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RESEARCH ARTICLE

The Direct and Indirect Effects of Mobile Phone Ownership on Maize Yields in Tanzania

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Abstract
The study uses the Living Standards Measurement Study–Integrated Surveys on Agriculture to evaluate mobile phone ownership's direct and indirect effect on yields in Tanzania. The results indicate that transitioning from not owning to owning a mobile phone improves maize yields by about 16%. Mobile phones indirectly affect maize yield by facilitating farmers' access to extension services – regardless of the type of provider – but only account for about 2% of the total effects. Considering both direct and indirect effects, this study suggests that extension services partially moderate this causal relationship. Further, the impact of mobile phones is stronger among male-headed farm households.

Keywords: Correlated random effects; extension services; farmers

JEL classifications: Q12; Q16

1. Introduction

Agricultural productivity in sub-Saharan Africa (SSA) lags the global average. As of 2021/22, maize yields in SSA were at 2.60 tons per hectare, significantly lower than the global average of 3.51 tons per hectare and even further behind the yields in South America (5 tons per hectare) and South and Southeast Asia (4.03 tons per hectare) (USDA, 2022). This disparity has promoted renewed efforts to enhance agricultural efficiency in the region (Bjornlund et al., 2020). A key component of this initiative is agricultural extension, and educational and outreach endeavors crucial for increasing agricultural productivity in SSA (Issahaku and Awudu, 2020; Oduniyi and Tekana, 2021; Sebaggala and Matovu, 2020; Taye, 2013). The major role of agricultural extension is to disseminate tailored, research-driven knowledge and skills to farmers, advancing their technical and managerial skills, livelihoods, and personal goals (Christoplos, 2010; Gêmo et al., 2013). Empirical evidence consistently demonstrates a positive impact of agricultural extension on farm productivity, income, food security, and nutrition in SSA (Danso-Abbeam et al., 2018; Hasan et al., 2012, Owens et al., 2003)-Danso-Abbeam et al., 2018; Hasan et al., 2012, Owens et al., 2003).

Traditionally, public-sector agricultural extension services have been the norm in SSA, with limited involvement of the private sector (Anandajayasekeram et al., 2008). However, these services have faced criticism for inefficiency due to inadequate funding (El Bilali et al., 2022; Kansiime et al., 2021). Initiatives like the Comprehensive Africa Agriculture Development Programme (CAADP), the African Peer Review Mechanism (APRM), and the Washington Consensus on Agriculture have merged to enhance extension effectiveness by advocating privatization, public-private partnerships, and increased agriculture budgeting (Bruce and Costa, 2019; Kydd and Dorward, 2001; Zimmermann et al., 2009).

Despite reforms to engage private sector and non-government players in the extension landscape, smallholder farmers' access to agricultural information remains limited (El Bilali et al., 2022), hindered by scarce public resources and reliance on external aid (Niagia et al., 2022; Sylla et al., 2019). The extension staff-to-farmer ratio is low in the region (Kansiime et al., 2021; Mabaya et al., 2021; Marenya et al., 2017). In Tanzania, for instance, the ratio of extension officer to farmer is 1:2,500, which is below the recommended ratio of 1:200-500 (Marenya et al., 2017). Furthernore, the existing extension system is also characterized by high costs for in-person extension contacts, which reduce visitation frequency to remote rural villages (Lee et al., 2023).

The penetration of mobile phones in SSA offers an innovative avenue to enhance the extension reach (Silvestri et al., 2020; Munthali et al., 2018; Singh, 2018), economic growth (Danquah and Iddrisu, 2018; Mwananziche et al., 2023), and financial inclusion (Tabetando et al., 2022). Mobile technology enables farmers in isolated regions to receive timely and tailored extension services (Cole and Fernando, 2021). Additionally, mobile technology fosters new connections between extension providers and farmers (Witteveen et al., 2017), reducing information costs and strengthening the value chain links (GSMA Intelligence, 2015; Martin and Abbott, 2011; Sife et al., 2010). Evidence from Ghana shows that farmers use mobile phones for diverse agricultural purposes through calling, listening to the radio, watching videos, texting, mobile apps, social media, and internet browsing (Abdulai et al., 2023).

Previous studies have examined the effects of mobile phones on agricultural outcomes. Some studies report no effect and others positive effect on agricultural outcomes. Aker and Ksoll (2015), using a random experiment, reported no statistically significant impact of mobile phone-based interventions – access to a shared basic mobile phone and learning how to use it – on crop quantity grown in Niger. Dzanku et al., (2021) found similar results in Mali, indicating that voice SMS reminders do not affect yields. However, Quandt et al., (2020) observed that mobile phone use for agricultural purposes enhances agricultural profits in Tanzania. Similarly, about 70% of the 49 studies in a recent systematic review reported that the use of Information and Communication Technologies (ICTs) – particularly mobile apps, SMS, videos, and voice calls – leads to enhanced crop yields and income (Mulungu et al., 2025). Analyzing Ghana Living Standards Survey Round Six data, Issahaku et al. (2017) identified agricultural extension, adoption of modern farming practices, and market participation as key causal mechanisms through which mobile phones influence yields. However, their study did not disentangle direct and indirect effects, leaving uncertainty about whether these channels fully or partially mediate the relationship between mobile phones and yields. Moreover, while mobile phones' role in improving access to agricultural extension is well-documented (Cole and Fernando, 2021; Kansiime et al., 2019), their influence on specific sources, particularly government and private extension, remains largely unexplored. Also, little is known about how mobile phones affect rural livelihoods differently by gender. This is crucial for designing best-fit mobile phone-based extension approaches rather than relying on a one-size-fits-all strategy (Mulungu et al., 2025). Disentangling indirect and direct effects, examining gender-specific impacts, and distinguishing between government and private extension services would offer valuable insights for policymakers on the role of mobile phones in enhancing agricultural productivity and supporting both female and male farmers.

This paper aims to address this gap focusing on Tanzania, a country experiencing rapid mobile phone penetration (Fig 1). It evaluates how mobile phone ownership, directly and indirectly, affects maize yields by analyzing panel data from the Living Standards Measurement Study—Integrated Surveys on Agriculture (LSMS-ISA). We focus on maize considering its prominence in Tanzania, accounting for at least 45% of the total cultivated area (Frederick et al., 2020). The paper differentiates the direct benefits of mobile phones, such as accessing inputs (Abdul-Rahaman and Abdulai, 2022), price information (Krell et al., 2021; Ogbeide et al., 2015; Quandt et al., 2020), and social capital (Quandt et al., 2020), from indirect benefits, like the use of mobile phones to connect

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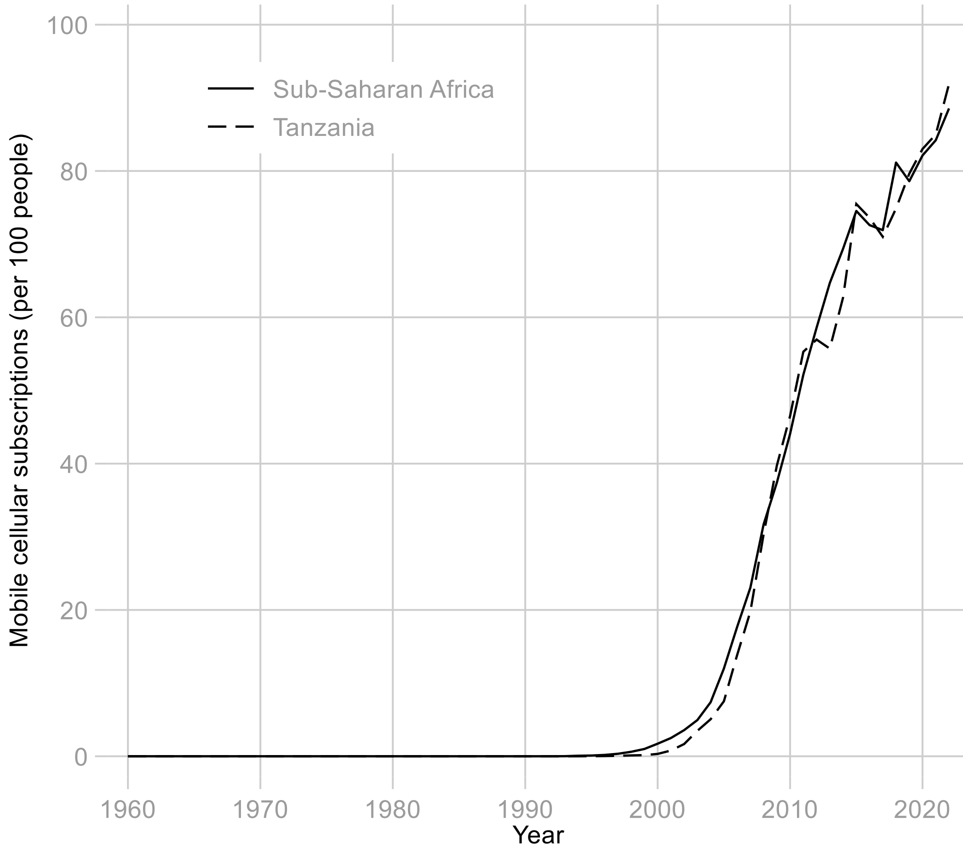

Figure 1. Mobile cellular subscriptions per 100 people in Tanzania (World Bank ICT Indicators Database [link]).

the extension agents (Issahaku et al., 2017; Kansiime et al., 2021). This paper also explores the heterogeneous effects of mobile phones. Ultimately, this work seeks to unravel mobile phones' nuanced roles in advancing agricultural productivity in Tanzania.

Overall, this study reveals that transitioning from not owning to owning a mobile phone facilitates access to extension services, with a stronger impact observed on access to private extension services. Morover, this transition -from not owning to owning a mobile phone- enhances maize yields by around 16%. However, extension services only partially mediate the causal relationship between mobile phone ownership and yields, suggesting that other mechanisms also contribute to yield increases. Research further indicates that the impact of mobile phone ownership is primarily observed among male farmers, highlighting the need to tailor mobile phone-based agricultural interventions to different gender needs.

The paper proceeds with an overview of digital agricultural extension services via mobile phones in Tanzania in section 2, followed by the methodological approach in section 3, a discussion and results in section 4, and section 5 concludes.

2. Context and mobile phone-based digital agricultural extension services in Tanzania

The agricultural sector accounts for over 30% of Tanzania's gross domestic product and employs nearly 65% of the workforce (FAO and ITU, 2022). However, the country's agricultural productivity remains generally poor (Malimi, 2023). This is attributed to deficient communication between agricultural extension providers and smallholder farmers (Ortiz-Crespo et al., 2021;

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Sanga et al., 2014), among other factors. In 2015, it was estimated that 60 to 75% of farmers had no contact with agricultural extension services (Arce and Caballero, 2015). Several mobile-based agricultural extension services have been introduced in the country – bridging the knowledge and information gap for smallholder farmers and capacitating the extension officers to serve large numbers of farmers (Kihoma et al., 2023; Quandt et al., 2020; Sanga et al., 2013, 2014). Because of insufficient funds from extension providers to deliver in-person extension services (MAFAP, 2013), smallholder farmers are progressively accessing extension services through mobile phone communication channels from any network service reception location (GSMA Intelligence, 2015). Again, due to the increasing number of mobile cellular subscribers in Tanzania (see Fig 1), mobile technology is significantly enhancing the performance of the agriculture extension (GSMA, 2020).

Tanzania's agricultural extension system has 28 mobile-based agricultural extension providers (GSMA, 2020). Tigo Kilimo, initiated by Tigo in 2012, is a notable example offering relevant and timely agronomic practices advice, market price, and weather forecast updates through various mobile-based services such as Unstructured Supplementary Service Data, SMS, Interactive Voice Response, and helplines. Tigo Kilimo has nearly 400,000 users and provides information in English and Swahili to accommodate user preferences (GSMA Intelligence, 2015).

Despite these advancements, less educated and poor smallholder farmers often lack access to more advanced mobile extension services requiring smartphones, which may be cost-prohibitive. Most Tanzanian farmers interact with extension providers via basic mobile phones, utilizing offline mobile communication methods due to the absence of internet capabilities on their devices (FAO and ITU, 2022). Simple channels like SMS and voice calls are more practical for linking these farmers with extension services (Mtega, 2021).

The scarcity of extension officers leads to challenges in information dissemination, particularly during peak agricultural seasons (e.g., Mabaya et al., 2021; Ortiz-Crespo et al., 2021). To mitigate this, some providers, such as Ushauri (link), have implemented pre-recorded messages, allowing farmers to access relevant information quickly without waiting on overwhelmed extension officers (Ortiz-Crespo et al., 2021). This situation highlights the double-edged nature of technological progress in Tanzania and similar countries in Sub-Saharan Africa, where new technologies offer significant benefits but also face limitations due to existing structural challenges in striving for inclusive development.

This paper evaluates the role of these efforts in increasing yields, directly and indirectly, through increasing access to extension. We also differentiate between public and private extension access. As shown in the expose above, mobile phone ownership may lead to an increase in access to private extensions and not public or increased access to both.

3. Data and method of analysis

3.1 Data

The study uses data from the National Panel Survey (NPS) collected by the World Bank in collaboration with the Tanzania National Bureau of Statistics within the framework of the Living Standards Measurement Study–Integrated Surveys on Agriculture (LSMS-ISA) project (link). The NPS is a nationally representative household panel survey based on a two-stage stratified cluster random sampling method. Stratification was based on two key dimensions: (i) eight administrative zones (seven in Mainland Tanzania and Zanzibar as the eighth zone), and (ii) rural versus urban clusters within each administrative zone, resulting in 16 strata. In the first stage, clusters – defined as census enumeration areas (EAs) in urban areas and villages in rural areas – were randomly selected within each stratum with a probability proportional to their population size, based on the 2002 Population and Housing Census (see Fig 2). In the second stage, households were randomly selected from each cluster using a comprehensive household listing (Himelein, 2014). Eligibility for the first NPS round (2008/09) and subsequent rounds

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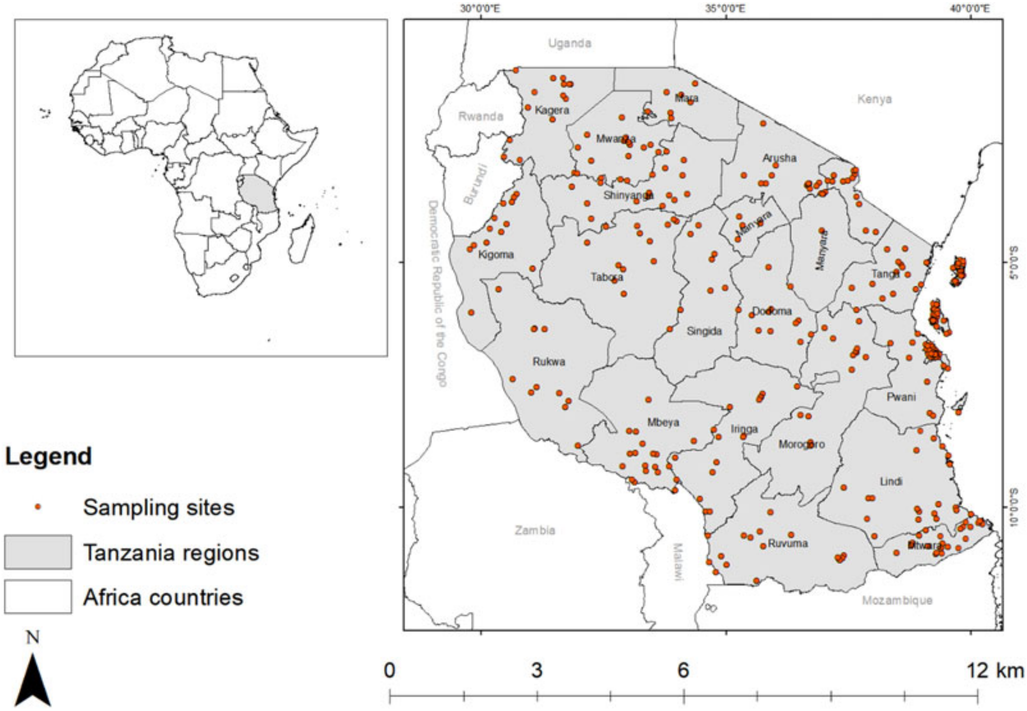

Figure 2. Overview of distribution of census enumeration areas.

required households to have at least one member aged 15 years and above, excluding live-in servants. The number of households sampled per cluster varied proportionally to the population size. Selected households were followed across all waves of the NPS to monitor their outcomes over time. Tracking was limited to households that relocated within Tanzania; those that moved to another country were not included in the follow-up. The NPS was initially designed to track households biennially. However, this schedule was not maintained during the fifth wave conducted in 2020/21. This may be due to a shift in the World Bank's strategic priorities, among other factors.

The surveys were conducted in five rounds: 2008/09, 2010/11, 2012/13, 2014/15, and 2020/21 with household samples of 3280, 3265, 3625, 3360, and 3352, respectively. The focus is on the maize crop, as maize is the primary staple crop in Tanzania, occupying about 45% of the total cultivated area (Arce and Caballero, 2015; Frederick et al., 2020). The sample sizes for maize farmers across the first five rounds were 1027, 1270, 1546, 1236, and 1256 households, totaling 6335 households. The analysis was conducted after addressing outliers. We considered observations below the 5th percentile and above the 95th percentile as outliers. Instead of trimming outliers, we replaced them using the *winsor2* Stata command with the replace cut (5 95) option. This method prevents extreme values from skewing the analysis while maintaining the integrity of the dataset. The survey data include sociodemographic characteristics, household assets like mobile phone ownership, access to agricultural extension services and prices, and agricultural variables such as cultivated crops, agricultural output, and plot size, as indicated in the original questionnaire (link).

Access to extension services in this study is treated as a binary indicator, reflecting whether households received any extension services, with literature supporting this methodology despite critiques about its lack of depth in evaluating service intensity and diversity (e.g., Issahaku et al., 2017; Lee et al., 2023; Malimi, 2023, Nyaplue-Daywhea et al., 2021). Our model assesses three

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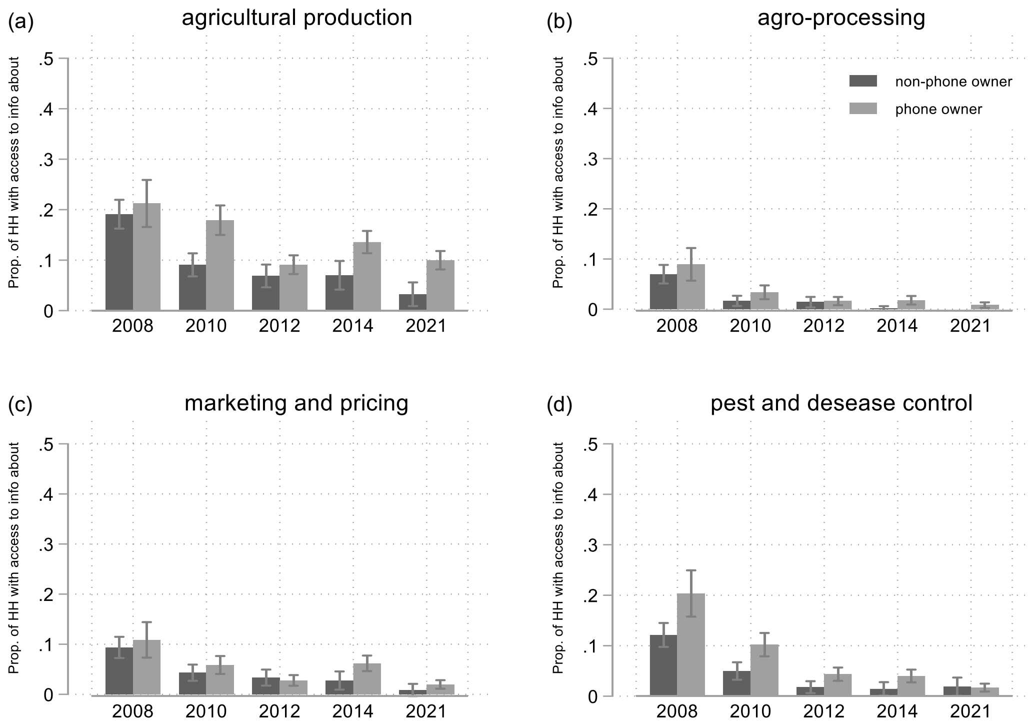

Figure 3. Trends in access to extension services for mobile phone owners vs. non-owners over the years.

types of extension services: government extension services (GES), private extension services (*PES*), and a general category (GE) for any extension service received. The absence of GES and PES classifies a household as having no extension service access. These services offer advice on various agricultural aspects, including production, agro-processing, marketing, pest and disease control, and pricing. While access to these services has declined over the years, Figure 3 shows that farmers with mobile phones had relatively better access than those without.

Table 1 provides some descriptive statistics for the sample and the key variables used in the estimations. Table 1 shows a significant drop, with access to (general) extension decreasing from 62% in 2008/09 to about 50% in 2010/11, further plummeting from 62% in 2012/13 to 40% in 2020/21. This may be explained by the decline in the public budget allocated to agricultural extension services. According to the MAFAP (2013) report, the budget for these services decreased from 10% of the total budget allocated to agriculture in 2007/08 to 5% of the total budget for agriculture in 2010/2011. Another plausible explanation for this significant drop might be attributed to the impacts of COVID-19 events on the delivery of extension services (Baffoe-Bonnie et al., 2021). When looking at agricultural extension sources separately, the proportion of smallholder maize farmers relying solely on government extension services has reduced from 20% in 2008/09 to 5% in 2020/21. On the other hand, the proportion of smallholder maize farmers relying on private extension services experienced a steady decline, dropping from 51% in 2008/09 to around 35% in 2020/21. However, the proportion of smallholder maize farmers who are users of mobile phones has dramatically increased from about 30% in 2008/09 to 83% in 2020/21. On average, the share of households (HH) with mobile phones to the total number of rural households at the community level significantly increased from 11% in 2008/09 to 56% in 2020/21. This supports the effectiveness of the Tanzanian Rural Development Strategy that led to the introduction of ICT in rural areas (FAO and ITU, 2022). The increased percentage of phone ownership provides an opportunity to improve the coverage of agricultural extension services in

Table 1. Descriptive statistics of the sample

Variables	Description	2008/09	2010/11	2011/12	2014/15	2020/21
General extension (GE)	1 if the smallholder farmer has received agricultural extension services from any extension source, 0 otherwise	0.62 (0.49)	0.49 (0.50)	0.62 (0.49)	0.64 (0.48)	0.40 (0.49)
Government extension (GES)	1 if the smallholder farmer has received agricultural extension services from a government extension source; 0 otherwise	0.20 (0.40)	0.12 (0.32)	0.07 (0.25)	0.08 (0.27)	0.05 (0.22)
Private extension (PES)	1 if the smallholder farmer has received agricultural extension services from a private source, 0 otherwise	0.51 (0.50)	0.41 (0.49)	0.57 (0.50)	0.58 (0.49)	0.35 (0.48)
Phone ownership	1 if the smallholder farmer owns a mobile phone, 0 otherwise	0.29 (0.45)	0.51 (0.50)	0.64 (0.48)	0.74 (0.44)	0.83 (0.38)
Share of HH with phone ownership	Proportion of HH with mobile phones to the total number of rural households at the community level	0.11 (0.09)	0.30 (0.17)	0.54 (0.11)	0.67 (0.16)	0.56 (0.28)
Maize yields	Maize yields (kilogram/acre)	411.10 (336.66)	412.55 (322.32)	437.71 (365.39)	520.61 (396.29)	520.12 (392.91)
Age of household head	Years	47.65 (14.68)	48.11 (14.16)	48.11 (14.19)	45.81 (13.66)	48.96 (12.08)
Gender of household head	1 if male; 0 otherwise	0.74 (0.43)	0.77 (0.42)	0.78 (0.42)	0.74 (0.44)	0.74 (0.44)
Marital status of household head	1 if married, 0 otherwise	0.64 (0.48)	0.60 (0.49)	0.66 (0.47)	0.65 (0.48)	0.65 (0.48)
Education of household head	Years	16.41 (2.39)	16.71 (2.44)	16.77 (2.46)	17.07 (2.84)	17.79 (2.59)
Household size prime age	Number of prime-age adults (aged between 15 and 65 years)	4.90 (1.81)	2.65 (1.33)	2.59 (1.31)	2.48 (1.29)	2.77 (1.44)
Distance to market	kilometer	7.88 (7.09)	11.49 (9.58)	10.93 (9.59)	8.60 (8.34)	7.21 (7.13)
Distance to road	kilometer	1.77 (2.04)	1.95 (2.25)	1.93 (2.33)	1.90 (2.36)	1.67 (2.09)
Inorganic fertilizer	Quantity applied in kilogram	6.00 (14.64)	6.30 (14.16)	6.62 (15.20)	7.046 (16.17)	7.16 (15.75)
Pesticide	Quantity applied in kilogram	0.32 (0.87)	0.32 (0.88)	0.28 (0.82)	0.23 (0.69)	0.45 (0.94)
Variety of seed	1 if improved variety, 0 local variety	0.23 (0.42)	0.17 (0.38)	0.60 (0.49)	0.51 (0.50)	0.52 (0.50)
Soil quality	Using a 3-level scale (from 1 “good” to 3 “bad” soil quality)	1.54 (0.50)	1.58 (0.53)	1.58 (0.57)	1.65 (0.60)	1.70 (0.54)
Temperature	Degrees Celsius (°C) *10	221.12 (20.56)	220.83 (20.81)	220.96 (20.75)	228.09 (0.00)	226.30 (28.12)
Precipitation	Millimeters (mm)	1029.67 (294.45)	1035.64 (281.81)	1033.25 (273.97)	1105.95 (000.00)	1289.16 (334.03)

Note: standard deviations are in parentheses.

Tanzania. Moreover, there has also been a noteworthy increase in maize yields, rising from 411 kg per acre in 2008/09 to 520 kg per acre in 2020/21, indicating an effective collaboration among the Tanzanian government, international, and local organizations to enhance agricultural productivity (USAID, 2015). Table 1 also indicates a slight improvement in the education levels of household heads, accompanied by a significant decrease in the number of adults within the households from 2008/09 to 2010/11. However, the number of adults remained stable from 2010/11 to 2020/21, probably due to the National Agricultural Policy launched in 2011 aimed at reducing rural-urban migration by promoting rural development and enhancing economic opportunities in rural areas (MAFSC (Ministry of Agriculture Food Security and Cooperatives), 2013). Furthermore, the use of both inorganic fertilizers – such as phosphate, UREA, Calcium Ammonium Nitrate, and Sulphate of Ammonium – and pesticides has relatively remained steady from 2008/09 to 2020/21, while there has been a significant increase in the adoption of improved varieties of maize seeds over the same period. This reflects the effectiveness of government and local initiatives in promoting sustainable agriculture within Tanzania (USAID, 2015). Additionally, Table 1 indicates that soil quality has remained relatively stable (relatively good soil) over the years, suggesting minimal impact from climate change over the last decade. This may be attributed to the negligible changes in temperature between 2008/09 and 2020/21. Meanwhile, precipitation has shown a steady increase, rising from about 1,029 mm in 2008/09 to 1,289 mm in 2020/21.

3.2 Empirical strategies

The empirical procedures encompass three steps: first, we use the correlated random effects (CRE) estimation approach to investigate the relationship between mobile phone ownership and access to extension services as well as the relationship between mobile phone ownership and maize yields. Second, considering the potential endogeneity of the mobile phone ownership variable, we employ an instrumental variables estimation to assess the causal relationship between mobile phone ownership and maize yields. Finally, we adopt a mediation technique to meticulously disentangle the indirect effects of mobile phone ownership on maize yields from its direct effects.

Additionally, we conduct two distinct analyses. Initially, we estimate the effects of mobile phone ownership assuming no heterogeneity and compare the effects of mobile phone ownership across government and private extension sources. Next, we estimate the effects of mobile phone ownership by gender to measure the heterogeneous effects of mobile phone ownership between male and female-headed farm households.

3.2.1 Correlated random effect estimation

This study employs panel data estimation models utilizing the data from LSMS-ISA data. The fixed-effects (FE) approach is favored for mitigating endogeneity bias due to unobserved heterogeneity that is constant over time. However, FE models cannot estimate the impact of time-invariant variables such as gender (Joshi and Wooldridge, 2019; Schunck, 2013). Additionally, FE models may not be ideal when the treatment variable exhibits little variation over time, as could be the case for extension access since household fixed effects can absorb much of the variation. Alternatively, the random effects (RE) approach could be considered to identify the effect of time-invariant variables. However, it relies on a very strong assumption rarely fulfilled in practice. The RE approach assumes that explanatory variables included in the model are uncorrelated with the unobserved individual heterogeneity (Greene, 2008).

Therefore, we utilize the correlated random effects (CRE) approach also known as the Mundlak (1978) procedure to address these limitations, amalgamating the strengths of both FE and RE methods (Wooldridge, 2018). This approach allows for a correlation between time-invariant unobserved heterogeneity and explanatory variables by incorporating the time averages of the

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time-varying covariates (Joshi and Wooldridge, 2019). It is also particularly effective for handling unbalanced panels (Wooldridge, 2018). The CRE method has been previously applied to similar datasets for causal inquiries (Arslan et al., 2018; Malimi, 2023; Mukasa, 2018), and by including the time averages of the varying covariates, it effectively provides the FE estimates for these variables (Mundlak, 1978). More specifically, we apply a CRE estimation based on the following models:

$$S_{it} = \alpha_0 + \alpha_1 m_{it} + \alpha_i X_{it} + \delta_t + \varphi_i + \epsilon_{it} \tag{1}$$

$$S_{it} = \begin{cases} 1 & \text{if household } i \text{ have access to agricultural extension} \\ 0 & \text{otherwise,} \end{cases}$$

$$ln\ (y_{it}) = \beta_0 + \beta_1 S_{it} + \beta_2 m_{it} + \beta_i X_{it} + \rho_t + \omega_i + e_{it} \tag{2}$$

Where the S denotes access to agricultural extension services by the ith household at the time t, m is farmers' mobile phone ownership, y is maize yield, X is a set of household- and plot-specific characteristics, farm inputs, and location-fixed effects, α_0 and β_0 are the intercepts terms, α and β the vector of parameters to be estimated, and ε_{it} and e_{it} the random error terms. Notably, φ_i and ω_i are the household fixed effects that control for unobserved time-invariant household heterogeneity. Additionally, δ_t and ρ_t are the year-fixed effects that control for standard shocks from one year to the other, e.g., changes in government policies that affect all households. This way, we control for time-varying confounders, time-invariant observable, unobservable factors, and common yearly variations to identify the causal effect of mobile phone ownership on yield.

3.2.2 Instrumental variable estimation

Mobile phone ownership measure is subject to endogeneity due to reverse causality, as farmers with higher agricultural productivity are more likely to use mobile phones (e.g., Nyagango et al., 2023). To account for the possible endogeneity of mobile phone ownership and crop yields, we apply instrumental variables estimation (Joshi and Wooldridge, 2019). Drawing on the research of Nie et al., (2021) and Rotondi et al., (2017), this study initially suggests the share of households owning a mobile phone at the village-year level, excluding household i, as an instrument for the mobile phone variable. This instrument is derived from existing literature that emphasizes the crucial role of peer effects and social learning in shaping households' decisions to use mobile phones (Krell et al., 2021; Nie et al., 2021; Rotondi et al., 2017; Sathye et al., 2018; de Silva et al., 2012). This instrument has been applied in previous studies (e.g., Rotondi et al., 2017). The instrument is theoretically aligned with exclusion criteria, as farmers' maize yields cannot be directly affected by the fraction of households having a mobile phone except through enhancing mobile phone adoption and spread of agricultural information as well through peer effects. However, building on Manski's (1993) reflection principle, we suspect that the reflection problem arising from endogenous social effects might affect this instrument. Specifically, a household's mobile phone ownership is likely influenced by the share of households owning a mobile phone in village j, and vice versa. To address this, we excluded household i when calculating the share of households owning a mobile phone in village j, thereby reducing the risk that the instrument captures intra-household peer effects. Although this helps mitigate bias, it does not fully resolve the reflection problem. To strengthen identification and enhance the efficiency of the IV estimator, we employed Lewbel's (2012) method. By generating heteroskedasticity-based instruments from straightforward functions of the model's existing data, this method supplements our external instrument. We used the *ivreg2h* Stata command to estimate the heteroskedasticity-based instrument model. Following Baum and Lewbel (2019), we applied *ivreg2h* to panel data using within transformation. We assessed the quality of both the generated and external instruments through the three key traditional tests – underidentification, weak identification, and

Hansen J statistic. The results[1] confirm that the instruments are strong and valid, with the following statistics: Kleibergen-Paap rk LM statistic = 88.7 ($p = 0.000$), Cragg-Donald Wald F statistic = 27.47, and Hansen J statistic = 11.90 ($p = 0.536$). We estimate the following model, namely the second-stage equation of the IVREG2H model:

$$ln(y_{it}) = \phi_0 + \phi_1 S_{it} + \phi_2 m^*_{it} + \phi_i X_{it} + \tau_t + \xi_i + \pi_{it} \tag{3}$$

Where m^*_{it} denotes the predicted value of the endogenous variable of individual mobile phone ownership. The value of m^*_{it} was derived automatically by estimating the first-stage equation through the IVREG2H approach as follows:

$$m^*_{it} = \eta_0 + \eta_1 Z_{it} + \eta_i X_{it} + \lambda_t + \Gamma_i + \mu_{it} \tag{4}$$

where Z is the instrumental variable, which includes both the fraction of households having a mobile phone at the village level (external instrument) and heteroskedasticity-based instruments, while μ denotes the error term in the equation (4). This makes the causal claim much stronger.

3.2.3 Decomposing the direct and indirect impacts of mobile ownership

This section outlines the statistical analysis of mediation effects to assess mobile phone ownership's direct and indirect effects on crop yields among smallholder maize farmers. Mediation occurs when the mobile phone ownership variable influences maize yields indirectly through access to extension services variable (Preacher and Hayes, 2008). The direct effect is attributed solely to the farmers owning a mobile phone. For example, a farmer might use a mobile phone to get immediate market information, and weather forecasts, or consult with other farmers on best practices, leading to better decision-making and potentially higher yields (e.g., Kansiime et al., 2019; Malimi, 2023; Munthali et al., 2018; Witteveen et al., 2017). However, Lei et al. (2015) point out that partial mediation is observed when both the coefficient for direct effect and the mediation are statistically significant. The indirect effect encompasses the influence of mobile phone ownership on maize yield that operates through access to extension services (Issahaku et al., 2017). In this pathway, owning a mobile phone helps farmers gain better access to agricultural extension services, providing valuable information and advice on improving their farming practices. This, in turn, can lead to improved maize yields. The assumption is that extension services mediate the relationship between mobile phone ownership and maize yield (mediator effect). The total effect is the sum of these two effects.

The direct, indirect, and total effects of mobile phone ownership on crop yields can be specified as:

$$\text{Direct Effect (DE)} = \beta_2 \tag{5.a}$$

$$\text{Indirect Effect (IE)} = \alpha_1 * \beta_1 \tag{5.b}$$

$$\text{Total Effect (TE)} = \text{DE} + \text{IE} = \beta_2 + \alpha_1 * \beta_1 \tag{5.c}$$

The DE of mobile phone ownership is calculated by holding the mediator (access to extension services) constant, which stows the indirect causal mechanism. Conversely, the IE is determined by keeping the treatment (mobile phone ownership) constant, allowing us to assess the mediating impact of mobile phone ownership on maize yields (Frölich and Huber, 2017; Pearl, 2001). Following Mize et al. (2019), we use seemingly unrelated estimation (SUEST) to retrieve the coefficients and estimate both IE and TE. To generate the indirect effects, a bootstrap with 500 repetitions was used.

[1]These results are related to the general model [Government and private models provide similar results].

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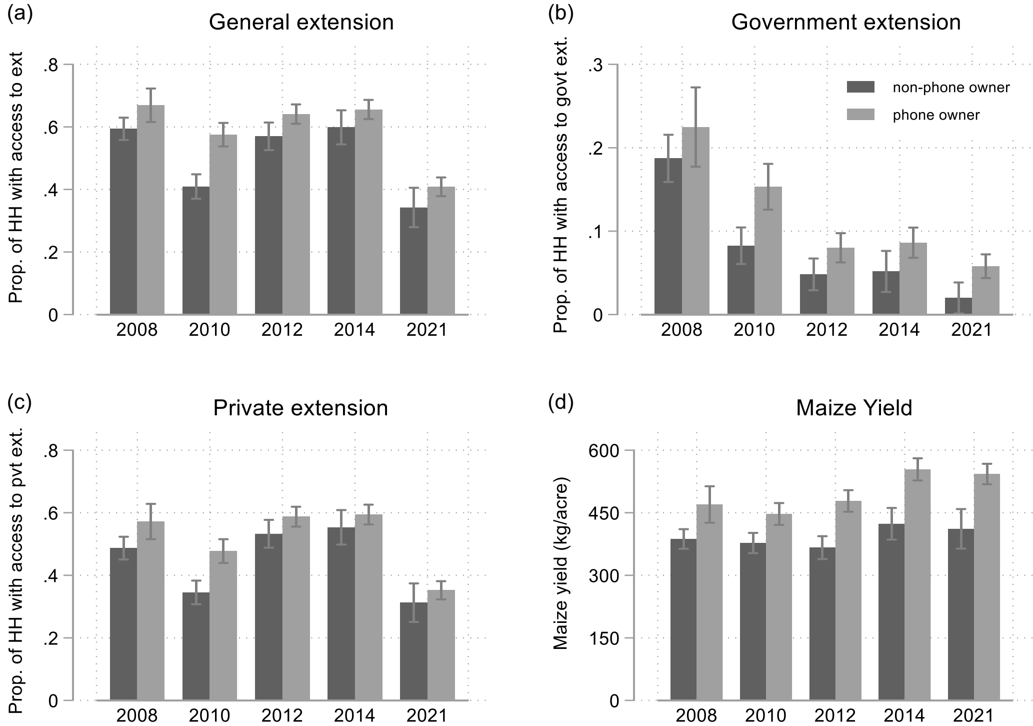

Figure 4. Trends in access to agricultural extension services and maize yields among non-phone owners and phone owners in Tanzania.

In the econometric analysis, we cluster the standard errors at the household level to mitigate the potential impact of heteroskedasticity. Additionally, we apply sampling weights in the analysis to enhance estimate accuracy.

4. Empirical esults and iscussions

4.1 Descriptive results

Figure 4 presents a comparative analysis of the yearly trends in access to extension services and maize yields between phone owners and non-phone owners. Overall, mobile phone owners consistently showed higher proportions of access to extension services compared to their non-phone-owning counterparts. This trend holds true for government and private extension services, emphasizing the crucial role of mobile phones in facilitating exchange between farmers and extension officers. However, a significant decline in access to extension services was observed in 2020/21, largely due to the country's heavy reliance on traditional extension approaches such as farmers' field school, on-farm demonstrations, and farm visits, which were shown to be ineffective during the COVID-19 lockdown as public assembly restrictions and social distancing measures rendered in-person services unfeasible. Agricultural extension services had to be delivered through unconventional approaches such as mobile phones (Baffoe-Bonnie et al., 2021). Figure 4 also indicates a significant difference in maize yields between phone owners and non-phone owners, with phone owners consistently achieving higher yields. This suggests that mobile phones contribute positively to agricultural productivity by improving access to agricultural extension services. Additionally, Figure 4 indicates that yields did not decrease sharply despite reduced access to extension services in 2020/21, probably because the benefits from earlier extension interventions were still present. Even without prompt follow-up extension services, farmers who

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had previously received extension services may continue to apply the knowledge they had learned. This suggests that the benefits of extension services could be cumulative and long-lasting. Econometric models were applied to confirm the relationship between phone ownership and maize yields.

4.2 Decomposition of the effects of mobile phone ownership on maize yields

The results from the correlated random effects model analysis and instrumental variables estimation using heteroskedasticity-based instruments (IVREG2H) are summarized in Table 2. The results for general extension are presented in columns 1-2 (CRE) and 3-4 (IVREG2H), while government extension results are shown in columns 5-6 (CRE) and 7-8 (IVREG2H), and private extension results in columns 9-10 (CRE) and 11-12 (IVREG2H). While CRE and IVREG2H estimations provide similar results, this study primarily relies on the IVREG2H model, which provides more robust estimates in the presence of potential endogeneity.

We observe a positive and significant impact of mobile phone ownership on extension services. Specifically, a smallholder farmer shifting from not owning to owning a mobile phone is 8.2 percentage points (pp) more likely to use general extension services, 3.0 pp more likely to use government extension services and 6.8 pp more likely to use private extension services. Figure 5 reports similar results, showing that owning a mobile phone significantly increases access to extension services, particularly in agricultural production and pest and disease control. These results are consistent with previous studies (Aker and Ksoll, 2015; Issahaku et al., 2017; Khan et al., 2019; Kiberiti et al., 2016; Witteveen et al., 2017), which have also reported a positive impact of mobile phones on access to extension services. The favorable effect of mobile phone ownership can be attributed to the efficient communication channels it offers, such as SMS, phone calls, and WhatsApp, facilitating better interactions between major actors in the agricultural sector, including smallholder farmers and extension officers (e.g., Cole and Fernando, 2021; Issahaku et al., 2017; Mtega, 2021). Moreover, we find that mobile phones have a more pronounced effect on accessing private services than government services. This trend underscores the private sector's agility and innovation, potentially supported by external funding sources, which further amplifies the impact of mobile technology in agricultural extension in Tanzania (Kihoma et al., 2023; Sanga et al., 2014). This aligns partly with Ally (2024) who reported that farmers in Tanzania expressed dissatisfaction with public extension services. Further, evidence across sub-Saharan Africa consistently highlights the superior quality of private extension services compared to public services, mainly due to the private sector's effective management systems, such as well-staffed extension system with performance-based incentives (e.g., rewards and prizes), higher salaries for extension agents, adequate financial resources, and enhanced accountability among stakeholders engaged in extension activities (Kristin, 2020; Moshobane and Antwi, 2022; Sylla et al., 2019; Tham-agyekum et al., 2024). The pronounced impact on private extension services underscores the necessity for partnerships between government and private extension providers to enhance smallholder farmers' access to extension services and livelihoods.

In terms of the effect of mobile phone ownership on maize yields, we find a positive direct effect. Notably, maize yields increase by around 40% across general, government, and private extension models when a farmer transitions from not owning to owning a mobile phone. Although the coefficients differ slightly, the overall conclusion is that mobile phone ownership enhances maize yields. These results are consistent with previous research (Issahaku et al., 2017; Quandt et al., 2020). Interestingly, Quandt et al. (2020), using data from Tanzania, provide a plausible explanation that mobile phone usage in farming reduces both costs and time investments, which can be efficiently reinvested in improving productivity. Moreover, mobile phones help smallholder farmers access a diverse range of extension sources, including more effective private extension services (e.g., Sylla et al., 2019).

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Table 2. Correlated random effect (CRE) and IVREG2H estimates of the impact of mobile phone ownership on extension services and log of maize yields

	GENERAL EXTENSION				GOVERNMENT EXTENSION				PRIVATE EXTENSION			
	CRE		IVREG2H		CRE		IVREG2H		CRE		IVREG2H	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
VARIABLES	Extension	Maize yields	Extension	Maize yields	Extension	Maize yields	Extension	Maize yields	Extension	Maize yields	Extension	Maize yields
Direct Effect												
Mobile Phone	0.084***	0.145***	0.082***	0.400**	0.033***	0.1499***	0.030***	0.396**	0.055***	0.147***	0.068***	0.393***
	(0.019)	(0.037)	(0.020)	(0.155)	(0.011)	(0.037)	(0.012)	(0.154)	(0.019)	(0.037)	(0.020)	(0.153)
Extension		0.071**		0.084***		0.098**		0.049		0.068**		0.069***
		(0.031)		(0.026)		(0.047)		(0.044)		(0.030)		(0.027)
Indirect Effect												
Mobile phone		0.006**		0.007***		0.003*		0.001		0.004*		0.005**
		(0.003)		(0.003)		(0.002)		(0.001)		(0.002)		(0.002)
Total Effect												
Mobile phone		0.151***		0.407***		0.152***		0.399***		0.151***		0.400***
		(0.037)		(0.155)		(0.037)		(0.135)		(0.037)		(0.139)
Constant	0.303**	270.977***	−0.051***	−0.078	−0.071	275.258***	−0.071*	−0.099	0.290***	277.953***	0.219***	−0.085
	(0.0798)	(56.60)	(0.051)	(0.433)	(0.043)	(56.540)	(0.040)	(0.434)	(0.078)	(56.526)	(0.061)	(0.433)
Observations	4,622	4,622	6,199	6,199	4,622	4,622	6,199	6,199	4,622	4,622	6,199	6,199

Notes: Controls included age, gender, marital status, education, household size prime age, distance to market, distance to road, inorganic fertilizer usage, pesticide usage, improved seed variety, soil quality, temperature, precipitation, and location and year-fixed effects.
Clustered standard errors at the household level are reported in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$ and $p^{*} < 0.10$.

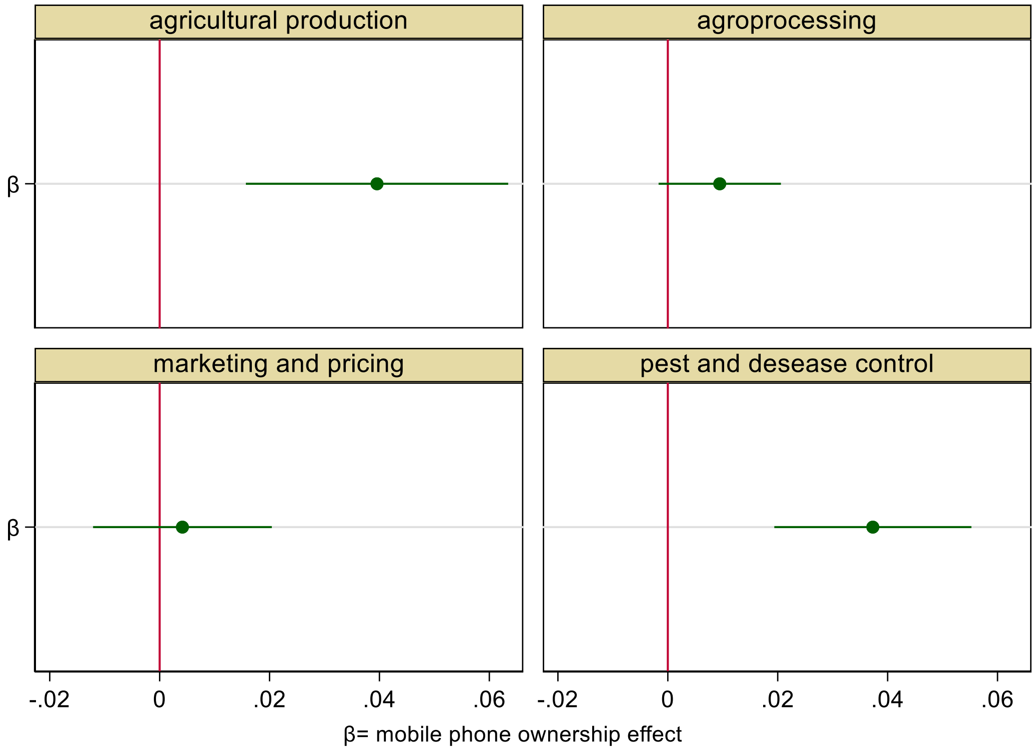

Figure 5. CRE estimates of the impact of mobile phone ownership on diverse extension services.

The effect of access to extension services on yield is statistically significant, with farmers experiencing maize yield increases of 9% and 7.1% after gaining access to general and private extension services, respectively. This confirms the positive impacts of extension services. These results align with those of Malimi (2023), who also observed the positive effects of extension access on smallholder farmers' maize productivity in Tanzania. Similarly, when looking at the impact of extension services on smallholder farmers' productivity in northern Ghana, Danso-Abbeam et al., (2018) found strong evidence that agricultural extension services led to increased productivity in maize plots. Our findings are consistent with the broader literature suggesting that smallholder farmers with access to farm inputs, including agricultural extension services, tend to be more productive. This is because extension services enhance knowledge about farming practices and greater ability to predict weather patterns, leading to more informed decision-making in farming activities (Kassem et al., 2020; Kansiime et al., 2019; Mtega, 2021; Ortiz-Crespo et al., 2021). However, government extension services have limited effects, probably due to quality issues and others (Ally, 2024).

Turning our attention to the indirect effect, a positive and significant indirect effect of mobile phone ownership on maize yields is revealed in the estimation. We find that mobile phone-induced access to general or private agricultural extension services mediates the causal relationship between mobile phones and maize yields. Specifically, mobile phone-induced access to general or private agricultural extension services accounts for only 1.3 to 2% of the total effect of mobile phone ownership on maize yields. This might be ascribed to farmers' limited smartphone use, which restricts their access to more advanced mobile agricultural extension services (FAO and ITU, 2022). These results are consistent with the study of Issahaku et al. (2017), who identified extension services as one of the key channels through which mobile phones affect farmers' productivity in Ghana. However, following Lei et al., (2015), we can conclude that extension

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services only partially mediate the causal relationship between mobile phone ownership and maize yields in Tanzania. Mobile phone ownership influences yields through multiple mechanisms, including agricultural extension services, adoption of modern agricultural technologies, market participation, mobile money, e-vouchers, among others (Issahaku et al., 2017; Tabetando et al., 2022). Consequently, when considering the total effect of mobile phone ownership, significant increases in maize yields are observed, with effect sizes of around 50% among smallholder farmers using general, government, and private agricultural extension services. These findings underscore the crucial role of mobile phone ownership in enhancing agricultural productivity and emphasize the benefits of aligning with effective extension services.

4.3 Results with heterogeneity by gender

Table 3 presents the effect of mobile phone ownership on male-headed and female-headed farm households estimated using IVREG2H. The results for general extension are summarized in columns 1 – 4, government extension in columns 5 – 8, and private extension in columns 9 – 12.

The analysis reveals that transitioning from not owning to owning a mobile phone significantly facilitates access to general and government extension services for both male and female-headed households, suggesting that mobile phones offer an opportunity to bridge the knowledge gaps between male and female farmers. Further comparison between male and female-headed households indicates that the coefficient of the mobile phone ownership variable in the government extension model is greater for female-headed households, suggesting a higher likelihood of using government extension services. This might stem from the Tanzanian government's adoption of the Beijing Platform for Action and the 2030 Agenda for Sustainable Development, which prioritize strengthening gender equality policies and enhancing rural and marginalized women's access to agricultural extension services[2]. However, the analysis also demonstrates a positive and significant impact of mobile phone ownership on the male-headed farm households' likelihood of using private extension services, but no significant impact for female-headed farm households. This evidence supports the assertion that mobile phone ownership has a stronger effect on improving male-headed farm households' access to private extension services in comparison to their female counterparts, revealing a disparity in access to (digital) agricultural extension services between male and female smallholder farmers. These results are consistent with Krell et al.'s (2021) findings, indicating that female farmers in Kenya are less likely to use mobile mobile phone-based agricultural services compared to their male counterparts. This digital divide has been attributed to a number of factors, including female smallholder farmers' lower awareness and knowledge about how to use mobile services (Krell et al., 2021), less mobile phone ownership, and societal gender norms (McCormack, 2018). The gender-based disparity in access to extension services can also be attributed to the absence or ineffectiveness of gender-sensitive measures in the region (McCormack, 2018; Meinzen-Dick et al., 2011).

In terms of the effect on maize yields, male-headed farm households shifting from not owning to owning a mobile phone demonstrate significantly higher productivity in maize yields when compared to their female counterparts. Gaining access to extension services has the same effect as owning a mobile phone. Additionally, gaining access to general, government, and private extension services assumes a mediating role in the causal link between mobile phones and maize yields in male-headed households. However, this mediating effect is not observed in the context of the relationship between mobile phones and maize yields in female-headed households. The main conclusion from these results is that significant heterogeneity across gender in the impact of mobile phone ownership on smallholder farmers' outcomes exists. Sanga (2018) provides a plausible explanation for the limited impact of mobile phones on female smallholder farmers' outcomes,

[2]https://www.unwomen.org/sites/default/files/2024-09/b30_report_tanzania_en.pdf.

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Table 3. Effect of mobile phone ownership on extension and log of maize yields across gender

	GENERAL EXTENSION				GOVERNMENT EXTENSION				PRIVATE EXTENSION			
	IVREG2H				IVREG2H				IVREG2H			
	Male-headed household		Female-headed household		Male-headed household		Female-headed household		Male-headed household		Female-headed household	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
VARIABLES	Extension	Maize yields	Extension	Maize yields	Extension	Maize yields	Extension	Maize yields	Extension	Maize yields	Extension	Maize yields
Direct Effect												
Mobile Phone	0.080***	0.477***	0.081	0.042	0.028**	0.490***	0.043*	−0.023	0.072***	0.478***	0.043	0.054
	(0.024)	(0.163)	(0.051)	(0.260)	(0.014)	(0.161)	(0.025)	(0.259)	(0.024)	(0.163)	(0.049)	(0.259)
Extension		0.097***		0.026		0.097*		−0.134		0.064**		0.070
		(0.031)		(0.057)		(0.050)		(0.109)		(0.030)		(0.058)
Indirect Effect												
Mobile phone		0.008**		0.002		0.003		−0.006		0.005*		0.0034
		(0.003)		(0.005)		(0.002)		(0.006)		(0.002)		(0.004)
Total Effect												
Mobile phone		0.485***		0.044		0.493***		−0.028		0.483***		0.057
		(0.163)		(0.261)		(0.161)		(0.259)		(0.163)		(0.260)
Constant	0.329***	−0.206	0.392**	0.298	−0.049	−0.229	−0.050	0.261	0.296***	−0.211	0.300	0.309
	(0.086)	(0.515)	(0.175)	(0.901)	(0.047)	(0.517)	(0.084)	(0.899)	(0.066)	(0.515)	(0.176)	(0.900)
Observations	4,690	4,690	1,509	1,509	4,690	4,690	1,509	1,509	4,690	4,690	1,509	1,509

Notes: Controls are the same as in Table 2.
Clustered standard errors at the household level are reported in parentheses.
***$p < 0.01$, **$p < 0.05$ and *$p < 0.10$

pointing out that information transmitted through phones, which are mostly owned by males might not be shared or when transmitted to women's phones, may lead to conflict. This is because cultural norms in various parts of Tanzania prohibit women from exchanging SMS with strangers (McCormack, 2018; Sanga, 2018). Restricting female smallholder farmers from freely exchanging ideas and information with unfamiliar extension officers could hinder effective communication. Consequently, the information deficit could have detrimental effects on female smallholder farmers' agricultural output.

5. Conclusions

This study sheds light on the causal mechanism linking mobile phone ownership to crop yields among smallholder maize farmers in Tanzania, using panel data from LSMS-ISA. Specifically, the study examines the mediation effect of agricultural extension services in the causal relationship between owning a mobile phone and maize yields, quantifies the contribution of this mediator to the total effect of mobile phone ownership, and assesses the heterogeneous effects of mobile phone ownership. To achieve this, the study employs a correlated random effects approach and heteroskedasticity-based instruments to control for unobserved heterogeneity across farm households and potential endogeneity of mobile phone ownership and maize yields. The study reveals that despite an increase in the number of mobile phone owners, a considerable proportion of smallholder maize farmers still face limited access to agricultural extension services. This highlights the urgent need to revise and improve the country's extension system to ensure better outreach and support for smallholder farmers. However, mobile phone owners receive more extension services compared to non-mobile phone owners, indicating the potential of mobile technology in improving outreach. This effect is particularly strong among farmers relying on private extension services, emphasizing the value of public-private partnerships in extension delivery.

The results also demonstrate significant direct and indirect effects for both general and private models, suggesting that extension services only partially mediate the causal relationship between mobile phones and maize yields – accounting for only about 2 percent of the total effect. This suggests that mobile-based interventions should go beyond extension services to include, for example, mobile money services and e-vouchers to maximize benefits for farmers. The impact of mobile phones could be further enhanced through measures such as subsidies for smart mobile devices, digital literacy programs, and partnerships with mobile service providers to lower communication costs for farmers. Given the prevalence of basic mobile phones with limited internet capacity among smallholder farmers in Tanzania, [digital] agricultural extension providers should design best-fit mobile phone-based extension services that ensure accessibility through both offline and online mobile channels, reaching large numbers of farmers. However, mobile phone ownership impact was primarily observed among male-headed farm households, pointing to a gender gap. Therefore, customizing mobile phone-based interventions to different gender needs could enhance the effectiveness of mobile-based extension services that benefit all smallholder farmers, regardless of gender, leading to more sustainable improvements in the agricultural sector.

Leveraging a nationally representative household panel survey, designed with a stratified cluster random sampling framework to ensure equal inclusion chances, and a weighted analysis, the results are generalizable to Tanzania. They should, however, be interpreted with caution when applied to other countries, as differences in mobile phone ownership, digital literacy, and other factors may affect their relevance. While the research sheds light on the impacts of mobile phone ownership on access to agricultural extension services and crop yields, it does not explore the different impacts of basic phones and smartphones due to data limitations. Future research using datasets with detailed information on phone types across different contexts could help address this gap.

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Data availability statement. Data will be made available upon request.

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Competing interests. The authors have no conflicts of interest to declare.

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