentially reflecting a compensatory adaptation behaviour. Farmers with limited land diversify their adaptation portfolio to manage risk, while those with adequate land may specialise.

Incidence Rate Ratios (IRR) as Significant predictors of adaptation

Table 5
Incidence Rate Ratios (IRR)

Variable	IRR	CI_lower	CI_upper	P- value	Significance
Farm_6–10 ha	0.643	0.537	0.769	0.001***	35.7% lower intensity
Farm size: 10–15 ha	0.668	0.428	1.042	0.075 ^{ns}	Marginally lower
Female (ref: male)	1.118	0.932	1.338	0.226 ^{ns}	Not significant
Household size	1.027	0.990	1.065	0.158 ^{ns}	Not significant
<i>Note: IRR = Incidence Rate Ratio; model: Poisson regression, Log-Likelihood = -339.80, Pseudo R² = 0.042, LLR p = 0.001. ns-not significant; ***highly significant</i>					

Predictors of Perceived Effectiveness

Tables 6 and 7 present the binary logistic regression results predicting high perceived effectiveness (score ≥ 4). The model was highly significant (LLR $p < 0.001$, pseudo- $R^2 = 0.185$). Land access emerged as the strongest predictor. Households with medium landholdings (6–10 ha) had nearly 5 times higher odds of reporting high effectiveness (OR = 4.95, 95% CI: 2.19–11.15, $p < 0.001$), while those with larger holdings (10–15 ha) showed a striking 20-fold increase (OR = 20.15, 95% CI: 1.90–213.5, $p = 0.013$) compared to land-constrained households (< 5 ha). Adaptation intensity also strongly predicted effectiveness: each additional strategy adopted increased the odds of high effectiveness by 118% (OR = 2.18, 95% CI: 1.61–2.95, $p < 0.001$). This provides robust evidence that portfolio breadth matters, and bundled strategies substantially outperform single strategies.

Table 6
Using Binary Logistic Regression (High vs Low Effectiveness)

Variable	Odds ratio	95% CI	p-value
Farm size: 6–10 ha (ref:<5ha)	4.95	2.19–11.15	< 0.001***
Farm size: 10–15 ha	20.15	1.90–213.5	0.013*
Adaptation Intensity (per strategy)	2.18	1.61–2.95	< 0.001***
Kazungula (ref: Chirundu)	0.39	0.15–1.04	0.061 ^{ns}
Siavonga	0.44	0.16–1.19	0.109 ^{ns}
Gwembe	1.09	0.42–2.85	0.863 ^{ns}
Female (ref: male)	1.58	0.78–3.17	0.201 ^{ns}
Household size	1.00	0.86–1.15	0.999 ^{ns}
Education dummies			> 0.05 ^{ns}
<i>Note: Binary logistic regression; dependent variable = high effectiveness (score ≥ 4); Pseudo R² = 0.185, LLR p < 0.001. ns-not significant; ***highly significant</i>			

Notably, neither district, gender, household size, nor education showed statistically significant associations with perceived effectiveness after controlling for land access and portfolio intensity. This underscores that structural resources (land) and behavioural factors (portfolio breadth) dominate over socio-demographic characteristics in determining adaptation success.

Table 7
Logit Regression Results:

constant	coef	Standard error	z	P< z	[0.025	0.975]
	-1.1719	1.280	-0.916	0.360	-3.680	1.337
female	0.4551	0.356	1.278	0.201	-0.243	1.153
hh_size	-8.647e-05	0.074	-0.001	0.999	-0.145	0.144
dist_Kazungula	-0.9350	0.499	-1.873	0.061	-1.913	0.043
dist_Siavonga	-0.8097	0.506	-1.601	0.109	-1.801	0.181
dist_Gwembe	0.0849	0.490	0.173	0.863	-0.876	1.046
farm_6–10 ha	1.5988	0.414	3.861	0.000	0.787	2.410
farm_10–15 ha	3.0031	1.204	2.495	0.013	0.644	5.362
edu_Secondary	-1.2522	1.189	-1.053	0.292	-3.584	1.079
edu_Primary	-1.0785	1.149	-0.938	0.348	-3.331	1.174
edu_Tertially	-43.3560	5.53e + 08	-7.84e-08	1.000	-1.083 + 09	1.08e + 09
Adaptation intensity	0.7795	0.155	5.041	0.000	0.476	1.083

Portfolio Type and Effectiveness

Figure 6 compares perceived effectiveness across portfolio types. The Kruskal-Wallis test revealed significant differences ($\chi^2(4) = 16.14$, $p = 0.0003$). Extensive portfolios (4–5 strategies) achieved the highest mean effectiveness (4.32/5), followed by bundled strategies (2–3 strategies, mean = 3.52/5). Single strategies were the least effective among adopters (mean = 3.40/5). Post-hoc Mann-Whitney tests confirmed significant differences between extensive portfolios and both bundled ($p = 0.002$) and single strategies ($p = 0.001$), while the bundled-single comparison was not significant ($p = 0.32$).

Extensive portfolios (4–5 strategies) show significantly higher effectiveness (mean = 4.32) than both bundled (2–3 strategies, mean = 3.52) and single strategies (mean = 3.40). Kruskal-Wallis test: $H = 16.14$, $p = 0.0003$. Boxes show median and IQR; dashed lines indicate means. These findings provide clear evidence that portfolio breadth enhances perceived effectiveness, with the most comprehensive portfolios delivering superior resilience outcomes.

Interaction: Land Size × Portfolio Type

Figure 7 examines the interaction between farmland size and portfolio type with respect to perceived effectiveness. A clear pattern emerges: for land-constrained households (< 5 ha), effectiveness remains low regardless of portfolio type (ranging from 2.8 to 3.2). However, among households with medium (6–10 ha) and larger (10–15 ha) landholdings, extensive portfolios (4–5 strategies) achieve substantially higher effectiveness (4.4–4.8).

Land-constrained farmers (< 5 ha) show low effectiveness regardless of portfolio breadth (Fig. 7). Among medium (6–10 ha) and larger (10–15 ha) landholders, extensive portfolios (4–5 strategies) achieve substantially higher effectiveness. This suggests land access enables effective portfolio implementation. This interaction suggests that land access enables effective portfolio implementation: farmers with adequate land can fully realise the benefits of bundled strategies, while land scarcity imposes structural constraints that limit the effectiveness of adaptation, even when multiple strategies are nominally adopted.

DISCUSSION

6.1 Portfolio-Based Adaptation: Moving Beyond Single-Strategy Interventions

This study provides robust empirical evidence that adaptation portfolios bundled combinations of practices substantially outperform single strategies in enhancing perceived food system resilience among smallholder farmers in Zambia's semi-arid Agro-Ecological Region I. The finding that each additional strategy adopted doubled the odds of reporting high effectiveness (OR = 2.18, $p < 0.001$) represents a critical contribution to climate adaptation scholarship (Karan et al., 2022; Ndhlovu, 2023), challenging the dominant paradigm of promoting isolated climate-smart interventions (Y. Azadi et al., 2019; Rahman, 2025). Our results align with emerging literature on climate-smart agriculture and multi-practice adoption, which suggests that bundled strategies offer stronger resilience benefits by spreading risk across production, ecological, and economic domains. (Mukhovi et al., 2020; Tirado et al., 2022; Zurek et al., 2022; Zuza et al., 2024). However, this study goes beyond existing work by quantifying the marginal benefit of each additional strategy and identifying which combinations deliver optimal outcomes. The portfolio combining all five strategies irrigation, diversification, drought-tolerant varieties, extension, and agroforestry achieved near-universal high effectiveness (97.5%, mean = 4.90/5), serving as an empirical benchmark for adaptation programming (Alves et al., 2026; Khumalo et al., 2026; Mukhovi et al., 2020). The cluster analysis, which reveals six distinct adaptation profiles (Silhouette = 0.805), demonstrates that farmers are not adopting strategies randomly but rather following identifiable portfolio logics. Importantly, Cluster 5 (comprehensive adopters) and Cluster 1 (irrigation specialists) represent opposite ends of the effectiveness spectrum, with a 1.04-point gap on a 5-point scale a substantively meaningful difference in perceived resilience. This finding supports the compound-risk perspective that single-risk explanations are insufficient for semi-arid food systems where multiple,

interacting stressors require coordinated responses (Bezner Kerr et al., 2022; Campbell et al., 2023; Hadley et al., 2023; Varyvoda & Taren, 2024).

6.2 The Adoption-Effectiveness Divergence: A Methodological and Practical Warning

A striking finding with significant implications is the divergence between strategy adoption rates and perceived effectiveness. While irrigation was the most widely adopted strategy (85.1% of households), drought-tolerant varieties demonstrated the highest mean effectiveness among adopters (4.28/5). This divergence challenges a common but problematic assumption in the adaptation literature: that adoption rates serve as proxies for effectiveness or farmer preferences (Karan et al., 2022; Meyer, 2020; Wood et al., 2023). Several explanations may account for this pattern. First, project and extension messaging may prioritise irrigation due to its visibility and alignment with narratives of agricultural modernisation, even when drought-tolerant varieties might offer better risk reduction amid increasing climate variability (A. Dzvene & Zhou, 2026; Mmbando, 2025; Zuza et al., 2024). Second, short-term necessity may drive irrigation adoption: farmers need water immediately for survival while drought-tolerant varieties provide longer-term, less visible benefits (Beltran-Peña, 2023; Chundu et al., 2024). Third, supply-side constraints may limit access to quality drought-tolerant seeds compared to irrigation technologies, which NGO and government programs often support. Qualitative insights from our focus group discussions (not presented here but informing this interpretation) suggested that farmers often adopt irrigation because "everyone is doing it" or because projects provide subsidised equipment. In contrast, drought-tolerant varieties require more nuanced agronomic knowledge and may perform variably depending on rainfall patterns. This finding aligns with recent critiques of climate adaptation programming that emphasise the need to distinguish between adoption as exposure to interventions versus adoption as genuine, effective adaptation (Arslan et al., 2022; Keegan et al., 2024; Ujjwal et al., 2024). The non-significant relationship between extension adoption and effectiveness ($p = 0.945$) is particularly concerning. Extension services were adopted by 59.9% of households but were not associated with greater effectiveness. This may reflect quality issues in extension delivery, low frequency of contact, generic messaging not tailored to local conditions, or extension agents themselves lacking up-to-date climate information (Chao, 2024; Stathers & Lamboll, 2023). Alternatively, it may indicate that extension complements, but does not substitute for, other strategies; extension alone, without accompanying technologies or inputs, may have limited impact (Karan et al., 2022; Usman et al., 2023).

6.3 Land Access as the Dominant Structural Constraint

Perhaps the most policy-relevant finding is the overwhelming importance of land access in shaping both adaptation intensity and perceived effectiveness. Households with medium landholdings (6–10 ha) showed 5-fold higher odds of reporting high effectiveness ($OR = 4.95$, $p < 0.001$), while those with larger holdings (10–15 ha) demonstrated a striking 20-fold increase ($OR = 20.15$, $p = 0.013$) compared to land-constrained households (< 5 ha). This finding resonates with compound-risk frameworks that conceptualise food system vulnerability as the outcome of interacting climatic and structural drivers rather than isolated climate impacts (Adu et al., 2018; Hadley et al., 2023; Mukhovi et al., 2020). In the

Zambian semi-arid context, climate stress does not affect all farmers equally; its impacts are mediated through land access, which determines households' capacity to experiment with new strategies, absorb risks, and invest in long-term resilience (Chisengele & Nyanga, 2025; Malanda et al., 2026; Masasi, 2025; Ndhlovu, 2023).

The interaction analysis (Fig. 6) provides particularly compelling evidence: for land-constrained farmers (< 5 ha), portfolio type had minimal effect on effectiveness (range 2.8–3.2). These households remained stuck in low-effectiveness states regardless of how many strategies they nominally adopted. In contrast, among medium and larger landholders, extensive portfolios (4–5 strategies) achieved substantially higher effectiveness (4.4–4.8). This suggests that land access enables effective portfolio implementation; farmers with adequate land can fully realise the benefits of bundled strategies, while land scarcity imposes structural constraints that limit adaptation effectiveness even when multiple strategies are adopted (Malanda et al., 2026; Ndhlovu, 2023; Reidsma et al., 2023). This finding has profound implications for climate adaptation policy. It suggests that promoting climate-smart technologies without addressing land governance and tenure security will have limited impact for the most vulnerable households. Land-constrained farmers cannot simply "adapt their way out" of climate risk through technology adoption alone; they require complementary interventions addressing structural land access issues (Adu et al., 2018; Al Mamun et al., 2023; Chisengele & Nyanga, 2026).

The Poisson regression finding that land-constrained households adopt more strategies (IRR for 6–10 ha = 0.643, indicating a 35.7% lower intensity) further supports this interpretation. Farmers with very small landholdings appear to engage in compensatory adaptation behaviour, adopting more strategies to compensate for limited land resources. However, this greater effort does not translate into higher effectiveness, as shown by the logistic regression results. This represents a form of adaptation poverty trap: the most vulnerable households work harder (adopt more strategies) but achieve less because structural constraints limit the returns to their adaptation investments.

6.4 District Heterogeneity

Most district-level differences in effectiveness were not statistically significant after controlling for land access and portfolio intensity. This finding suggests that structural factors (land) and behavioural factors (portfolio breadth) matter more than geographic location per se in determining adaptation outcomes (Karan et al., 2022; Mgomezulu et al., 2024). However, descriptive patterns warrant comment. Chirundu and Gwembe showed higher mean effectiveness (3.86 and 3.92) compared to Kazungula and Siavonga (3.46 and 3.52), despite similar adaptation intensity levels. This may reflect differences in market access, extension quality, or agroecological conditions not captured by our land size variable (Chavula & Kayusi, 2026; Mabhaudhi et al., 2024; Simane et al., 2016). Kazungula and Siavonga border and lakeshore districts may experience greater market volatility due to cross-border trade exposure, potentially undermining adaptation effectiveness even when farmers adopt similar portfolios (Makondo & Thomas, 2020; Ndhlovu, 2023; Sax et al., 2023). The non-significance of district in the regression models after controlling for land access indicates that land distribution patterns across districts may explain much of the apparent spatial variation. If land-constrained households are concentrated in

certain districts, district-level effects would be confounded with land access effects (Reidsma et al., 2023). This finding underscores the importance of structural variables over spatial ones in adaptation research and programming (Karan et al., 2022; Ndhlovu, 2023).

6.5 Gender, Household Demography, and Adaptation Outcomes

Contrary to some literature suggesting gendered differences in climate adaptation capacity (Arslan et al., 2022; Diaz-Bonilla et al., 2023), neither gender nor household size emerged as a significant predictor of adaptation effectiveness in our regression models. Female-headed households showed modestly higher odds of high effectiveness (OR = 1.58, $p = 0.201$), but this did not reach statistical significance. Several interpretations are possible. First, the high proportion of female respondents (60.4% overall, ranging from 40% in Chirundu to 73% in Kazungula) may reflect the active engagement of female-headed households in adaptation decision-making (Bryan et al., 2024; Chisenga & Siame, 2026), potentially driven by male out-migration for labour. Second, the non-significant finding may indicate that adaptation programs are reaching women effectively in this region, contrary to concerns about gender-blind programming. Third, the null result may reflect that structural constraints (land) override gender effects; when land access is controlled for, gender differences disappear. This finding should not be interpreted as evidence that gender is irrelevant to climate adaptation. Rather, it suggests that in this specific context, land access may be the more immediate binding constraint for both male and female farmers (Aslam et al., 2021; Bryan et al., 2023, 2024). However, given that women typically have less secure land tenure in Zambia, gender and land access are likely interrelated. Future research should examine whether the observed land access effects are themselves gendered. Household size showed no association with effectiveness (OR = 1.00, $p = 0.999$), despite descriptive patterns suggesting larger households might have more labour for adaptation activities. This null finding may reflect countervailing pressures: while larger households have more labour, they also have more people to feed, potentially offsetting any labour advantage.

6.6 Methodological Contributions and Limitations

This study offers several key methodological contributions to research on climate and food systems. Firstly, by clearly differentiating between adoption and perceived effectiveness, we avoid the common mistake of assuming that adoption automatically implies successful adaptation. Secondly, our portfolio-based analytical approach, combining descriptive typologies, PCA, clustering, and regression, provides a replicable framework for understanding how various practices work together rather than in isolation. Thirdly, our interaction analysis shows how structural constraints can influence the effectiveness of adaptation portfolios, offering valuable insights for targeted interventions.

Several limitations should also be acknowledged. The cross-sectional design limits causal inference; we cannot determine whether effective adaptation leads to greater land access (reverse causality) or whether unobserved factors such as farmer motivation or social capital influence both land accumulation and adaptation success. Self-reported effectiveness may be affected by recall bias, social

desirability bias, or differing interpretations of effectiveness questions. The relatively small sample size (N = 202) reduces statistical power to identify small effects and test complex interactions. Including objective measures of food security outcomes, such as dietary diversity or the number of months of adequate household food provisioning, would improve future research.

Moreover, the absence of significant district effects after accounting for land access might be due to the districts studied all being within the same agro-ecological region. Different outcomes could be observed in a more geographically diverse sample. The binary coding of strategies (adopted/not adopted) does not reflect the intensity or quality of implementation; for example, a farmer who uses drip irrigation daily differs from one who uses manual irrigation occasionally. Both are classified as "adopters."

6.7 Comparison with Regional and Global Evidence

Our findings both align with and extend existing literature on climate adaptation in semi-arid Africa. The importance of land access as a structural determinant of adaptation capacity echoes studies from Zimbabwe, Malawi, and Mozambique showing that land tenure security and farm size shape climate vulnerability (Antwi-Agyei et al., 2025; Jabik, 2023; Karan et al., 2022; Mabhaudhi et al., 2024; Maphosa & Moyo, 2024; Masvaure, 2026; Mgomezulu et al., 2024; Ndhlovu, 2023; Zvobgo, 2024) (Mabhaudhi et al., 2024; Ulimwengu & Blumenthal, 2023). However, the magnitude of the land effect (20-fold higher odds for larger landholders) is striking even by regional standards, potentially reflecting the extreme land pressure in parts of Agro-Ecological Region I where population density and small farm sizes are increasing. The finding that irrigation is widely adopted but not necessarily most effective contrasts with studies from more arid regions where water access is the primary constraint (Ghanem et al., 2024; Rimhanen et al., 2023; Soubry & Sherren, 2022). In our study area, drought-tolerant varieties, a lower-cost, less infrastructure-dependent strategy, were more effective. This suggests that promoting irrigation as the default climate adaptation response may need reconsideration in contexts where groundwater is limited or where small-scale irrigation systems are unreliable (Beltrán-Peña 2023; Kimaro et al., 2026; Nikolaou et al., 2020; Rosa, 2022, 2022).

The portfolio effectiveness gradient (extensive > bundled > single > none) provides empirical support for the adaptation intensity hypothesis, which holds that more comprehensive portfolios deliver greater resilience. This finding is consistent with recent work on climate-smart agriculture "packages" (Karan et al., 2022; Lipper et al., 2021; Yang et al., 2025; Zougmore et al., 2021) However, extends it by quantifying the marginal returns to each additional strategy and identifying non-linearities (e.g., irrigation + extension underperforming irrigation alone).

CONCLUSION

This study explored adaptation portfolios and perceived effectiveness among 202 smallholder farmers in semi-arid agro-ecological region I in southern Zambia. It makes three key contributions to climate-food systems research by shifting focus from single practices to portfolio combinations and from mere adoption to the relationship between adoption and effectiveness. First, we show that adaptation

portfolios greatly outperform individual strategies. Each extra strategy adopted doubled the odds of high effectiveness, with a full portfolio (all five strategies) achieving nearly universal effectiveness (97.5%). This challenges the continued promotion of isolated climate-smart interventions and supports portfolio-based approaches that acknowledge the interconnected nature of climate and food-system risks in semi-arid environments. A key distinction is between adoption and actual effectiveness. Although irrigation (adopted by 85%) was the most common, it was not the most effective; drought-tolerant varieties proved more effective among adopters. This challenges the assumption that adoption rates reflect adaptation success and highlights the importance of effectiveness-focused monitoring over mere adoption counts. Third, we identify land access as the leading structural constraint shaping adaptation outcomes. Medium landholdings increased the odds of high effectiveness fivefold, while larger landholders had 20 times higher odds compared to households with limited land. Farmers with restricted land consistently produced low-to-moderate yields, regardless of their methods, indicating a 'structural adaptation poverty trap' in which disadvantaged households see efficiency decline as effort increases, mainly due to limited land. Cluster analysis identified six distinct adaptation profiles, with the full-adopter and irrigation specialist clusters representing opposite ends of the effectiveness spectrum. Structural factors seem more influential than geographic location in determining land access, and the lack of significant effects by gender or household size suggests that land access is the primary limitation here. Overall, the findings support a 'compound-risk' view where household structural conditions, especially land access, influence climate impacts. Achieving a climate-resilient food system requires addressing structural issues in land governance, tenure security, and farm-size distribution, as well as adopting climate-smart technologies.

RECOMMENDATIONS

Four recommendations follow directly from the evidence presented above. They are ordered by the strength of the underlying finding, beginning with the portfolio effect and the land-access constraint, which were the most robust results in the analysis.

8.1 Shift adaptation programming from single strategies to portfolios

The clearest finding of this study is that bundled strategies substantially outperform isolated practices. Each additional strategy adopted roughly doubled the odds of high perceived effectiveness (OR = 2.18, $p < 0.001$), and the five-strategy portfolio achieved near-universal high effectiveness (mean = 4.90 out of 5). However, adaptation interventions in Agro-Ecological Region I continue to promote individual strategies, such as irrigation schemes, drought-tolerant seed distribution, or extension training, as standalone activities. Extension curricula, subsidy design, and demonstration sites should, therefore, be reoriented around complementary combinations of strategies rather than single practices, so that households are supported to assemble portfolios suited to their context.

8.2 Treat land access as a structural adaptation constraint, not a background variable

Land-constrained households (below 5 ha) were unlikely to achieve high effectiveness regardless of how many strategies they adopted. In contrast, medium- and large-landholders were markedly more likely to do so (ORs = 4.95 and 20.15, respectively). This marks a structural limit to technology-based adaptation: promoting additional practices among the most land-constrained farmers increases their effort without increasing their outcomes. Climate adaptation policy must therefore engage land governance directly by embedding tenure security and negotiated access provisions within National Adaptation Plans and Nationally Determined Contributions, and by providing additional, targeted support to land-constrained households to partially offset their structural disadvantage.

8.3 Evaluate and fund adaptation on effectiveness, not adoption counts

Adoption and effectiveness diverged in this study. Irrigation was the most widely adopted strategy (85.1%). However, drought-tolerant varieties were the most effective among adopters (4.28 out of 5), and extension, though adopted by 59.9% of households, showed no association with effectiveness ($p = 0.945$). Programmes evaluated on adoption counts can therefore appear successful while delivering limited gains in resilience. Governments and donors should shift to effectiveness-based results frameworks with the share of households reaching high effectiveness (score ≥ 4) as the primary indicator and reallocate extension and subsidy resources toward the strategies, such as drought-tolerant varieties and diversification, that yield the highest effectiveness returns. This also implies attending to the quality of extension, not only its reach.

8.4 Set realistic, land-tiered adaptation targets

Because effectiveness is conditioned by landholding, a uniform expectation that all farmers adopt comprehensive portfolios is neither realistic nor equitable. Tiered targets are more defensible: land-constrained households (below 5 ha) should be supported to concentrate on the highest-return strategies, drought-tolerant varieties and diversification, rather than full portfolios; medium landholders (6–10 ha) on intermediate combinations; and larger landholders on comprehensive portfolios incorporating agroforestry and extension. Pairing these tiers with land-size-stratified effectiveness benchmarks would allow programmes to be judged against what is achievable within each household's structural constraints.

Declarations

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Author contributions

Conceptualisation, data collection, quantitative analyses, qualitative analyses, and writing of the original draft: L.C; review: B.M and J.M; Review, editing, design and supervision: P.N. All authors have reviewed and approved the final version of the manuscript.

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Data availability

De-identified data and analysis code supporting this study's findings can be obtained from the corresponding author upon reasonable request. These materials are kept private.

Ethics approval and consent to participate

The research protocol received approval from the University of Zambia's Natural and Applied Sciences Research Ethics Committee (NASREC: 2025-APR-007) in April 2025. It adheres to the ethical standards of the 1964 Declaration of Helsinki and its subsequent amendments, as well as relevant national and institutional guidelines for research involving human participants. This study is not a clinical trial, so trial registration is not necessary. All participants provided informed consent before taking part, and no minors or individuals under 18 participated.

Consent for publication

Not applicable.

Competing interests

The authors are affiliated with the Department of Geographical Sciences, Environment and Planning at the School of Natural and Applied Sciences, University of Zambia. This research was part of the PhD work and was not supported by commercial funding. The authors declare no financial or commercial conflicts of interest related to this study.

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Figures

Zambia Study Areas (Southern Region) within Agroecological Region I

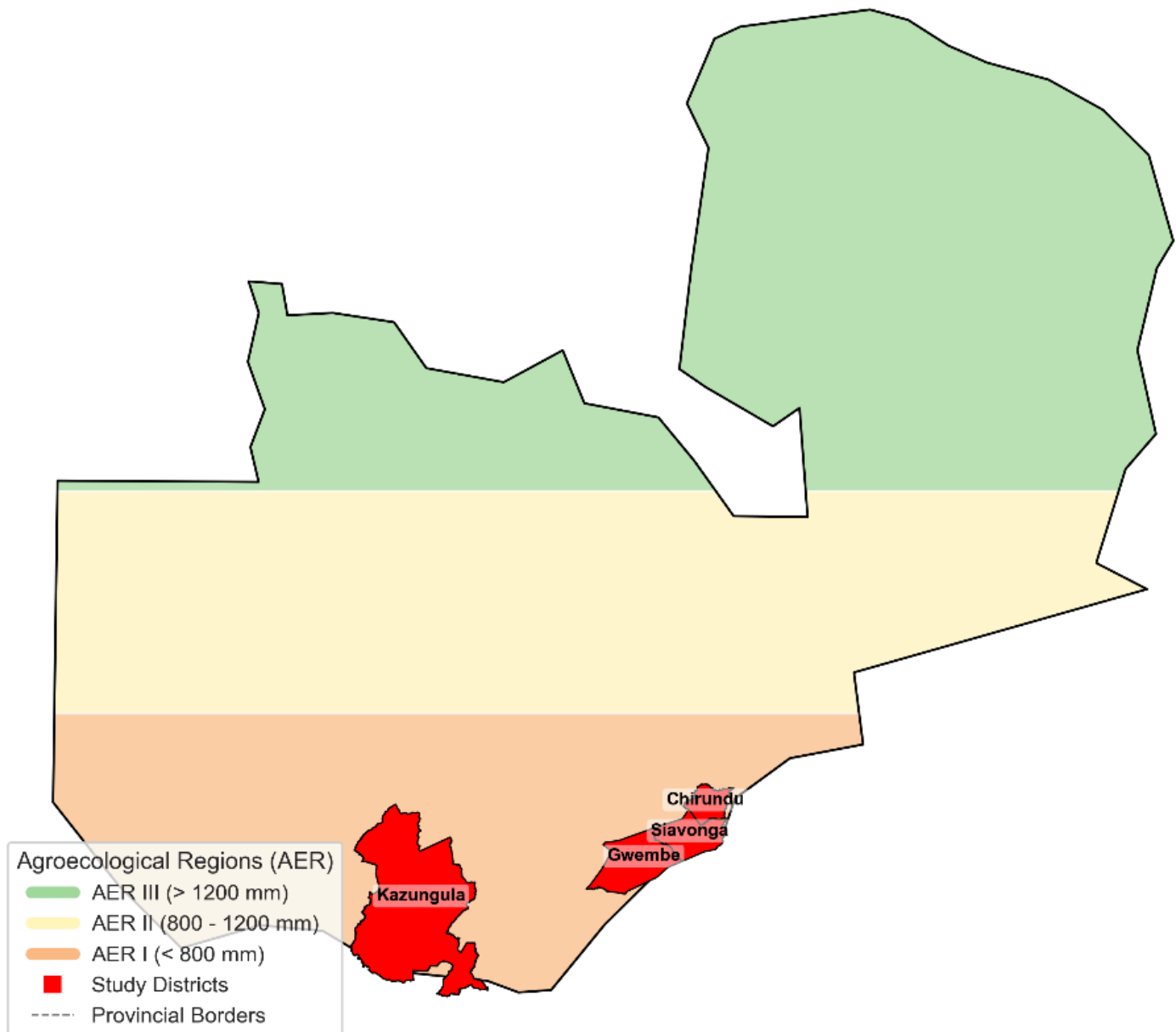


Figure 1

Map showing study areas

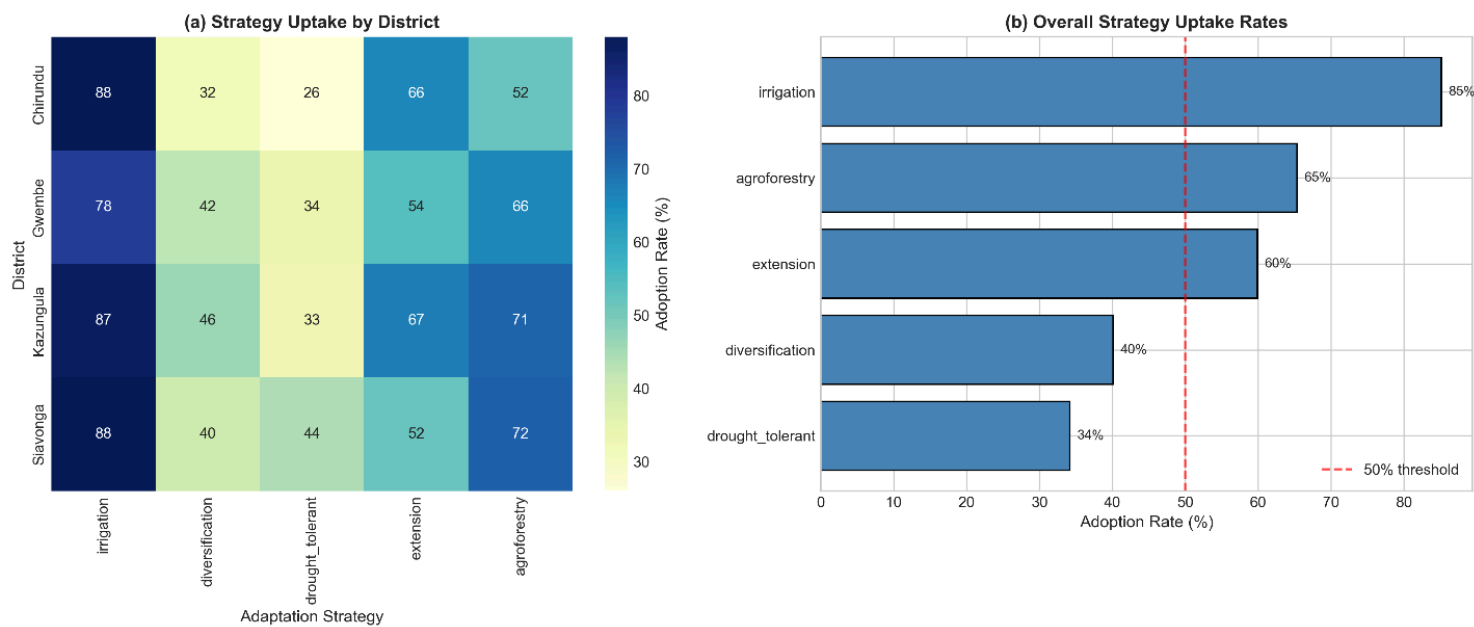


Figure 2

Distribution of adaptation portfolio types among smallholder farmers (N=202)

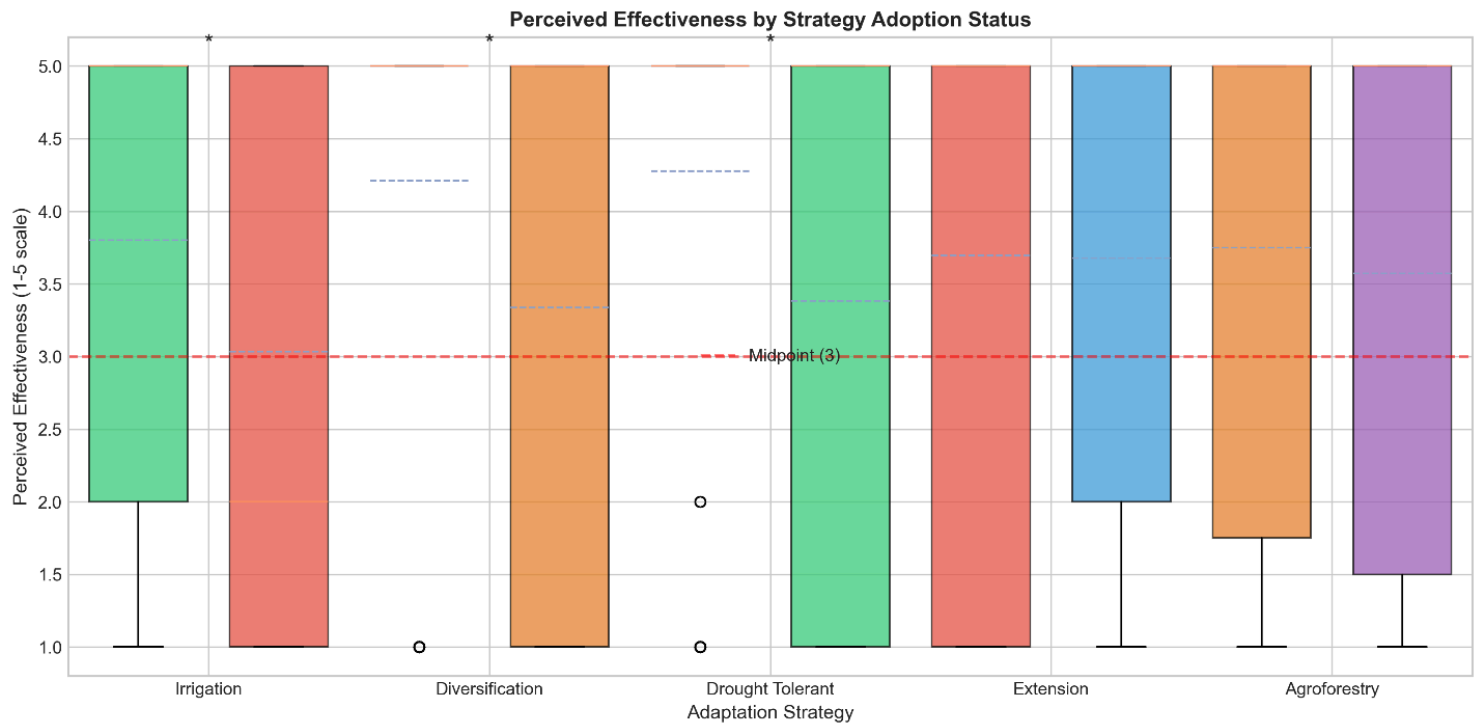


Figure 3

Perceived effectiveness by individual strategy adoption status

Boxplots show median, interquartile range, and means (dashed lines). Asterisks indicate significant differences from Mann-Whitney U tests (* $p < 0.05$, *** $p < 0.001$). Note that while irrigation has the highest

adoption rate (85.1%), drought-tolerant varieties have the highest mean effectiveness among adopters (4.28/5).

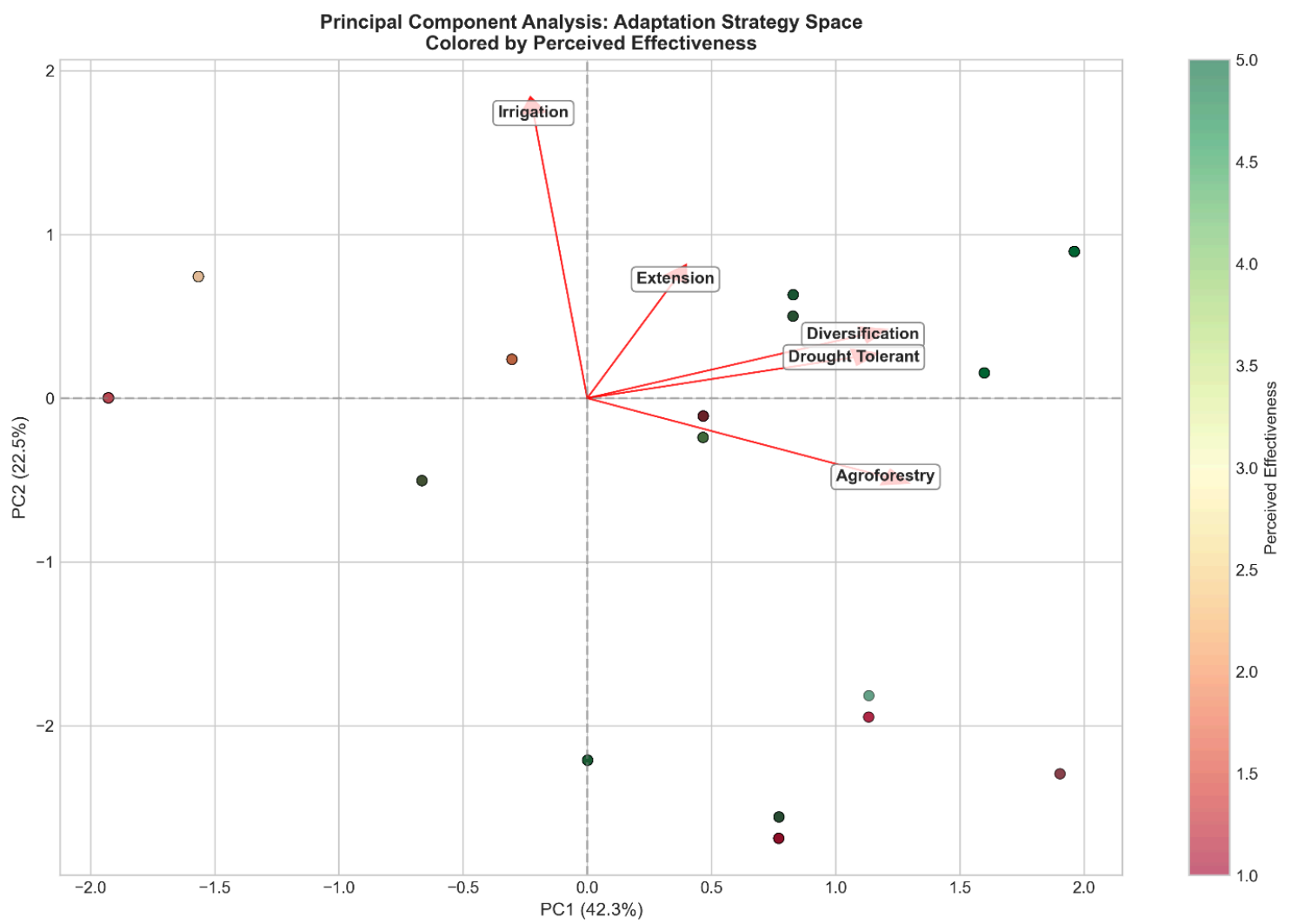


Figure 4

PCA biplot of adaptation strategies colored by perceived effectiveness. Each point represents a household (N=202)

N.B. Vectors show strategy loadings—high-effectiveness households (yellow-green) cluster in regions with multiple strategy vectors, indicating bundled adoption. Red points (low effectiveness) indicate weaker associations with strategy.

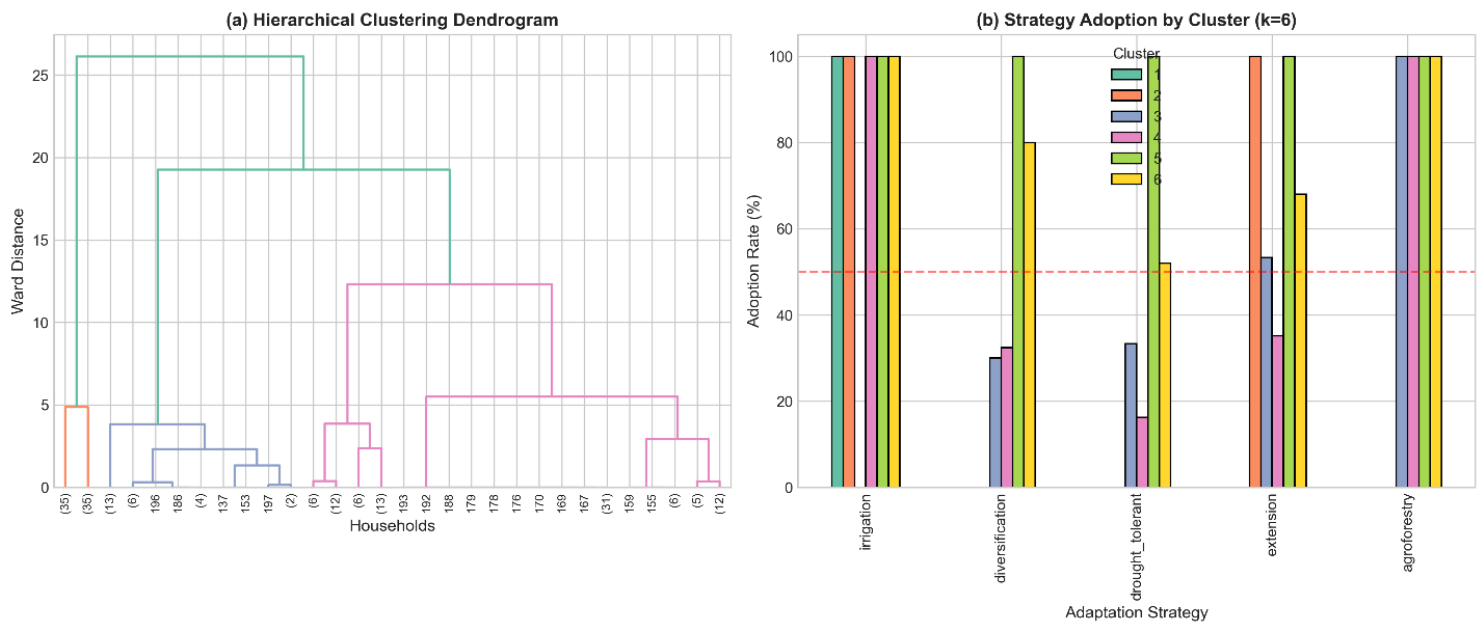


Figure 5

Hierarchical clustering of households by adaptation strategy profiles. (a) Dendrogram showing cluster formation based on Ward's method. (b) Strategy adoption rates by cluster (k=6, Silhouette=0.805).

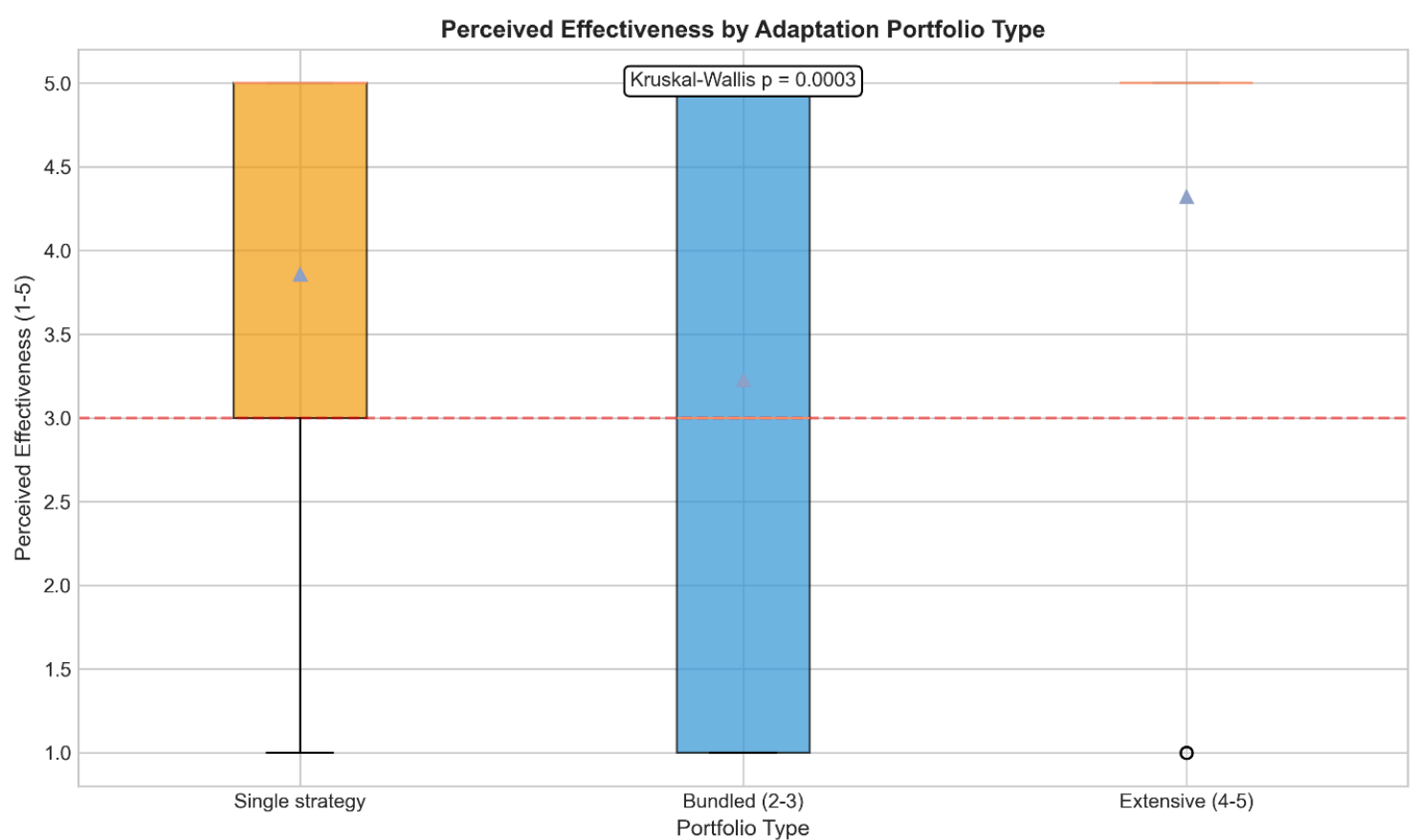


Figure 6

Perceived effectiveness by adaptation portfolio type

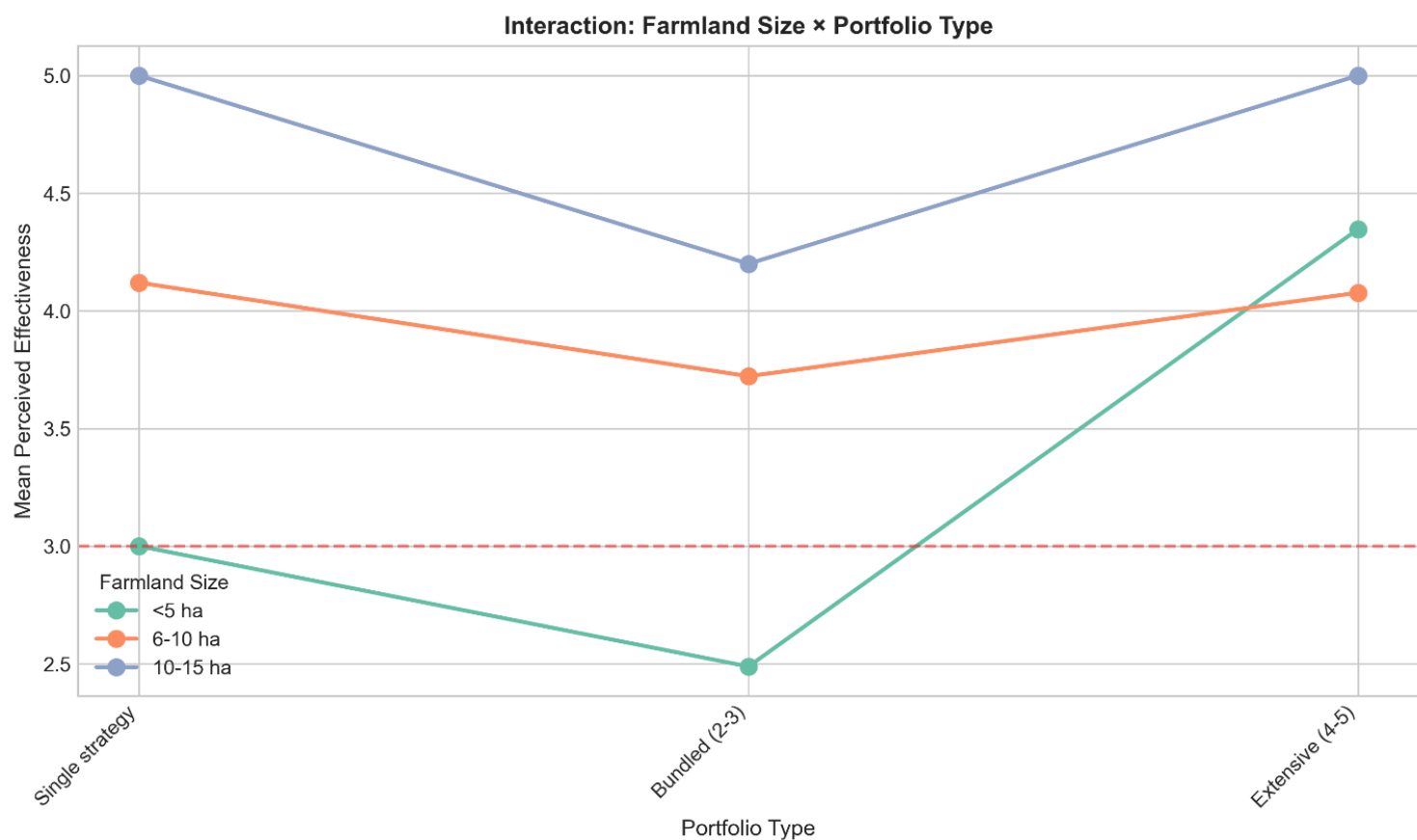


Figure 7

Interaction plot of farmland size by portfolio type

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [QuestionnaireAdaptationportfolioJune2026BMC.pdf](#)