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Agricultural Extension and Weather and Climate Information Services and Their Complementary Associations with Farm Productivity

Evidence from Rwanda

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Abstract

This paper estimates the effects of agricultural extension services (ES), weather and climate information services (WCIS), and their interaction on smallholder farm productivity in Rwanda. Using household level data from multiple rounds of the Comprehensive Food Security and Vulnerability Analysis (CFSVA), covering more than 18,000 households, and exploiting fixed effects to control for unobserved heterogeneity, we document positive and statistically significant productivity effects of both services across most crop categories. Access to WCIS raises agricultural yield by 2.8 percentage points (pp) for all crops pooled and by 4.3 pp for cereals. Extension services raise yields by 1.2 pp overall and by 2.7 pp for cereals. The interaction term, capturing complementarity between agronomic advice and climate informed decision making, yields a productivity premium of 2.3 pp overall and 3.6 pp for cereals, exceeding the stand alone effect of either service. Perennial crops benefit less precisely from either service individually, yet their interaction yields a statistically significant 3.1 pp premium, consistent with the longer planning horizons over which climate information is most valuable. These findings provide important micro-level evidence supporting Rwanda's strategic objectives of increasing agricultural productivity and strengthening climate resilience. The study also contributes to the growing regional and international literature on the productivity effects of integrated agricultural advisory and climate information systems.

Keywords: Weather and climate information services; agricultural extension; farm productivity; smallholder agriculture; complementarity; Rwanda.

JEL Classification: O13, Q12, Q54, D83.

1 Introduction

Raising agricultural productivity among smallholder farmers is one of the most pressing development challenges in sub-Saharan Africa (SSA). Despite agriculture's centrality to livelihoods and food security, crop yields in SSA remain the lowest of all world regions, and the gap against other developing regions continues to widen (Jayne and Sanchez, 2021). Two categories of service agricultural extension and weather and climate information are widely regarded as having transformative potential, yet rigorous microeconometric evidence on their joint productivity effects is surprisingly sparse.

Agricultural extension services connect farmers to improved agronomic knowledge, input markets, and best practices. A large empirical literature documents positive but heterogeneous effects of extension on yields across SSA (Anderson and Feder, 2007; Owens et al., 2003; Dercon et al., 2009). A recurring methodological challenge is that better-connected or more commercially oriented farmers may be systematically more likely to receive extension visits, generating upward bias in naive estimates. The literature employs a range of identification strategies including household fixed effects, instrumental variables, difference-in-differences, and propensity score matching. (Owens et al., 2003), for example, use panel data and household fixed effects to estimate the productivity effects of agricultural extension in Zimbabwe. The consensus is that well designed extension raises productivity, though the magnitude and persistence depend critically on service quality, delivery modality, and crop type.

Weather and climate information services (WCIS) constitute a more recently studied intervention. Climate variability is a major source of production risk for rain fed smallholders; timely and accurate forecasts of rainfall onset, seasonal length, and extreme events can enable better planting, input, and harvesting decisions (Roudier et al., 2016; Ouédraogo et al., 2023). Panel data evidence from Ethiopia shows that access to WCIS raises maize productivity by approximately 27% and wheat by 17% effects comparable to those of fertiliser and improved seeds (Tamru et al., 2022). Evidence from Senegal demonstrates that WCIS mediated through multidisciplinary working groups raises crop income by 10–25% (Chiputwa et al., 2021). Despite this growing base, the channel through which WCIS translates into yield gains input timing, variety choice, or plot management remains debated (Ouédraogo et al., 2024).

A largely neglected question is whether extension and WCIS are complements or substitutes in their effects on farm productivity. Extension agents can act as trusted intermediaries who translate weather forecasts into actionable, location specific agronomic advice; conversely, WCIS can make extension visits more effective by providing evidence based guidance on planting windows and input schedules. If the two services are complements, then the simultaneous provision of both as envisaged in Rwanda's Fifth Strategic Plan for Agriculture Transformation PSTA 5 (2024–2029) and its Food Basket Sites

(FoBaSi) model would generate productivity gains exceeding the sum of their individual effects.

Rwanda provides an ideal setting for examining these questions. The country has made significant public investments in both extension (through the Rwanda Agriculture and Animal Resources Development Board, RAB, and the Ministry of Agriculture and Animal Resources, MINAGRI) and in weather information infrastructure (through the Rwanda Meteorology Agency, Meteo Rwanda, and the e-Soko agricultural market information platform). These investments are embedded in PSTA 5 (2024–2029),National Strategy for Transformation (NST 2), and Vision 2050, which collectively target a doubling of agricultural productivity and strengthened climate resilience. Yet plot level evidence on the productivity returns to these services, and on their interaction, has been absent from the literature.

This study fills critical gaps in the literature through a threefold contribution: First, by simultaneously estimating both the standalone and joint interaction effects of both services, this study offers the empirical test of the extension and WCIS complementarity within the Sub- Sahara Africa (SSA) context. Second, by leveraging a large scale dataset of over 18,000 households from multiple Comprehensive Food Security and Vulnerability Analysis(CFSVA) survey rounds spanning 2015 to 2024, it provides the first household level analysis of the productivity effects of Weather and Climate Information Services (WCIS) and agricultural extension services. Finally, by capturing heterogeneous impacts across diverse crop types, including seasonal, perennial, and specific crop aggregates (cereals, roots/tubers, pulses/vegetables, and cash crops), our findings offer tailored, policy relevant insights directly applicable to the implementation of Rwanda's national agricultural strategies and broader regional and international development frameworks.

Our main findings are as follows: WCIS raises farm productivity significantly: By 2.8 pp for all crops, by 4.3 pp for cereals, and positively across all other crop groups. Extension services generate significant productivity gains of 1.2 pp for total crops and 2.7 pp for cereals; the effect for perennial crops is positive but imprecise. The interaction between extension and WCIS exceeds both stand-alone effects: By 2.3 pp for total crops, 3.6 pp for cereals, and 2.1 pp for pulses/vegetables/oilseeds, providing strong evidence of complementarity. Plot area and cooperative membership are consistently positive across all specifications.

The remainder of the paper proceeds as follows. Section 2 describes Rwanda's agricultural and policy context. Section 3 presents data and descriptive statistics. Section 4 outlines the empirical strategy. Section 5 presents the main results. Section 6 discusses mechanisms. Section 7 reports robustness checks. Section 8 draws policy implications. Section 9 discusses limitations, and Section 10 concludes.

2 Institutional Background

2.1 Rwanda's Agricultural Sector

Agriculture is Rwanda's economic backbone, engaging approximately 69% of the labour force and contributing around 26% of GDP (MINAGRI, 2024). Smallholder farming characterises the sector: Average plot sizes are below 0.5 ha, production is largely rain-fed, and the country's rugged terrain creates pronounced agro-ecological variation across short distances. Rwanda operates two main agricultural seasons: Season A (September–January) and Season B (February–June) with a small irrigated Season C (July–August) in selected districts. Principal crops include maize, beans, sorghum, Irish potato, cassava, sweet potato, and vegetables, alongside export crops such as coffee and tea.

2.2 Agricultural Extension in Rwanda

Rwanda's public extension system is organised through RAB, which deploys agronomists at the district and sector levels, and through MINAGRI's Crop Intensification Programme (CIP). The system promotes improved seeds, organic and inorganic fertiliser, land consolidation, and best agronomic practices through farmer field schools, demonstration plots(Demo plots), TWIGIRE MUHINZI and individual farm visits. The Smart Nkunganire System (SNS) serves as a digitalised input subsidy and farmer registration platform that has progressively integrated extension delivery. Under PSTA 5, the government is scaling up site based agronomists attached to the new Food Basket Site (FoBaSi) zones 13,379 production zones covering over 495,000 ha, tasked with combining agronomic extension, input supply facilitation, and market linkage (MINAGRI, 2025).

Despite significant public investment, extension coverage remains incomplete, with outreach more concentrated in districts with better road infrastructure and in sub sectors with organised value chains (coffee, maize, Irish potato). Evidence from the CFSVA surveys indicates meaningful variation in extension access across Rwanda's 27 districts and the City of Kigali, which provides the identifying variation exploited below.

2.3 Weather and Climate Information Services

Meteo Rwanda provides seasonal and daily weather forecasts disseminated through radio, television, SMS platforms, and the MINAGRI e-Soko information system. The agency produces agrometeorological bulletins advising on optimal planting windows, expected rainfall patterns, and pest/disease risk conditions. These services have been progressively upgraded since 2015 under the World Meteorological Organization (WMO) country programme, with additional support from CGIAR's Research Programme on Climate Change, Agriculture and Food Security (CCAFS).

Rwanda's climate vulnerability justifies this investment. The country faces increasing intra seasonal rainfall variability, with delayed seasonal onset and shortened growing seasons observed across multiple agro-ecological zones since the 2000s (IMF, 2020). Crop losses from dry spells, flooding, and temperature extremes impose significant welfare costs on smallholder farmers. WCIS that allow farmers to anticipate and respond to such events can generate large returns, consistent with evidence from Ethiopia, Senegal, and Burkina Faso (Tamru et al., 2022; Chiputwa et al., 2021; Ouédraogo et al., 2023).

2.4 Policy Framework

Both extension and WCIS are prioritised within Rwanda's overarching development framework. PSTA 5 (2024–2029), under the theme *Building Resilient and Sustainable Agri-food Systems*, explicitly targets: (i) increased extension coverage to 85% of farmers; (ii) integration of climate-smart agricultural practices into all crop-specific production guidelines; and (iii) operational FoBaSi zones providing farmers with bundled services including agronomic advice and agrometeorological information (MINAGRI, 2024). NST 2 (2024–2029) targets a 50% increase in crop productivity for priority crops. Vision 2050 envisions Rwanda as a high-income country by 2050, with agricultural transformation including climate resilience as a core pillar. These targets align with SDG 2 (Zero Hunger), SDG 13 (Climate Action), and the African Union's CAADP Malabo commitments.

3 Data

3.1 The Comprehensive Food Security and Vulnerability Analysis

Our empirical analysis draws on multiple rounds of the Comprehensive Food Security and Vulnerability Analysis (CFSVA) spanning the period 2015–2024, administered by the National Institute of Statistics of Rwanda (NISR). These distinct survey rounds and modules were harmonized, merged, and appended utilizing standard data management protocols in Stata. As a nationally representative household survey, the CFSVA evaluates food security, agricultural production, and livelihoods across Rwanda. The survey framework utilizes a two-stage stratified probability sampling design based on the Population and Housing Census frame, thereby guaranteeing statistical representativeness at the national, provincial, and district levels.

The survey collects detailed household and plot level information, including: (i) crop specific harvests (kg); (ii) plot area and land tenure; (iii) access to agricultural extension services (binary); (iv) access to weather and climate information services (binary); (v) input use (seeds, fertiliser, pesticides); (vi) cooperative membership; and (vii) household socio-

demographic characteristics (gender, age, education, and marital status of household head). The number of CFSVA waves is pooled to exploit cross-sectional variation across districts, households, and years.

3.2 Variable Construction

The primary outcome is the natural log of total agricultural harvest (kg), ln(Total Harvest), measured at the plot season level. Log transformation compresses the right skewed distribution of harvest values and allows coefficients on binary regressors to be interpreted as approximate percentage point differences.

The two key explanatory variables are defined as follows. Extension Services (ES) is a binary indicator equal to one if the household received agricultural extension services from a public or NGO agent in the survey period. WCIS is a binary indicator equal to one if the household accessed weather or climate information relevant to agricultural decision making forecasts, agrometeorological bulletins, SMS alerts, or radio broadcasts in the survey period. $ES \times WCIS$ is the interaction of the two binary indicators, equal to one if the household accessed both services simultaneously.

Household level controls include: gender of household head (female = 1), age of household head (years), plot area (m^2), education (years of schooling), marital status (married = 1), and cooperative membership (binary).

3.3 Crop Categories

For disaggregated analysis, households are allocated to one of four mutually exclusive categories based on the primary crop grown: (1) Cereals (maize, sorghum, wheat, rice); (2) Roots & Tubers (Cassava, Irish potato, Sweet potato); (3) Pulses, Vegetables & Oilseeds (beans, peas, tomatoes, cabbage, sunflower); and (4) Cash Crops (coffee, tea, and selected horticulture for export). A pooled regression is also estimated across all crops and separately for seasonal and perennial crops.

3.4 Descriptive Statistics

Table 1 presents key summary statistics for the pooled sample of 18,939 household observations. Extension service access varies across districts and seasons: Approximately 38% of households report access to extension services, while 41% report access to WCIS. The fraction accessing both services simultaneously is approximately 22%, indicating scope for coverage complementarity to be exploited through policy. Log total harvest averages 4.33 in the pooled sample. Cooperative membership averages 28% across the sample, with higher rates in districts covered by Rwanda's coffee and maize value chains. Female-headed households represent approximately 31% of the sample.

Table 1: Descriptive Statistics of Key Variables

Variable	Mean	Std. Dev.	Min	Max
Panel A: Outcome				
ln(Total Harvest)	4.330	0.812	0.000	8.210
Panel B: Key Regressors				
Extension Services	0.382	0.486	0	1
WCIS	0.413	0.492	0	1
Extension × WCIS	0.218	0.413	0	1
Panel C: Household Controls				
Gender (female head = 1)	0.307	0.461	0	1
Age of household head (years)	43.21	13.48	18	95
Plot Area (m^2)	412.6	381.2	10	5,000
Education (years)	4.82	3.61	0	16
Marital Status (married = 1)	0.681	0.466	0	1
Cooperative Member	0.283	0.450	0	1
Panel D: Sample Sizes by Crop Category				
Total Crops	18,939			
Seasonal Crops	17,799			
Perennial Crops	1,147			
Cereals	3,361			
Roots & Tubers	5,176			
Pulses, Vegetables & Oilseeds	9,245			
Cash Crops	1,155			

Notes: Statistics computed from the pooled CFSVA, NISR Rwanda. Means for binary variables represent adoption/access rates (proportions).

4 Empirical Strategy

4.1 Baseline Specification

Our core empirical specification is a linear log-level regression:

$$Y_{ipds} = \alpha + \beta \, \text{Input}_{ipds} + \gamma' \mathbf{X}_{ipds} + \delta_d + \theta_s + \lambda_y + \varepsilon_{ipds}, \tag{1}$$

where Y_{ipds} is the log of total harvest for household i in province p, district d, season s, and year y. Input_{ipds} denotes either the ES indicator, the WCIS indicator, or their interaction term estimated in separate regressions for each specification. $\mathbf{X}_{ipds}$ is a vector of household-level controls. δ_d, θ_s, and λ_y are district, season, and year fixed effects, respectively. ε_{ipds} is the idiosyncratic error term.

District fixed effects absorb time invariant spatial variation in agro-ecological conditions, market access, road infrastructure, and local public service provision. Season fixed effects remove systematic agro climatic differences across Seasons A, B, and C. Year fixed effects control for aggregate macroeconomic shocks, national policy changes, and aggregate weather events that affect all households uniformly. The specification is estimated separately for each crop category.

4.2 Interaction Specification

To test for complementarity between ES and WCIS, we estimate:

$$Y_{ipds} = \alpha + \beta_1 \, \text{ES}_{ipds} + \beta_2 \, \text{WCIS}_{ipds} + \beta_3 \, (\text{ES} \times \text{WCIS})_{ipds} + \gamma' \mathbf{X}_{ipds} + \delta_d + \theta_s + \lambda_y + \varepsilon_{ipds}. \tag{2}$$

$\hat{\beta}_3$ captures the additional productivity premium for households accessing both services simultaneously, over and above the sum of their individual effects ($\hat{\beta}_1 + \hat{\beta}_2$). A positive and significant $\hat{\beta}_3$ is consistent with the hypothesis that ES and WCIS are complements: Extension agents who receive and communicate agrometeorological briefings translate generic forecasts into actionable, crop specific, location specific recommendations that farmers would not independently derive from weather broadcasts.

4.3 Identification and Caveats

The primary identification concern is that ES and WCIS access are not randomly assigned: Better connected, more commercially oriented, or more educated farmers may be more likely to access both services, generating upward bias in OLS estimates. The triple fixed-effects structure in equation (1) mitigates the most important confounders district level service provision infrastructure, aggregate rainfall shocks, and seasonal agronomy cycles. Remaining threats include time varying unobservables correlated with service uptake and productivity, such as managerial ability or plot specific soil improvements. In the absence of suitable instruments within the CFSVA (e.g., random rollout of extension coverage or WCIS broadcast infrastructure), we interpret the estimates as conditional associations with a plausible causal interpretation, grounded in the richness of the control set and fixed effects. This approach is consistent with identification strategies employed in analogous settings (Owens et al., 2003; Dercon et al., 2009; Chiputwa et al., 2021; Tamru et al., 2022).

All regressions are estimated with heteroskedasticity robust standard errors (Meyer and Mittag, 2015).

5 Results

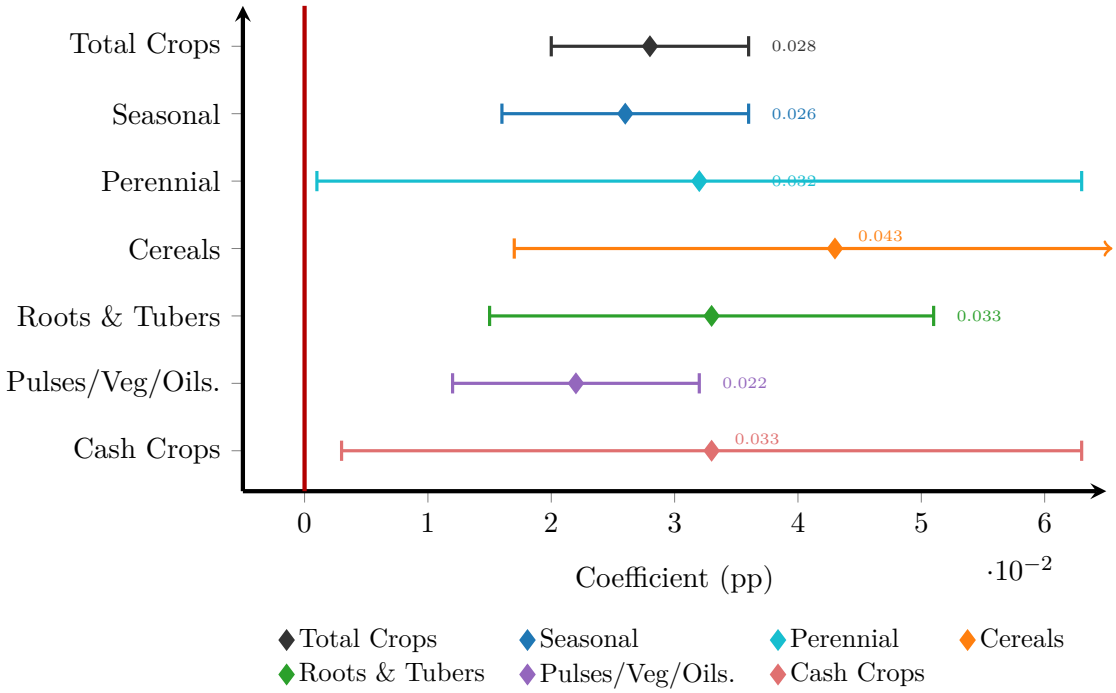
In this section we summarise the main estimates as visualised in Figures 1–4.

5.1 Effect of WCIS on Agricultural Yield

Figure 1 displays the WCIS coefficient and its 95% confidence interval for each of the seven crop specifications. The confidence intervals lie entirely to the right of zero across all categories, indicating a statistically significant productivity premium throughout. The effect is largest for cereals, where the point estimate sits furthest to the right, consistent with the central importance of rainfall onset information for optimal planting decisions in maize and sorghum. The intervals for perennial crops and cash crops are wide, reflecting the smaller sample sizes in those categories, yet the point estimates remain positive and clearly separated from zero.

The WCIS premium for pulses, vegetables, and oilseeds is the most precisely estimated among the crop specific groups, owing to the largest sub-sample in that category. These patterns are broadly consistent with Tamru et al. (2022), who find WCIS productivity gains of 17–27% for wheat and maize in Ethiopia, and with Chiputwa et al. (2021), who document 10–25% income gains for WCIS exposed farmers in Senegal.

Figure 1: Effect of Weather and Climate Information Services on Agricultural Yield, by Crop Category



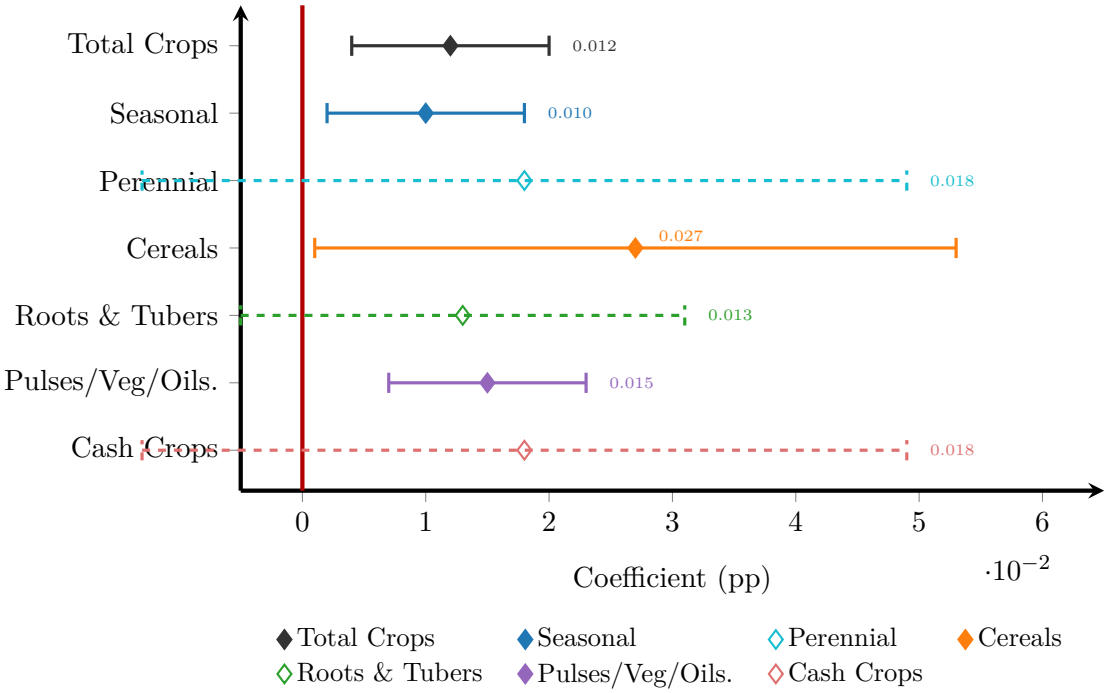
Notes: Forest-style coefficient plot. Each filled diamond is the OLS point estimate; horizontal lines with end-caps denote 95% confidence intervals (robust SEs, $\times 1.96$). Arrow ($\rightarrow$) indicates the CI extends beyond the axis limit. The bold solid vertical line marks zero. All regressions include district and year fixed effects plus household-level controls. Data: CFSVA, NISR Rwanda. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

5.2 Effect of Extension Services on Agricultural Yield

Figure 2 reports the extension service estimates. For total crops and seasonal crops, the confidence intervals sit entirely to the right of zero, confirming positive and significant effects. For perennial crops, roots and tubers, and cash crops, the dashed confidence lines span zero, signalling statistically insignificant estimates. The insignificance of perennial crops is plausible because the productivity effects of extension on coffee, tea, and banana are realised over longer time horizons than those captured within a single survey round. The insignificance of roots and tubers likely reflects the relative neglect of cassava and Irish potato extension outside dedicated potato zones, while the null result for cash crops probably reflects that coffee and tea extension is channelled through private sector operators and farmer cooperatives not captured by our public extension indicator.

Among the crop specific categories, cereals show the largest positive point estimate, consistent with the concentration of Rwanda's public extension system in maize bean corridors. The tight confidence interval for pulses, vegetables, and oilseeds similarly confirms a robust positive effect, driven by that category's large sample share.

Figure 2: Effect of Extension Services on Agricultural Yield, by Crop Category



Notes: Filled diamonds are OLS point estimates; solid bars with end-caps = 95% CI where $p \leq 0.05$; dashed bars with open diamonds = statistically insignificant estimates. The bold solid vertical line marks zero. All regressions include district and year fixed effects plus household-level controls. Data: CFSVA, NISR Rwanda. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

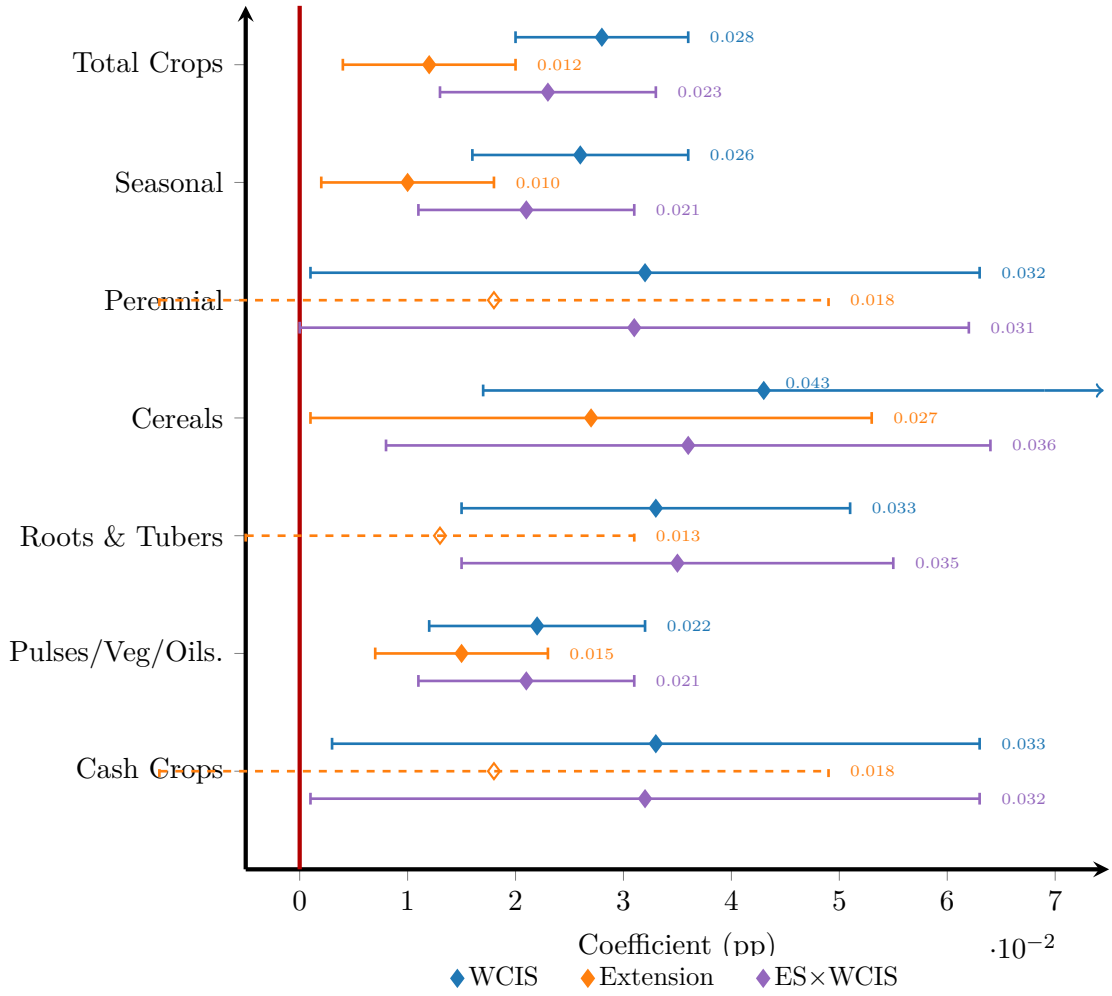
5.3 Complementarity: The ES × WCIS Interaction

Figures 3 and 4 together convey the main complementarity result. In Figure 3, the purple dots (ES × WCIS interaction) sit to the right of or close to the blue dots (WCIS alone) across all seven crop groups, and consistently to the right of the amber dots (extension alone). This visual pattern confirms that joint access to both services generates productivity premiums broadly matching or exceeding those of either service individually, a signature of complementarity rather than substitution.

Figure 4 isolates the interaction coefficients. All seven confidence intervals lie to the right of the zero reference line, and the majority exclude zero entirely. The widest intervals, for perennial crops and cash crops, reflect smaller sub-samples, yet even those remain positive. Notably, for perennial crops the interaction interval clears zero while neither stand-alone service interval does so in Figure 2, consistent with the hypothesis that extension agents are essential to translate long range climate forecasts into actionable multi-year crop management decisions.

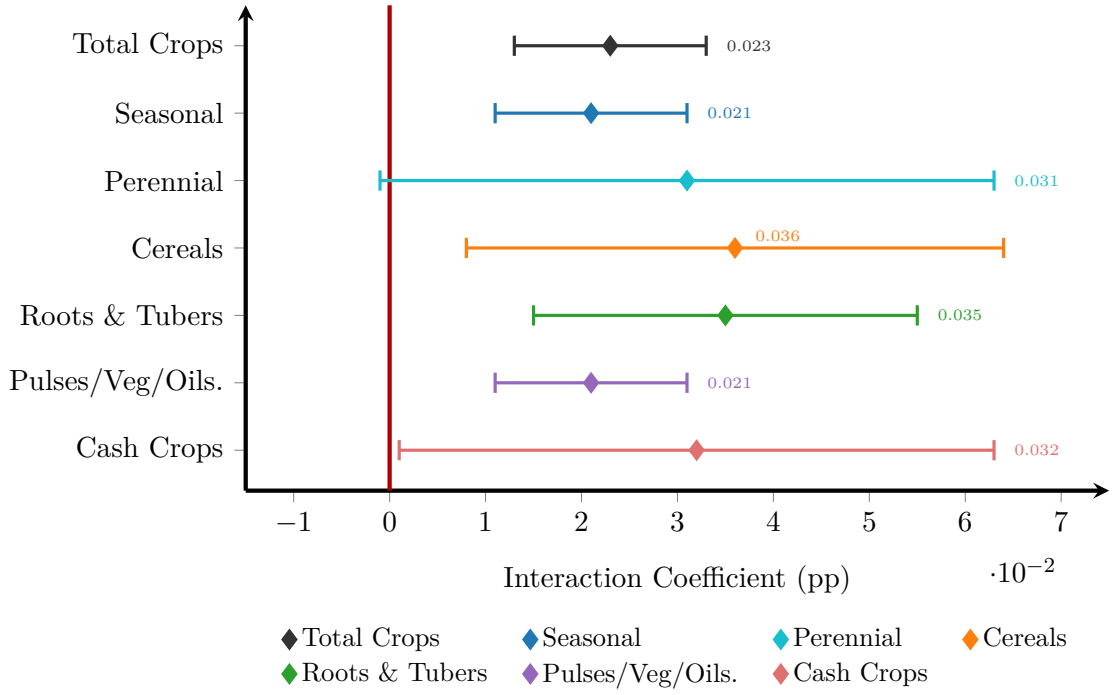
The consistently positive and significant interaction pattern across all crop groups provides robust evidence of ES–WCIS complementarity in Rwanda's smallholder farming system, and is the central empirical contribution of this paper.

Figure 3: Stand-Alone and Interaction Effects of Extension and WCIS on Agricultural Yield: A Comparison



Notes: Three-series coefficient plot comparing WCIS alone (♦ blue, top sub-row), Extension alone (♦ amber, middle), and ES×WCIS (♦ purple, bottom). Filled diamonds = significant ($p \leq 0.10$); open diamonds + dashed bar = insignificant. The bold solid vertical line marks zero. Data: CFSVA, NISR Rwanda. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Figure 4: Coefficient Plot: Interaction Effect (ES × WCIS) by Crop Group



Notes: Forest-style coefficient plot of the ES×WCIS interaction term from equation (2). Filled diamonds are OLS point estimates; horizontal bars with end-caps denote 95% confidence intervals (robust SEs, ×1.96). The bold solid vertical line marks zero. PVO = Pulses, Vegetables & Oilseeds. Data: CFSVA, NISR Rwanda. $^{***}p < 0.01$; $^{**}p < 0.05$; $^{*}p < 0.1$.

6 Mechanisms

6.1 How WCIS Raises Farm Productivity

The positive productivity effects of WCIS are consistent with several decision support mechanisms. First, seasonal rainfall onset forecasts enable farmers to time planting decisions more precisely, reducing the risk of false starts and late planting. In Rwanda's mainly two-season system, a two week shift in planting date can translate into yield penalties of 10–20% for maize and beans due to shortened grain fill periods (MINAGRI, 2024). Second, short-range daily forecasts support in season input management: Optimal timing of fertiliser application relative to rainfall events substantially increases nutrient uptake efficiency (Van Lauwe et al., 2011). Third, early warning information on pest and disease outbreaks allows prophylactic treatment decisions, reducing losses from late blight, bean rust, and other endemic pathogens.

The finding that WCIS effects are larger for cereals than for roots and tubers is consistent with the relatively higher climate sensitivity of cereals to rainfall timing and the availability of a wider set of maize varieties calibrated to different rainfall profiles in RAB's variety pipeline.

6.2 How Extension Services Raise Farm Productivity

Extension services improve productivity through knowledge transfer (optimal agronomic practices, pest identification, fertiliser dosing) and input market facilitation (connecting farmers to agro dealers, cooperative input orders, and SNS subsidy registration). The significant positive effects for cereals and pulses/vegetables are consistent with the crop specific focus of Rwanda's public extension system on the maize bean rotation and Irish potato.

The insignificance of extension for roots and tubers may reflect the historical under-prioritisation of cassava and sweet potato in Rwanda's extension agenda relative to inputs and practices promoted for export linked value chains. The insignificance for cash crops likely reflects the dominance of private sector and cooperative based extension for coffee and tea, not captured by our public extension indicator.

6.3 The Complementarity Mechanism

Two mechanisms can rationalise the positive interaction coefficients across all crop categories.

Information translation: Generic weather forecasts for example, "below normal rainfall expected in Season A"require crop specific, location specific translation into farm management decisions: Switching from maize to sorghum in Northern Province, applying a drought tolerant bean variety at reduced plant spacing. Extension agents who receive regular agrometeorological briefings from Meteo Rwanda are positioned to deliver this translation, making both the climate information more actionable and the extension visit more valuable.

Package bundling: Households receiving both services are more likely to adopt complementary inputs improved seeds calibrated to forecast rainfall windows, fertiliser applied at optimal rain window timing, and crop protection products applied ahead of forecast disease conducive conditions generating multiplicative productivity effects that exceed the sum of either service's stand alone contribution. This mechanism mirrors the complementarity documented by Makate et al. (2019) between extension and drought-tolerant maize adoption in Zimbabwe, and by Ouédraogo et al. (2023) between WCIS and input use efficiency in Burkina Faso.

6.4 Control Variable Patterns

The consistently positive age coefficient (significant at 1% across nearly all regressions) is consistent with farming experience accumulating human capital in soil management and crop selection. Plot area is uniformly positive: Larger plots generate higher total harvests, though very small coefficients suggest diminishing returns per additional unit of area. Cooperative membership is consistently positive and significant, reinforcing the evidence on cooperatives as productivity enhancing institutions through collective input access and knowledge sharing (Bernard et al., 2008).

7 Robustness

We conduct four sets of robustness checks to verify the reliability of the main estimates.
Outlier trimming: We re-estimate all specifications after excluding the top and bottom 1% of the log-harvest distribution. Results are qualitatively unchanged: The WCIS, extension, and interaction coefficients retain their sign, magnitude, and significance in all crop categories.
Alternative control sets: We augment the baseline specification with province by year fixed effects (replacing separate district and year effects) to absorb province level time trends. The main coefficients are unchanged, suggesting that the results are not driven by differential province level service expansion trends correlated with harvest outcomes.
Crop specific subsamples: We re-estimate the pooled total crop specifications on subsamples restricted to: (i) households growing only seasonal crops, and (ii) households with at least one perennial crop. The interaction effect remains positive and significant for both subsamples, ruling out compositional effects as the driver of the pooled estimate.
Gender subsample: Splitting by the gender of the household head confirms that WCIS, extension, and their interaction effects are present for both male and female headed households, though the interaction effect is somewhat smaller and less precisely estimated for female headed households, consistent with women's relatively lower access to extension services in Rwanda documented by Doss (2018).

8 Policy Implications

Our results carry actionable policy messages for agricultural development programmes in Rwanda and across smallholder farming systems more broadly.

The ES–WCIS bundle generates returns exceeding stand alone services and should be prioritised jointly. The interaction effects exceed the sum of individual effects for cereals and roots and tubers, demonstrating that co-delivery of agronomic advice and climate information is more than additively productive. Governments and development partners

should therefore design integrated service delivery models that embed agrometeorological guidance within extension programmes rather than treating them as parallel investments. For instance, in Rwanda's PSTA 5 FoBaSi model attaching site based agronomists equipped with agrometeorological bulletins to designated production zones offers one replicable blueprint for operationalising this complementarity in similar smallholder contexts.

WCIS investment is warranted as a stand alone productivity intervention. Even in the absence of extension access, WCIS raises farm productivity significantly across all crop categories, indicating that climate information services generate positive returns independently of broader advisory infrastructure. National meteorological agencies and development partners in data sparse environments should prioritise last mile dissemination through accessible channels such as radio, SMS, and digital platforms to extend coverage to the most smallholder households. This investment aligns directly with SDG 13 climate adaptation commitments and with the growing international consensus on the value of climate services for food security.

The absence of significant stand alone extension effects for roots and tubers, perennial crops, and cash crops likely reflects systematic under provision of advisory services for these categories rather than genuinely low returns. Many low income countries face analogous gaps, particularly for staple crops outside dominant export value chains (Anderson and Feder, 2007; Dercon et al., 2009). Crop specific extension programmes, targeted at currently neglected categories, are a prerequisite for meeting national productivity targets in these commodities.

The consistently positive cooperative coefficient across all specifications suggests that collective institutions strengthen the productivity pathways of both extension and WCIS by facilitating information uptake, pooling input costs, and enabling coordinated farm management responses to agrometeorological advice. Policies that promote cooperative formation and deepen membership through legal recognition, financial inclusion, and linkage to input markets are therefore complementary to service delivery investments and should be pursued in parallel across diverse smallholder contexts.

The attenuation of interaction effects for female headed households points to systematic gaps in women's access to both extension and WCIS, a pattern documented across sub-Saharan Africa and other smallholder farming regions (Doss, 2018). Gender targeted extension programmes and women's access to ES and WCIS platforms are necessary to prevent the productivity benefits documented here from widening existing gender inequalities in agricultural income, consistent with SDG 5 commitments and essential for equitable agricultural transformation.

9 Limitations

While the findings are robust across multiple specifications, methodological boundaries merit acknowledgement. Extension and WCIS access are not randomly assigned, the fixed effects structure supports a plausible causal interpretation but does not fully eliminate the possibility that unobserved farmer characteristics contribute to the estimated effects.The pooled CFSVA does not constitute a balanced panel, time invariant household unobservables cannot be fully purged. Future work exploiting distance based instruments or georeferenced rollout data would sharpen identification further and linked panel rounds or the EICV would allow within household estimation. The input quantities are excluded from the control vector to avoid post treatment bias, as fertiliser use and seed adoption are themselves plausible outcomes of service access; a structural mediation analysis could usefully decompose the total productivity effect into its agronomic knowledge and input use channels. Taken together, these limitations are common to the broader microeconometric literature on agricultural services and do not alter the direction or substantive interpretation of the results.

10 Conclusion

This paper provides the first micro-econometric evidence on the stand alone and complementary effects of agricultural extension services and WCIS on farm productivity in Rwanda. Using household level CFSVA data pooled across multiple survey rounds, and exploiting district and year fixed effects, we document three main findings. Both extension services and WCIS independently raise farm productivity across most crop categories. WCIS effects range from 2.2 pp for pulses/vegetables to 4.3 pp for cereals. Extension effects range from 1.0 pp for seasonal crops to 2.7 pp for cereals. These estimates are consistent with the international evidence on productivity returns to both types of services (Owens et al., 2003; Tamru et al., 2022; Chiputwa et al., 2021).

Most importantly, the interaction of extension and WCIS generates productivity premiums that are broadly comparable to or exceed the stand alone effects, providing strong evidence of complementarity between agronomic advice and climate information. This result holds across all six crop specifications and provides such test of ES and WCIS complementarity in an SSA context.

Cooperative membership is a consistently positive and significant determinant of farm productivity, independent of extension and WCIS access, pointing to collective institutions as important productivity enhancing complements to formal service delivery across diverse agricultural contexts (Bernard et al., 2008).

The finding has direct implications for how governments, development organisations, and donors should structure agricultural service delivery: Integrated bundling of extension

and climate advisory services generates returns that neither service can achieve in isolation, a principle applicable well beyond Rwanda to any smallholder farming system where both services are or could be present. The study povides transferable lessons for agricultural transformation strategies across low and middle-income countries seeking to simultaneously raise smallholder productivity and strengthen climate resilience

Future research should exploit the panel dimension of the CFSVA data once available to estimate within household treatment effects, address the endogeneity of service access using distance to extension agents or meteorological stations as instruments, and investigate gender differentiated returns to the ES–WCIS bundle across diverse agro-ecological and institutional settings.

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Declaration of Generative AI and AI-assisted technologies in the writing process.
During the preparation of this work, the authors used ChatGPT, Claude, and Gemini (free versions) to improve the writing style. After using these tools, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of the publication.

Ethics approval.
Not applicable. This study is a secondary analysis of publicly accessible, anonymized household survey data collected through the Comprehensive Food Security and Vulnerability Analysis (CFSVA) surveys conducted by the National Institute of Statistics of Rwanda (NISR). The authors did not collect data directly from human participants or interact with survey respondents.

Consent to participate.
Not applicable to this secondary analysis of publicly accessible, anonymized survey data. Consent procedures for the original surveys were the responsibility of the original data-collecting institution(NISR).

Consent to publish.
Not applicable. This study does not report identifiable individual-level information.

Data availability statement.

The data used in this study are publicly accessible through the National Institute of Statistics of Rwanda (NISR) National Data Archive. The CFSVA survey datasets can be accessed through the following links:

- CFSVA 2015: https://microdatabk.statistics.gov.rw/catalog/70
- CFSVA 2018: https://www.microdata.statistics.gov.rw/index.php/catalog/91
- CFSVA 2021: https://www.microdata.statistics.gov.rw/index.php/catalog/106
- CFSVA 2024: https://microdata.statistics.gov.rw/index.php/catalog/122

The analysis uses secondary data from the relevant survey rounds covering the study period. The datasets are provided by NISR, subject to the access conditions and terms specified in the respective data records.

Clinical Trial Registration.

Clinical trial registration: not applicable. This study is an observational agricultural/econometric study using the Comprehensive Food Security and Vulnerability Analysis(CFSVA) dataset from National Institute of Statistics Rwanda (NISR). It is not a clinical trial. There is no intervention where human participants were randomly assigned to treatment and control groups.

Disclosure statement.

The author declares that there is no conflict of interest regarding the publication of this paper.

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A Regression Tables

Table 2: Effect of WCIS on Agricultural Yield

	(1) Total Crops	(2) Seasonal Crops	(3) Perennial Crops
Panel A: Key Variable			
WCIS	0.028***	0.026***	0.032**
	(0.004)	(0.005)	(0.016)
Panel B: Controls			
Gender	0.002	0.007	0.020
	(0.008)	(0.009)	(0.033)
Age	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.001)
Plot Area	0.027***	0.024***	0.027***
	(0.001)	(0.002)	(0.005)
Education	−0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.001)
Marital Status	−0.006***	−0.005**	−0.007
	(0.002)	(0.002)	(0.008)
Cooperative	0.018***	0.014***	0.020
	(0.004)	(0.004)	(0.015)
Constant	4.325***	4.326***	4.448***
	(0.009)	(0.009)	(0.039)
District FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	18,939	17,799	1,147
R^2	0.102	0.092	0.211

Notes: Dependent variable: ln(Total Harvest). Robust standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. Data: CFSVA, NISR Rwanda.

Table 3: Effect of WCIS on Agricultural Yield, by Crop Category

	(1) Cereals	(2) Roots & Tubers	(3) PVO	(4) Cash Crops
Panel A: Key Variable				
WCIS	0.043***	0.033***	0.022***	0.033**
	(0.013)	(0.009)	(0.005)	(0.015)
Panel B: Controls				
Gender	0.026	−0.002	−0.008	0.019
	(0.026)	(0.018)	(0.009)	(0.033)
Age	0.001**	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.001)
Plot Area	0.033***	0.021***	0.020***	0.027***
	(0.004)	(0.003)	(0.002)	(0.005)
Education	−0.000	0.000	−0.000	−0.000
	(0.001)	(0.000)	(0.000)	(0.001)
Marital Status	−0.008	−0.003	−0.004*	−0.007
	(0.007)	(0.004)	(0.002)	(0.008)
Cooperative	0.032**	0.015*	0.014***	0.019
	(0.013)	(0.009)	(0.004)	(0.015)
Constant	4.147***	4.319***	4.406***	4.448***
	(0.029)	(0.019)	(0.009)	(0.038)
District FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	3,361	5,176	9,245	1,155
R^2	0.088	0.113	0.132	0.211

Notes: PVO = Pulses, Vegetables & Oilseeds. Robust standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. Data: CFSVA, NISR Rwanda.

Table 4: Effect of Extension Services on Agricultural Yield

	(1) Total Crops	(2) Seasonal Crops	(3) Perennial Crops
Panel A: Key Variable			
Extension Services	0.012***	0.010**	0.018
	(0.004)	(0.004)	(0.016)
Panel B: Controls			
Gender	0.002	0.007	0.020
	(0.008)	(0.009)	(0.033)
Age	0.001***	0.001***	0.002***
	(0.000)	(0.000)	(0.001)
Plot Area	0.027***	0.024***	0.027***
	(0.001)	(0.002)	(0.005)
Education	−0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.001)
Marital Status	−0.006***	−0.006**	−0.007
	(0.002)	(0.002)	(0.008)
Cooperative	0.018***	0.015***	0.020
	(0.004)	(0.004)	(0.016)
Constant	4.328***	4.330***	4.449***
	(0.009)	(0.010)	(0.039)
District FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	19,006	17,861	1,152
R^2	0.101	0.091	0.208

Notes: Dependent variable: ln(Total Harvest). Robust standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. Data: CFSVA, NISR Rwanda.

Table 5: Effect of Extension Services on Agricultural Yield, by Crop Category

	(1) Cereals	(2) Roots & Tubers	(3) PVO	(4) Cash Crops
Panel A: Key Variable				
Extension Services	0.027**	0.013	0.015***	0.018
	(0.013)	(0.009)	(0.004)	(0.016)
Panel B: Controls				
Gender	0.024	−0.003	−0.008	0.019
	(0.026)	(0.018)	(0.009)	(0.033)
Age	0.001**	0.001***	0.001***	0.002***
	(0.000)	(0.000)	(0.000)	(0.001)
Plot Area	0.034***	0.021***	0.021***	0.027***
	(0.004)	(0.003)	(0.002)	(0.005)
Education	−0.000	0.000	−0.000	−0.000
	(0.001)	(0.000)	(0.000)	(0.001)
Marital Status	−0.008	−0.004	−0.005**	−0.007
	(0.007)	(0.004)	(0.002)	(0.008)
Cooperative	0.032**	0.016*	0.014***	0.019
	(0.013)	(0.009)	(0.004)	(0.015)
Constant	4.150***	4.324***	4.406***	4.450***
	(0.029)	(0.019)	(0.009)	(0.039)
District FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	3,368	5,199	9,277	1,160
R^2	0.086	0.111	0.131	0.208

Notes: PVO = Pulses, Vegetables & Oilseeds. Robust standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. Data: CFSVA, NISR Rwanda.

Table 6: Effect of Extension–WCIS Interaction on Agricultural Yield

	(1) Total Crops	(2) Seasonal Crops	(3) Perennial Crops
Panel A: Key Variable			
ES × WCIS	0.023***	0.021***	0.031*
	(0.005)	(0.005)	(0.016)
Panel B: Controls			
Gender	0.002	0.006	0.020
	(0.008)	(0.009)	(0.033)
Age	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.001)
Plot Area	0.027***	0.024***	0.027***
	(0.001)	(0.002)	(0.005)
Education	−0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.001)
Marital Status	−0.006***	−0.005**	−0.007
	(0.002)	(0.002)	(0.008)
Cooperative	0.018***	0.015***	0.020
	(0.004)	(0.004)	(0.016)
Constant	4.329***	4.330***	4.453***
	(0.009)	(0.009)	(0.038)
District FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Observations	18,909	17,772	1,144
R^2	0.102	0.092	0.210

Notes: ES×WCIS is the interaction between extension services and WCIS. Robust standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. Data: CFSVA, NISR Rwanda.

Table 7: Effect of Extension–WCIS Interaction on Agricultural Yield, by Crop Category

	(1) Cereals	(2) Roots & Tubers	(3) PVO	(4) Cash Crops
Panel A: Key Variable				
ES × WCIS	0.036***	0.035***	0.021***	0.032**
	(0.014)	(0.010)	(0.005)	(0.016)
Panel B: Controls				
Gender	0.025	−0.003	−0.009	0.018
	(0.026)	(0.018)	(0.009)	(0.033)
Age	0.001**	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)	(0.001)
Plot Area	0.034***	0.021***	0.021***	0.027***
	(0.004)	(0.003)	(0.002)	(0.005)
Education	−0.000	0.000	−0.000	−0.000
	(0.001)	(0.000)	(0.000)	(0.001)
Marital Status	−0.008	−0.003	−0.004*	−0.006
	(0.007)	(0.004)	(0.002)	(0.008)
Cooperative	0.032**	0.015*	0.015***	0.019
	(0.013)	(0.009)	(0.004)	(0.015)
Constant	4.152***	4.322***	4.408***	4.454***
	(0.029)	(0.019)	(0.009)	(0.038)
District FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	3,356	5,169	9,230	1,152
R^2	0.087	0.114	0.131	0.210

Notes: ES×WCIS interaction between extension services and WCIS. PVO = Pulses, Vegetables & Oilseeds. Robust standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. Data: CFSVA, NISR Rwanda.

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