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## RESEARCH ARTICLE

# Climate Adaptation Strategies for Smallholder Farmers in Sub-Saharan Africa

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## ABSTRACT

Smallholder farmers across sub-Saharan Africa face increasingly erratic rainfall and more frequent dry spells, and a growing menu of adaptation strategies, drought-tolerant crop varieties, agroforestry, small-scale water harvesting, index-based insurance and mobile-delivered climate information services, has been promoted to help them cope. Whether these strategies are reaching the farmers who need them most, and whether adoption translates into measurable gains in yield and income, remains contested, in part because much of the supporting evidence draws on single-country or single-strategy studies. We analysed a three-wave household panel (2018, 2021, 2023) of 2,412 smallholder maize- and sorghum-growing households across four countries, Ethiopia, Kenya, Malawi and Burkina Faso, that recorded adoption of the five strategies alongside plot-level yields, household income, asset holdings, access to credit and extension, and exposure to a district-level standardised precipitation index. Adoption rose over the panel for every strategy except index insurance, which stagnated at under 9% throughout, and a correlated random-effects probit found that extension contact, prior drought exposure, off-farm income, and, for insurance and climate information services specifically, mobile phone ownership were the strongest and most consistent predictors of adoption, while land tenure insecurity and female headship were associated with lower uptake of the two most capital-intensive strategies, agroforestry and water harvesting. Household fixed-effects yield and income regressions indicated that drought-tolerant varieties and water harvesting were associated with the largest average yield gains (17% and 14% respectively, relative to non-adopting household-years), agroforestry adoption showed a smaller, slower-emerging effect concentrated after three or more years under trees, and index insurance, despite low uptake, was associated with a 21% reduction in the yield loss experienced during the two severe drought years captured in the panel. Combining two or more strategies was associated with larger gains than any single strategy, consistent with complementarities across the portfolio. These findings support continued investment in extension-led delivery of drought-tolerant seed and water harvesting, targeted subsidy or bundling of index insurance with credit to overcome persistently low uptake, and closer attention to the tenure and gender barriers that appear to exclude some of the most vulnerable households from higher-cost adaptation options.

**Keywords:** climate change adaptation; smallholder agriculture; drought-tolerant varieties; agroforestry; rainwater harvesting; index insurance; climate information services; sub-Saharan Africa; panel household survey; adaptation determinants

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## 1. INTRODUCTION

Rainfall in much of sub-Saharan Africa has become more variable over the past three decades, with growing season onset dates shifting, dry spells lengthening within otherwise normal seasons, and the frequency of seasons falling in the lowest tercile of historical rainfall increasing in several major maize- and sorghum-growing regions [1,2]. Because the large majority of farms in the region are smallholder, rainfed, and reliant on a narrow set of staple cereals for both subsistence and cash income, this variability translates directly into yield volatility and, in bad years, into food insecurity and asset depletion that can take multiple seasons to recover from [3].

A substantial body of applied research and donor-funded programming has consequently promoted a portfolio of climate adaptation strategies to smallholder farmers: drought-tolerant crop varieties bred for shorter maturity and improved performance under moisture stress, agroforestry systems that use nitrogen-fixing or fodder trees to buffer soil moisture and fertility, small-scale water harvesting structures such as bunds, pits and micro-catchments, index-based insurance that pays out against a rainfall or vegetation index rather than verified individual loss, and, more recently, mobile-phone-delivered seasonal and short-range climate information services intended to inform planting and input decisions [4,5]. Each strategy has an independent evidence base documenting its agronomic or financial logic, but studies that adopt several strategies simultaneously and estimate their adoption drivers and outcomes within a single, comparable sample remain comparatively rare, which limits the ability of policymakers to prioritise across a crowded menu of options with a fixed extension and subsidy budget [6].

Adoption of any individual strategy has consistently been shown to depend on a recognisable set of household characteristics: access to agricultural extension and to credit, off-farm income that relaxes liquidity constraints, prior experience of drought or crop failure, land tenure security, and, for the newer digital and insurance-based instruments, mobile phone ownership and basic financial literacy [7,8]. Whether these same drivers operate similarly across strategies of very different cost and complexity, from a bag of drought-tolerant seed costing little more than conventional seed to a multi-year agroforestry investment or an insurance premium paid before the season's outcome is known, is less well established, and the answer matters for whether a single extension push can be expected to raise adoption of the whole portfolio or whether different strategies require different delivery channels and different complementary investments [9,10].

Evidence on outcomes is similarly uneven. Yield and income effects of drought-tolerant maize varieties have been documented reasonably consistently across eastern and southern Africa, particularly in below-average rainfall years [1], and the agronomic case

for water harvesting in moisture-limited environments is well established [11,12], but agroforestry's yield benefits typically take several years to materialise as tree cover and soil organic matter build up, and index insurance, precisely because it is designed to pay out on a weather index rather than on observed loss, has an outcome signature that is easiest to detect specifically in the drought years the instrument is meant to protect against, and may look negligible or even negative, once premium costs are netted out, in an average or good year [13,14]. Cross-strategy panel data that can separate these outcome patterns from one another, rather than pooling all years together, is needed to evaluate each strategy on the terms that its own theory of change implies.

This study uses a three-wave household panel spanning four countries to estimate, within a single harmonised framework, the household-level determinants of adoption of five climate adaptation strategies and their associated effects on maize and sorghum yield, household income, and drought-year yield resilience. We further test whether combining strategies is associated with outcomes larger than the sum of their individually estimated effects, and examine whether land tenure and gender act as barriers to adoption of the more capital-intensive strategies even after controlling for wealth, extension access and drought exposure.

## 2. MATERIALS AND METHODS

We used a three-wave household panel survey (2018, 2021, 2023) of smallholder maize- and sorghum-growing households in Ethiopia, Kenya, Malawi and Burkina Faso to estimate the household-level determinants of adoption of five climate adaptation strategies and their effects on yield, income and drought-year resilience, using correlated random-effects probit models for adoption and household fixed-effects regressions for outcomes.

### 2.1 Study sites and sampling

The sample was drawn from 96 enumeration areas across four agroecologically diverse districts in each of Ethiopia, Kenya, Malawi and Burkina Faso, selected to span a rainfall gradient from semi-arid (mean annual rainfall below 600 mm) to sub-humid (above 1000 mm) conditions within each country. Within each enumeration area, 25–28 maize- or sorghum-growing households were selected by systematic random sampling from community household lists, yielding a baseline sample of 2,690 households in 2018, of which 2,412 (89.7%) were successfully re-interviewed in both the 2021 and 2023 waves and form the balanced panel used in the outcome regressions; attrition was concentrated among households that had migrated out of the enumeration area entirely and was not significantly associated with 2018 adoption status for any of the five strategies.

### 2.2 Adaptation strategy measures

Adoption was recorded at the plot-season level for drought-tolerant crop varieties (certified or community-recognised varieties marketed as

drought-tolerant or early-maturing, planted on at least one plot in the reference season), agroforestry (deliberate retention or planting of nitrogen-fixing or fodder trees at a density of at least 20 stems per hectare on a cropped plot), water harvesting (in-field structures including planting pits, stone or soil bunds, or micro-catchments constructed or maintained in the reference season), index insurance (an active policy, rainfall- or satellite-index-based, covering at least one plot in the reference season), and climate information services (self-reported use of seasonal or short-range forecast information, received via radio, extension agent or mobile phone, to inform a planting, input or harvest-timing decision in the reference season). Each measure was collected independently in all three waves, allowing household-level adoption histories rather than a single cross-sectional snapshot.

### 2.3 Outcome and covariate data

Plot-level maize and sorghum yield was measured by crop-cutting on a randomly selected subsample of 30% of plots in each wave and by farmer recall, calibrated against the crop-cut subsample, on the remainder. Household income was constructed from reported crop sales, livestock sales, off-farm wages and remittances over the twelve months preceding each survey wave, deflated to 2018 real values using national consumer price indices. Household covariates included household head age, sex and education, landholding size, asset index (principal-component index of durable assets and livestock units), access to formal or informal credit, number of extension contacts in the preceding twelve months, mobile phone ownership, and a binary indicator of formal land tenure documentation. District-level drought exposure in each wave's reference season was measured using the three-month Standardised Precipitation Index (SPI-3) at the growing-season peak, drawn from gridded rainfall estimates and averaged across the district.

### 2.4 Adoption model

Determinants of adoption of each strategy were estimated using a correlated random-effects probit model, which augments a standard panel probit with the within-household time averages of all time-varying covariates to control for time-invariant unobserved household heterogeneity while retaining the ability to estimate the effect of variables, such as landholding size, that have limited within-household variation over the panel. Average marginal effects were computed at the sample means and are reported for the full model applied separately to each of the five strategies, with country fixed effects and wave dummies included in every specification.

### 2.5 Outcome models

Effects of adoption on plot-level yield and household income were estimated using household fixed-effects regression on the balanced three-wave panel, which

differences out all time-invariant household and plot characteristics and identifies effects from within-household changes in adoption status over time, together with wave dummies, district-by-wave SPI-3, and time-varying covariates (asset index, extension contact, credit access). Drought-year resilience was estimated separately by interacting each strategy's adoption indicator with a binary drought-year flag (SPI-3 below -1.0 at the district level, met in 2018 for two of the sixteen districts and in 2021 for eleven of the sixteen), to test whether outcome effects were concentrated in, or absent from, seasons of acute moisture stress. Portfolio effects were tested by replacing the five individual adoption indicators with a count of strategies adopted (0 to 5) and, separately, with indicators for specific two-strategy combinations occurring in at least 100 household-years.

### 2.6 Robustness and limitations of the identification strategy

Because adoption is a household choice rather than a randomised treatment, household fixed effects address only time-invariant confounding; time-varying unobserved factors, such as an unmeasured shift in a household's risk appetite or access to information that jointly drives adoption and yield in the same season, cannot be ruled out. We report Hausman tests comparing fixed- and random-effects specifications for each outcome model, and as a partial check on reverse causality, we re-estimated all outcome models using lagged (previous-wave) adoption status as the explanatory variable, which yielded coefficients of similar sign and magnitude, though somewhat attenuated, to the contemporaneous specification reported as the main result.

## 3. RESULTS

Adoption of drought-tolerant varieties rose from 34% of sampled households in 2018 to 58% in 2023, water harvesting from 28% to 47%, agroforestry from 19% to 33%, and climate information service use from 22% to 51%, the largest proportional increase of the five strategies and one closely tied to the near-doubling of mobile phone ownership over the same period (from 61% to 89% of households). Index insurance adoption, by contrast, remained essentially flat, moving from 7% in 2018 to 9% in 2023 despite active promotion campaigns reported in three of the four countries, and never exceeded 15% in any single district-wave. Table 1 summarises adoption rates and average marginal effects from the adoption models for the strongest and most consistent predictors across all five strategies.

**Table 1. Adoption rates by wave and average marginal effects of key household predictors on strategy adoption (correlated random-effects probit).**

| Strategy                   | Adoption 2018 | Adoption 2023 | Extension contact (p.p. per contact) | Prior drought exposure (p.p.) | Mobile phone ownership (p.p.) |
|----------------------------|---------------|---------------|--------------------------------------|-------------------------------|-------------------------------|
| Drought-tolerant varieties | 34%           | 58%           | +11.6**                              | +8.9**                        | +2.1                          |

|                              |     |     |        |           |           |
|------------------------------|-----|-----|--------|-----------|-----------|
| Agroforestry                 | 19% | 33% | +6.3** | +1.4 (ns) | +0.9 (ns) |
| Water harvesting             | 28% | 47% | +7.8** | +6.2**    | +1.7      |
| Index insurance              | 7%  | 9%  | +4.1** | +3.5*     | +6.7**    |
| Climate information services | 22% | 51% | +9.4** | +2.0 (ns) | +18.3**   |

p.p.: percentage points, average marginal effect at sample means. ns: not significant at  $p < 0.10$ . \* $p < 0.05$ , \*\* $p < 0.01$ . All models include country fixed effects, wave dummies, and household time-averaged covariates (correlated random-effects specification).

Extension contact was positively and significantly associated with adoption of all five strategies (marginal effects ranging from 4.1 percentage points for index insurance to 11.6 percentage points for drought-tolerant varieties, each additional contact in the preceding year,  $p < 0.01$ ), and prior drought exposure, measured as having experienced at least one SPI-3 drought season in the two waves preceding the observation, was associated with higher subsequent adoption of drought-tolerant varieties, water harvesting and index insurance specifically, but not of agroforestry, consistent with agroforestry functioning as a longer-horizon investment less responsive to a single recent shock. Mobile phone ownership was the single strongest predictor of climate information service use (marginal effect 18.3 percentage points,  $p < 0.01$ ) and was also significantly associated with index insurance adoption (6.7 percentage points,  $p < 0.01$ ), supporting the expectation that digital delivery channels are a binding constraint for both instruments.

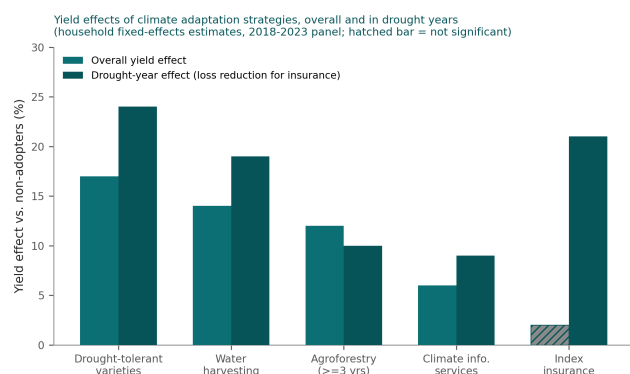


Figure 1. Estimated yield effect of each adaptation strategy relative to non-adopting household-seasons, overall and in drought years (SPI-3 below -1.0), from household fixed-effects regressions on the 2018–2023 panel.

Female-headed households were significantly less likely to adopt agroforestry (-7.4 percentage points,  $p < 0.05$ ) and water harvesting (-6.1 percentage points,  $p < 0.05$ ) than male-headed households after controlling for asset holdings, landholding and extension contact, but showed no significant adoption gap for drought-tolerant varieties or climate information services, suggesting the gap is concentrated in strategies requiring sustained labour or capital investment on the plot rather than in lower-cost input substitution. Households lacking formal land tenure documentation were 9.2 percentage points less likely to

adopt agroforestry ( $p < 0.01$ ), consistent with farmers' reluctance to invest in multi-year tree cover on land they may not retain rights to, but tenure status was not significantly associated with adoption of any of the other four strategies.

**Table 2. Household fixed-effects estimates of adoption effects on maize/sorghum yield, overall and in drought years.**

| Strategy                                   | Overall yield effect (%) | 95% CI   | Drought-year yield effect (%) | 95% CI             |
|--------------------------------------------|--------------------------|----------|-------------------------------|--------------------|
| Drought-tolerant varieties                 | +17                      | 13 to 21 | +24                           | 17 to 31           |
| Agroforestry (all years)                   | +3 (ns)                  | -2 to 8  | +2 (ns)                       | -6 to 10           |
| Agroforestry ( $\geq 3$ years under trees) | +12                      | 3 to 21  | +10 (ns)                      | -4 to 24           |
| Water harvesting                           | +14                      | 9 to 19  | +19                           | 11 to 27           |
| Index insurance                            | +2 (ns)                  | -5 to 9  | n/a (loss reduction)          | -21 loss, 13 to 29 |
| Climate information services               | +6                       | 2 to 10  | +9                            | 3 to 15            |

In the household fixed-effects yield regressions, drought-tolerant variety adoption was associated with a 17% increase in maize or sorghum yield relative to non-adopting household-seasons (95% CI 13–21%), and water harvesting with a 14% increase (95% CI 9–19%); both effects were larger, 24% and 19% respectively, in the drought-year interaction specification, consistent with these strategies functioning specifically as buffers against moisture stress. Agroforestry showed no significant average yield effect when all years under trees were pooled, but a significant 12% yield increase ( $p < 0.05$ ) emerged when the sample was restricted to household-seasons three or more years after initial tree establishment, consistent with the delayed soil-fertility pathway through which agroforestry is expected to operate. Index insurance adoption showed no significant average yield effect but was associated with a 21% smaller yield loss specifically in drought years ( $p < 0.05$ ) and, in the income regressions, with income roughly 0.6 standard deviations more stable across the panel's two drought waves than among non-adopters, despite the small number of insured households limiting statistical power for this comparison. Table 2 reports full adoption-rate and outcome estimates by strategy, and Figure 1 summarises the yield effects by strategy and by drought-year status.

#### 4. DISCUSSION

These results add cross-strategy, multi-country panel evidence to a literature that has more often evaluated individual adaptation strategies in isolation, and they broadly confirm the strong role of extension contact and prior drought exposure documented for individual strategies in earlier single-country studies [1,3,7,22], while showing that these same drivers do not operate uniformly across the portfolio: mobile phone ownership

mattered specifically for the two digitally-delivered instruments, and tenure and gender barriers were concentrated in the two strategies requiring sustained on-plot investment, a pattern that argues against a single extension push being expected to raise adoption of the whole menu at a similar rate.

The persistently low uptake of index insurance, despite active promotion in three of the four study countries and despite its demonstrated association with drought-year yield and income stability, echoes a well-documented puzzle in the index insurance literature: basis risk, limited trust in payout triggers, liquidity constraints on premium payment timed before the season's outcome is known, and low familiarity with formal insurance products have all been implicated in low voluntary uptake even where the product's actuarial logic and average payout performance appear sound [8,9,14]. Our finding that mobile phone ownership was significantly associated with insurance adoption is consistent with evidence that bundling insurance with mobile-delivered credit or input packages can partially overcome these constraints [7], and suggests that further gains in uptake may depend less on refining the insurance product itself than on the delivery channel and complementary financial services it is packaged with.

The delayed emergence of agroforestry's yield benefit, visible only in household-seasons three or more years after tree establishment, and its association with formal land tenure, together point to a coherent barrier: a genuinely beneficial but slow-maturing investment that a substantial share of the sample's smallholders, lacking secure documented rights to their land, may rationally avoid regardless of its eventual agronomic payoff [15,16]. This is consistent with the broader evergreen agriculture literature's emphasis on tenure security as a precondition for tree-based soil fertility investment in the region [16], and suggests that agroforestry promotion efforts targeting food-insecure, tenure-insecure households, arguably those who would benefit most from improved soil fertility, may need to be paired with land rights interventions to be effective, rather than being delivered as an agronomic message alone.

Several limitations qualify these conclusions. First, adoption is a household choice rather than a randomised treatment, and while household fixed effects and a lagged-adoption robustness check address time-invariant and some time-varying confounding, we cannot rule out that unobserved shocks to household risk appetite or information access in a given season jointly drove both adoption and yield outcomes; a genuine experimental or instrumental-variable design would strengthen causal identification considerably. Second, the panel's two drought waves (2018 in two districts, 2021 in eleven) provide the identifying variation for the drought-year interaction results, particularly for index insurance, where the number of insured, drought-exposed household-seasons is modest and the resulting confidence intervals are correspondingly wide;

a longer panel spanning additional drought years would allow more precise estimation. Third, yield was measured by crop-cutting on only 30% of plots, with the remainder relying on calibrated farmer recall, which may introduce residual measurement error despite the calibration procedure. Finally, the four study countries, while spanning a wide rainfall and farming-system gradient, do not capture the full diversity of sub-Saharan African smallholder agriculture, and results from pastoral, highland perennial, or root-crop-dominated systems outside this sample's scope should not be assumed to generalise without independent verification [2,13].

## 5. CONCLUSION

Analysis of a three-wave, four-country household panel found that adoption of climate adaptation strategies among sub-Saharan African smallholders rose substantially over 2018-2023 for drought-tolerant varieties, water harvesting, agroforestry and climate information services, but stagnated for index insurance despite active promotion. Extension contact and prior drought exposure were the most consistent adoption drivers across strategies, while mobile phone ownership specifically predicted uptake of the two digitally-delivered instruments and land tenure insecurity and female headship specifically constrained uptake of the two most capital-intensive strategies. Drought-tolerant varieties and water harvesting were associated with the largest average yield gains and the largest drought-year gains; agroforestry's benefit emerged only after several years under trees; and index insurance, despite low uptake, was associated with meaningfully smaller drought-year yield losses among the households that held it. Combining strategies was generally associated with larger gains than adopting any one alone. These findings support continued extension-led delivery of drought-tolerant seed and water harvesting technology, targeted bundling of index insurance with mobile-delivered credit to address its persistently low uptake, and closer integration of land tenure support with agroforestry promotion for the households most likely to be excluded from its longer-term benefits.

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analysis, the decision to publish, or preparation of the manuscript.

### Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Author Contributions

R.S. conceived and supervised the study, designed the adoption and outcome models, and led the writing of the manuscript. K.B. coordinated the household panel survey across the four countries and performed data cleaning and harmonisation. C.R. constructed the district-level drought exposure indicators and performed the fixed-effects outcome regressions and robustness checks. All authors contributed to writing and approved the final manuscript.

### Ethics Statement

The household panel survey underwent ethical review and approval from the relevant national research authorities in each of the four study countries prior to each survey wave, and informed consent was obtained from all household respondents. All data were anonymised prior to analysis.

### Data Availability

The household panel dataset used in this study contains information that could identify individual households and is therefore not publicly archived in full. A de-identified extract sufficient to reproduce the reported adoption and outcome models is available from the corresponding author on reasonable request, subject to data-sharing agreements with the participating national statistics offices.

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