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EDITED BY
Juan Lu,
Nanjing Agricultural University, China

REVIEWED BY
Nugun P. Jellason,
Teesside University, United Kingdom
Md Salauddin Palash,
Bangladesh Agricultural University, Bangladesh

*CORRESPONDENCE
Ephias Mugari
✉ Mapfori.Mugari@ul.ac.za;
✉ mugarie@gmail.com

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Influence of public agricultural extension services on sustainable land management practice adoption among smallholder farmers in Fetakgomo Tubatse Local Municipality, South Africa

Ephias Mugari*, Norman Mathebula, Tlou Elizabeth Mogale, Emogine Mamabolo, Makgabo Johanna Mashala, Kabisheng Mabitsela and Kwabena Kingsley Ayisi

Centre for Global Change, University of Limpopo, Sovenga, Limpopo, South Africa

Introduction: Sustainable land management practices (SLMPs) are critical to combating land degradation and food insecurity while improving local economies. However, the role of public agricultural extension services in facilitating SLMP adoption in rural, developing country contexts remains poorly understood.
Methods: This study investigated the influence of public agricultural extension services on the adoption of SLMPs among smallholder farmers in four villages (Mphanama, Ga-Radingwana, Ga-Matlala, and Maseleseleng) in Fetakgomo Tubatse Local Municipality, South Africa. Cross-sectional data were collected from 242 randomly selected farming households using semi-structured questionnaires and key informant interviews. A recursive bivariate probit regression model (RBP) was employed to examine the endogenous relationship between extension access and SLMP implementation.
Results: Contrary to expectations, the results revealed a significant negative influence of public extension services on SLMP implementation ($p < 0.001$). A perfect error correlation ($p = 1$) indicated that unobserved factors and systemic barriers jointly influenced extension access and SLMP implementation. While awareness of land degradation ($p < 0.001$) and formal employment ($p = 0.007$) strongly predict access to public extension services, SLMP implementation was primarily driven by access to irrigation ($p < 0.001$) and use of fertilizers ($p = 0.015$), with larger cropped areas discouraging SLMP implementation ($p = 0.012$).
Discussion: These results suggest public agricultural extension programs in the Mphanama area were misaligned with farmer needs or failed to address structural barriers like resource access. The findings underscore the need to transform traditional agricultural extension approaches by integrating digital and in-person advisory services while prioritizing localized knowledge. There is also a need for public agricultural extension services to extend beyond information dissemination to provide low-resource farmers with resources that reduce structural barriers while enhancing the effectiveness of extension services and the implementation of sustainable practices.
Conclusion: This study demonstrates that access to public agricultural extension services alone is insufficient when broader systemic and structural constraints remain unresolved. Future research should integrate mixed methods and longitudinal designs and expand qualitative inquiry to explore the underlying social and institutional factors affecting extension access and SLMP adoption.

KEYWORDS

extension services, endogeneity, land degradation, recursive bivariate probit regression, smallholder farming, sustainable agriculture, sustainable land management

1 Introduction

Smallholder agriculture remains key to rural areas in South Africa, supporting at least 1.75 million farmers while contributing to local economies, food security, and livelihoods (Manganyi et al., 2024). However, this critical sector faces mounting pressures from climate change-induced droughts, soil degradation, rising input costs, and intermittent crop yield fluctuations (Manganyi et al., 2024; FAO, 2022; Mokgolo and Mzezewa, 2023; Mpandeli and Maponya, 2014). These challenges are particularly acute in communities like Mphanama area, where poor land use practices, soil erosion, and abandonment of croplands are severely degrading the land. The consequences include poor soil fertility and low agricultural productivity (Mokgolo and Mzezewa, 2023; Kgaphola et al., 2023a; Kgaphola et al., 2023b), creating an urgent needs for sustainable land management solutions. While the land degradation crisis extends beyond localized impacts, research has demonstrated that adopting multiple sustainable land management practices (SLMPs) can significantly increase the yield and value of production while enhancing food security and climate resilience (Alemu et al., 2023; Etsay et al., 2019; Kolapo et al., 2022; Oduniyi and Chagwiza, 2022). However, smallholder farmer adoption rates of SLMPs remain low or discontinuous due to socio-economic and institutional factors (Oduniyi, 2022; Shiba et al., 2024).

Understanding smallholder farmers' decision-making around SLMPs requires attention to the socio-economic, institutional, and contextual realities that shape behavior. Theoretical frameworks such as the Theory of Planned Behavior, Diffusion of Innovations, Social Practice Theory, and Political Ecology help explain how farmers respond to risk, incentives, and institutional dynamics in land management. This is because factors beyond short-term profit, such as increased yields or reduced production costs, often influence farmers' decisions (Emerton and Snyder, 2018). The Theory of Planned Behavior, for instance, explains how adoption decisions are shaped by farmers' knowledge, attitudes, perceptions, and subjective norms, which are strongly influenced by local institutions and knowledge networks (Meijer et al., 2015; Jha and Gupta, 2021a; Ajzen, 1991). Recent studies emphasize how adoption is not only a matter of awareness but also contingent upon the interaction between farmers' capacities, social networks, and perceived benefits (Kunzekweguta et al., 2017; Antwi-Agyei and Stringer, 2021). Farmers often weigh the risks and uncertainties associated with SLMPs, particularly where resource constraints and land tenure insecurity prevail (Bayisa et al., 2024). Thus, adoption behavior is embedded within broader institutional contexts, such as the structure of agricultural extension systems and the trust farmers place in these services (Ngigi and Muange, 2022). Similarly, the Diffusion of Innovations theory highlights how farmers' adoption decisions are influenced by perceived relative advantage, compatibility, and complexity of new practices (Rogers, 2003), while the Social Practice Theory emphasizes the role of socio-cultural contexts and habits in shaping agricultural decisions (Sharifzadeh et al., 2023; Kaiser and Burger, 2022). These theories underscore the interplay between individual agency, social networks, and institutional support in adoption processes. The Political Ecology framework further explains how structural barriers, such as power dynamics, social structures, cultural narratives, resource access, and policy alignment, limit farmers' choices (Yemadje et al., 2012). Therefore, it is critical to consider the multifaceted cognitive, institutional, financial, monetary, and contextual factors that shape farmer decision-making, i.e., why farmers adopt or reject some SLMPs (Emerton and Snyder, 2018; Meijer et al., 2015; Wadduwage, 2021). Situating this study within these theoretical perspectives is an acknowledgement of the complex and multi-layered nature of adoption decisions in smallholder farming systems and not an imposition of theoretical models that were not directly tested in this study. The theories only provide a robust foundation for analyzing the contradictions that often exist between SLMPs that are recommended, promoted, or invested in through formal extension services and what farmers actually implement, bridging gaps between individual decisions and broader systemic influences.

Agricultural extension programs are pivotal in bridging gaps between research and practice, yet their effectiveness remains contested. This is particularly true in developing countries, where smallholder farmers rely heavily on public agricultural extension services for knowledge and innovation adoption (Mapiye et al., 2025). Public agricultural extension programs in rural areas have served as the primary channel for disseminating information on agricultural innovations, including sustainable land management practices (SLMPs) (Mbatha, 2024). SLMPs are critical for combating land degradation, enhancing soil health, and ensuring long-term food security (Alemu et al., 2023; Kolapo et al., 2022; Lian et al., 2022; Haregeweyn et al., 2023). Evidence shows that extension programs provide technical guidance and empower farmers to make informed decisions aligned with sustainable agricultural development goals. While global studies show that extension access can significantly increase technology adoption and yields (Lasway et al., 2020; Hazrana and Mishra, 2024), anecdotal evidence suggests that smallholder farmers receiving extension services often show lower adoption rates (Nguru et al., 2021). Studies have attributed the varying effectiveness of extension services to differences in accessibility, frequency of interactions, and the quality of information provided (Qwabe and Khapayi, 2025; Qwabe et al., 2022).

Over the years, digital platforms have revolutionized agricultural extension services by overcoming geographical barriers and improving information reach (Bontsa et al., 2023b; Von Maltitz et al., 2024). These can enhance the accessibility of extension services for farmers in remote, marginalized, and sparsely populated rural areas. For instance, mobile technologies, online forums, and interactive applications have enabled farmers to access real-time advice, weather forecasts, and market prices, enhancing their capacity to adopt innovative practices (Bontsa et al., 2023b; Oyinbo et al., 2022). However, digital tools may not substitute traditional in-person advisory services due to several challenges affecting extension advisors and the heterogeneous attributes of farmers (Afful and Mabena, 2024; Oyinbo et al., 2020). Instead, they should complement each other to

create a hybrid system that caters to diverse farmers' needs. In addition to digital platforms, farmers' social networks, both in-person and virtual, play a crucial role in information dissemination (Badolo et al., 2022; Salla, 2019). Peer-to-peer learning within farmer groups, cooperatives, and community networks can reinforce the public extension messages, fostering trust while accelerating the uptake of SLMPs.

Public agricultural extension services have evolved from just being conduits of information to driving agrarian development and food systems transformation in many developing countries (Manzeke-Kangara et al., 2024). Therefore, effective extension programs can contribute to resilient and sustainable food systems by promoting climate-smart practices, conservation techniques, and efficient resource use. Their role extends beyond technology transfer to capacity building, behavior change communication, and improving linkages between farmers, researchers, and policymakers (Von Maltitz et al., 2024). Despite these benefits, the impact of extension services on SLMP adoption is not homogeneous. While many studies have found extension visits and training to increase awareness among smallholder farmers, others have shown that this does not always translate into implementation (Nguru et al., 2021; Mdiya et al., 2023). The reasons for this include contextual and structural barriers, including extension information misaligned with farmers' needs (Gwala et al., 2024; Bontsa et al., 2023a), unconscious exclusion of deserving farmers (Mbatha, 2024; Khwidzhili and Worth, 2016), and unresolved tensions between traditional and scientific knowledge systems (Ludwig and Poliseli, 2018). On the other hand, while extension information can enhance farmers' awareness of SLMPs, this does not always guarantee adoption. Smallholder farmers' decisions are influenced by their socio-economic contexts, risk perceptions, agronomic practices, and the availability of financial incentives (Shiba et al., 2024; Bayisa et al., 2024; Gwala et al., 2024). In addition, social networks and knowledge-sharing platforms often fill gaps left by public agricultural extension (Salla, 2019). This is true in cases where extension services are intermittent or poorly tailored to meet farmers' needs.

Within the past decade, the Limpopo Department of Agriculture and Rural Development (LDARD) has increasingly promoted various SLMPs in rural farming communities in Limpopo Province. These efforts have been complemented by non-governmental initiatives such as the Global Environment Facility-funded projects. These sustainable farming techniques and initiatives have been critical to addressing land degradation, climate vulnerability, low agricultural productivity, and food insecurity (LDARD, 2025). However, sustainable agricultural practices were introduced around the year 2000 through the LandCare Program. LandCare is a government-supported, community-based initiative focused on improving agricultural productivity, food security, job creation, and a better quality of life through sustainable agricultural resource management. Despite the long history of sustainable land management in South Africa, long-term solutions in rural areas continue to encounter several challenges, including insecure land tenure systems, poor policies and sectoral coordination, weak governance mechanisms, poorly funded programs, low capacities, and knowledge and resource gaps (IUCN, 2021). These constraints continue to limit the productivity and sustainability of smallholder farming systems in most developing countries, including those in the Mphanama community and surrounding villages in the Fetakgomo Local Municipality in South Africa's Limpopo Province.

Therefore, this study examines the influence of public agricultural extension programs on the adoption of on-farm SLMPs in the Mphanama area, Limpopo Province. The study builds on a growing body of literature that examines the diverse factors influencing SLMP adoption among smallholder farmers. Previous studies have underscored the role of intrinsic (e.g., knowledge, perceptions, attitudes, aspirations, preferences, etc.) and extrinsic factors (e.g., resource availability, financial, economic, institutional arrangements such as extension services and delivery mechanisms, location, etc.) in shaping farmers' adoption outcomes (Meijer et al., 2015; Kunzekweguta et al., 2017; Antwi-Agyei and Stringer, 2021; Wadduwage, 2021; Hayden et al., 2021; Jellason et al., 2021). The studies further highlighted the interplay between formal and informal knowledge systems, digital innovations, and socio-economic inequalities in shaping farmers' decisions (Jha and Gupta, 2021a; Bayisa et al., 2024; Jha and Gupta, 2021b). The current study goes beyond the traditional adoption studies by employing a recursive bivariate probit regression model that accounts for (i) the endogenous relationship between extension access and implementation (Ngigi and Muange, 2022), (ii) spatial variations in extension access (Qwabe et al., 2022), and (iii) unobserved social capital effects (Elias et al., 2013). This approach uniquely captures how farmers in the Mphanama area navigate complex decision-making processes where public agricultural extension interacts with traditional/local knowledge networks and livelihood constraints.

While constructs of theories such as the Theory of Planned Behavior were not empirically tested, the theories were used interpretively to explain why some farmers implemented SLMPs more readily than others. Exploring these dynamics allows this study to draw lessons on how public agricultural extension services can be optimized to effectively drive more widespread implementation of sustainable practices to achieve sustainable food systems in the Mphanama area and beyond. Findings from this study provide timely implications as South Africa is implementing its Agriculture and Agro-processing Master Plan (2021–2030). Understanding the dynamics of public agricultural extension services and their influence on SLMP implementation will inform the plan to redesign extension content and delivery mechanisms, ensuring that they are better suited to the realities of smallholder farmers (FAO, 2022). The study also contributes to accelerating the attainment of Sustainable Development Goals 15 (Life on Land) and 13 (Climate Action) in rural farming communities (Pasara and Mhlanga, 2022). Overall, this study fills a critical knowledge gap on the role of public agricultural extension in promoting SLMPs in rural South Africa. We anchor the discussion of the findings from this study within the relevant theoretical and empirical foundations to critically engage with the contradictions, gaps, and confirmations that emerge in the discussion. These insights can improve the effectiveness of extension services and contribute to broader goals of sustainable development.

2 Methods

2.1 Study area

This study was conducted in four purposively selected villages within the Fetakgomo Tubatse Local Municipality under Sekhukhune district in Limpopo Province, South Africa (Figure 1). The study

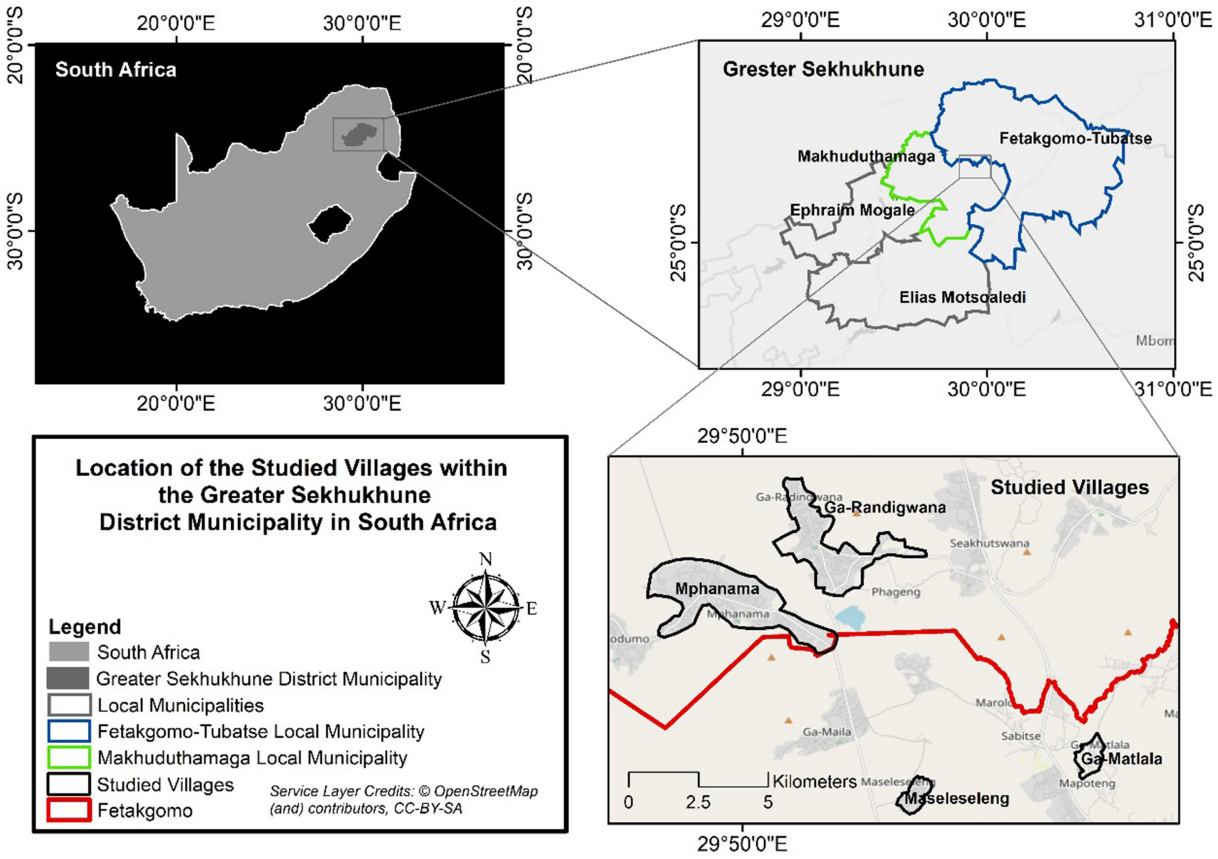

FIGURE 1
Study area map for the study villages in Fetakgomo Tubatse Local Municipality, Limpopo Province.

villages consisted of Mphanama, Ga-Radingwana, Ga-Matlala, and Maseleseleng. These villages represent semi-arid regions experiencing significant land degradation challenges faced by smallholder farmers. The selection process aimed to capture diverse socio-economic attributes, production aspects, and farmers' knowledge to comprehensively examine the influence of access to public agricultural extension services on the implementation of on-farm sustainable practices among smallholder farmers. The selected villages were part of the 30,000 hectares required for the land degradation neutrality project funded by the Global Environment Facility (GEF 7). The villages also have unique topographic, climatic, and agricultural characteristics. The climate of the study area is classified as hot semi-arid based on the Koppen classification (Engelbrecht and Engelbrecht, 2016). The climate is characterized by a unimodal wet season, which occurs during the warmer summer months of November through March. Annual precipitation ranges from 400 mm to 900 mm, decreasing along a north-westerly gradient. The average minimum temperature is 12.5 °C, while the maximum temperature is 30 °C, although this can reach up to 45 °C at the peak of summer, often resulting in heatwaves. The predominant land use activities include croplands, grasslands, mining, and built-up areas. A mix of crops and livestock production dominates smallholder farming. Maize, sorghum, and a variety of pulses are the main field crops, while horticultural crops include vegetables such as tomatoes, spinach, and carrots (Mpandeli et al., 2015). Livestock production is characterized by small-scale cattle, goat, sheep, and free-range chickens and contributes significantly to local livelihoods.

2.2 Sampling and data collection

Cross-sectional data were collected from 242 randomly selected farming households using a semi-structured questionnaire in Mphanama, Ga-Radingwana, Ga-Matlala, and Maseleseleng villages in Fetakgomo Tubatse Local Municipality in Sekhukhune District, similar to other studies (Bontsa et al., 2023a; Oduniyi and Tekana, 2021). The four villages were purposively selected as part of the GEF 7 Land Degradation Neutrality (LDN) project due to the prevailing challenges facing smallholder farmers in the area, including land degradation and poor access to extension services (Mokgolo and Mzezewa, 2023; Kgaphola et al., 2023a; Kgaphola et al., 2023b). A list of farming households compiled for the GEF 7 project for each village, based on village registers and verified by village leaders and extension officers, was used as a sampling frame. From these lists, households were randomly selected using systematic random sampling, with the number sampled in each village proportional to its farming population. This process yielded 242 farming households, ensuring spatial variation in socio-economic and environmental conditions across the study villages. About 10% extra participants were put on standby in each village to replace those who failed to participate on

the scheduled dates. The questionnaire was pretested in adjacent villages to improve reliability and validate the questions. Participants were pre-informed about the survey to ensure the interview timing was appropriate for the respondents. Only 13 (5.4%) participants on the initial list failed to participate and were replaced by participants on standby. The questionnaire solicited information on household demography, socio-economic attributes, farm production, land degradation and awareness, access to extension services, and implementation of on-farm SLMPs.

In addition to the household survey, 10 key informant interviews (KIIs) were conducted with eight purposively selected farmers (i.e., one male and one female in each village) and the two extension officers operating in the study area to gain insight into the challenges and solutions surrounding the accessibility of extension services and challenges in SLMP implementation. Farmers were selected based on their interaction with extension services, long-term farming experience, and distinct responses in the household survey (e.g., adoption or rejection of certain SLMPs). Extension officers were chosen for their involvement in SLMP promotion under public programs such as LandCare and the GEF 7 project. The KIIs provided qualitative insights into the challenges and motivations behind SLMP adoption, as well as operational issues within the extension system. These qualitative perspectives were used to triangulate, validate, and contextualize the quantitative survey results, particularly where patterns of misalignment between extension services and farmer needs emerged.

2.3 Data analysis

Survey data from farming households were analyzed using descriptive and inferential statistics. Land degradation awareness was measured by asking respondents whether they had received training on land degradation or noticed any physical signs of land degradation on their farms in the past 5 years (Yes = 1, No = 0). Degradation signs observed were computed as a total count of the different physical signs of degradation observed by the farmer on their farm, based on the listed signs that included soil erosion or gully formation, desertification, waterlogging, soil fertility loss or declining yields, and salinization. Each affirmative response was coded as 1, allowing for the computation of a total score. These variables were included to capture both perceptual awareness and experiential evidence of degradation.

Frequencies, percentages, and Chi-square tests were the descriptive statistics used to summarize variables on farmers' demographic, socio-economic, and production attributes, including access to extension services and implementation of on-farm SLMPs. Inferential statistics employed two bivariate models, a seemingly unrelated bivariate probit (SUBP) model and a recursive bivariate probit (RBP) model (Oduniyi and Tekana, 2021), to examine if access to public extension services and the implementation of on-farm SLMPs were jointly determined. In other words, the two bivariate models were used to determine if access to extension services directly resulted in the implementation of on-farm SLMPs. Insights from key informant interviews were used to triangulate and provide implications for the quantitative survey findings.

Smallholder farmers' decisions to implement SLMPs are often significantly influenced by their access to public agricultural extension services, which are the primary channels for disseminating agricultural innovations in rural areas (Mapiye et al., 2025; Mbatha, 2024; Afful and Mabena, 2024; Jha and Gupta, 2021b). In practice, this relationship is complex and bidirectional, requiring careful examination. For instance, farmers who receive or seek extension services may already possess inherent but unobservable traits, such as higher motivation or stronger social networks with other farmers, that encourage them to implement SLMPs. Such a scenario creates an endogeneity problem in empirical analysis, where failure to account for these hidden factors can distort and bias the estimated impact of extension services on SLMP implementation (Oduniyi and Tekana, 2021). Nonetheless, this study assumed that smallholder farmers who perceived the benefits of information acquired from public agricultural extension services implemented SLMPs on their farms. This implies that the decision-making process involves two distinct but interrelated or simultaneous stages. Firstly, farmers must access relevant information through public extension services, and secondly, they evaluate whether to implement these practices based on perceived benefits. In both stages, unobserved factors such as risk tolerance level and land tenure security may simultaneously influence farmers' decisions (Oduniyi and Tekana, 2021). These intertwined processes require the use of a method that estimates both decision stages simultaneously to account for their interdependencies properly.

2.4 Model specification

The analysis in this study employs bivariate probit modeling procedures that simultaneously estimate the probability of accessing extension services and the subsequent implementation of SLMPs while controlling for any potential correlation through shared unobserved factors. This approach addresses the concern of endogeneity by estimating the correlation between error terms across equations. A statistically significant correlation ($p < 0.05$) would confirm that some unobserved factors affected both decisions (Filippini et al., 2018). This would validate the need for the joint estimation of the two decision processes over simpler single-equation alternatives. Access to extension services (y_1) and implementation of SLMPs (y_2) are the two binary dependent variables. Access to extension services is denoted by $y_1 = 1$, otherwise $y_1 = 0$. Similarly, SLMP implementation is denoted by $y_2 = 1$, otherwise $y_2 = 0$. The independent variables are not necessarily the same despite sharing the same error terms. A key assumption of the bivariate model in this study is a recursive structure where access to extension services influences SLMP implementation, but not vice versa (Oduniyi and Tekana, 2021). Table 1 summarizes and justifies the variables used in the bivariate models.

2.4.1 Seemingly unrelated bivariate probit model

A seemingly unrelated bivariate probit (SUBP) model was used to examine the relationship between farmers' access to public extension services and the implementation of SLMPs. The SUBP allows investigation of whether these two decision processes are jointly determined, i.e., correlated through shared unobserved farmer characteristics, or operate as distinct decision pathways. The SUBP framework, therefore, provides an appropriate analytical tool for investigating such joint relationships between binary outcome variables (Oduniyi and Tekana, 2021). The model specification builds

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TABLE 1 Description, nature, expected effect, and justification of variables used in the bivariate probit models.

Variables	Variable type	Expected effect	Description of the variable	Inclusion in equation	Justification/ Assumption
Public extension services	Binary		Dependent variable 1: Access to public extension service *(0 = No; 1 = Yes)*		Some variables are more likely to influence access to public agricultural extension services but not directly influence SLMP implementation.
SLMP implementation	Binary		Dependent variable 2: Implemented at least one SLMP *(0 = No; 1 = Yes)*		Some variables are more likely to influence the implementation of SLMPs but not directly influence access to extension services.
Age	Categorical	+/−	Age of the household head (years) *(0 = Young; 1 = Adult; 2 = Elderly)*	Both	Older farmers may have more experience and access to networks, but younger farmers may be more open to adopting new practices.
Gender	Binary	+/−	Sex of the household head *(0 = Female; 1 = Male)*	y_1	In some contexts, gender may affect access to extension services due to social or cultural barriers.
Formal education	Binary	+	Completed primary school *(0 = No; 1 = Yes)*	Both	Higher education levels are often associated with better access to information (extension services) and more likely to adopt SLMPs.
Household size	Categorical	+/−	Number of people in the household *(0 = 1–4; 1 = 5–9; 2 = 10+)*	Both	Larger households may have more members to attend extension programs, seek information, and implement labor-intensive SLMPs.
Residency period	Categorical	+	Years spent in the area *(0 = 0–10; 1 = 11–20; 2 = 20+)*	Both	Longer residency suggests stronger local networks and tenure security, which increase access to extension services and investments in sustainable practices.
Formal employment	Binary	+/−	Formally employed *(0 = No; 1 = Yes)*	y_1	Farmers with formal employment may have better access to information and resources, including extension services.
Cropped area	Categorical	+/−	Area under crop production (ha) *(0 = 0–1; 1 = 1–4; 2 = 5+)*	y_2	Size of the cropped area may influence the feasibility and scale of implementing sustainable practices.
Fertilizer use	Categorical	+/−	Fertilizer use *(0 = None; 1 = Organic/Inorganic)*	y_2	Farmers using fertilizers may be more likely to adopt sustainable practices.
Farming type	Categorical	+/−	Type of farming practiced *[0 = Rainfed; 1 = Both (Rainfed + Irrigated)]*	y_2	Irrigation status may influence the implementation of certain feasible SLMPs.

(Continued)

TABLE 1 (Continued)

Variables	Variable type	Expected effect	Description of the variable	Inclusion in equation	Justification/ Assumption
Awareness of degradation	Binary	+	Awareness of land degradation problem on farms *(0 = No; 1 = Yes)*	Both	Farmers more aware of land degradation may be more likely to seek extension services and adopt SLMPs.
Degradation signs observed	Continuous	+	Number of different land degradation signs observed on the farm	Both	Observing more signs of degradation may motivate farmers to seek help and adopt SLMPs.
Compost manure use	Binary	+	Use compost manure on farm *(0 = No; 1 = Yes)*	y_2	Farmers already using compost manure may be more likely to adopt other SLMPs.

upon the standard probit model but extends it to accommodate two potentially correlated latent variables. This can be represented as:

$$y_1^* = \beta_1 X_1' + \varepsilon_1 \quad (1)$$

$$y_2^* = \beta_2 X_2' + \varepsilon_2 \quad (2)$$

where:

y_1^* and y_2^* are latent variables representing access to extension services and SLMP implementation, respectively.

X_1' and X_2' are vectors of explanatory variables.

β_1 and β_2 are vectors of unknown parameters to be estimated.

ε_1 and ε_2 are standard errors which follow a bivariate normal distribution with mean zero, variance one, and correlation ρ.

y_1 and y_2 are the observed binary outcomes related to the latent variables (y_1^* and y_2^*) through: $y_j = 1$ if $y_j^* > 0$, otherwise $y_j = 0$ (for $j = 1,2$).

The correlation coefficient (ρ) captures the interdependence between the error terms (unobserved characteristics) of extension access and SLMP implementation. A statistically significant ρ ($p < 0.05$) suggests that unobserved factors simultaneously influence both outcomes, indicating the presence of endogenous relationships that would be missed in single-equation models (Filippini et al., 2018). This approach is critical in agricultural innovation adoption studies where farmers' decisions often involve multiple, potentially interdependent stages, i.e., information acquisition and implementation.

2.4.2 Recursive bivariate probit model

A recursive bivariate probit (RBP) model was employed to address potential endogeneity between access to extension services and SLPM implementation. Several studies have employed this econometric technique to address the dual problem of observed and unobserved selection bias common in adoption studies (Ngigi and Muange, 2022; Oduniyi and Tekana, 2021). The RBP model was employed in this analysis as it allowed the access to extension services variable to be a dependent variable in the first equation and an explanatory variable in the implementation equation while accounting for potential correlation between the error terms. This was critical to establishing if access to extension services was endogenous in the SLMP implementation model, i.e., determining if access to extension services was jointly decided with unobserved factors captured by the error term (Filippini et al., 2018). For endogeneity to exist, the two choices must be jointly decided. The RBP model is specified as follows:

$$y_1^* = \beta_1 X_1' + \varepsilon_1 \quad (3)$$

$$y_2^* = \delta y_1^* + \beta_2 X_2' + \varepsilon_2 \quad (4)$$

$$y_j = 1 \text{ if } y_j^* > 0, \text{ otherwise } y_j = 0 \text{ (for } j = 1,2)$$

The parameters used in the RBP model are the same as those in the SUBP model. Equations 1, 3 are the same. Equation 4 is similar to Equation 2 except that the dependent variable δy_1^* (access to extension services) is also included as an explanatory variable in Equation 4, where δ captures the effect of access to extension services on SLMP implementation. A statistically significant ρ ($p < 0.05$) confirms that unobserved factors simultaneously influence both the access to extension services and SLMP implementation (Filippini et al., 2018).

3 Results

3.1 Characteristics of smallholder farmers in Mphanama area

Table 2 shows the attributes of surveyed farmers in the Mphanama area, which reveal some significant differences between farmers who accessed public extension services and those who did not. Key factors such as formal employment ($p = 0.002$), fertilizer use ($p = 0.004$), and awareness of land degradation ($p = 0.001$) were significantly different than otherwise. Specifically, farmers who were aware of land degradation and had access to extension services were significantly lower (39.3%) than their counterparts without access (60.7%). On the other hand, formally employed farmers with no access to extension services were significantly more (66.7%) than those with access (33.3%). About 54% of the farmers did not use fertilizer, while 34% used organic fertilizer. Only 32 (13.2%) farmers reported accessing extension services, with fewer of these farmers (28.1%) implementing

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TABLE 2 Characteristics of smallholder farmers in Mphanama area, Limpopo province.

Variable	Description	Extension access		Total	χ^2 stats	*p*-value
		Yes	No			
Age	Young (<36 years)	6	47	53		
	Adult (36–60 years)	17	102	119	0.292	0.864
	Elderly (60 + years)	9	61	70		
Gender	Male	12	80	92	0.004	0.948
	Female	20	130	150		
Formal education	Yes	2	40	42	3.171	0.075
	No	30	170	200		
Household size	1–4	19	93	112	2.743	0.254
	5–9	11	92	103		
	10+	2	25	27		
Residency period in the community	<10 years	2	18	20	0.481	0.786
	10–19 years	5	40	45		
	20 + years	25	152	177		
Formal employment	Yes	8	16	24	9.390	0.002***
	No	24	194	218		
Total arable land owned (ha)	<1 ha	26	154	180		0.213
	1–4 ha	3	45	48	3.089	
	5 + ha	3	11	14		
Arable land under crop production	<1 ha	29	190	219	0.144	0.931
	1–4 ha	1	9	10		
	5 + ha	2	11	13		
Type of fertilizer used	None	9	122	131		
	Organic	14	67	81	13.566	0.004***
	Inorganic	6	12	18		
	Both	3	9	12		
Farming type	Rainfed	10	76	86	0.296	0.586
	Rainfed + Irrigated	22	134	156		
Awareness of land degradation	Yes	11	17	28	18.744	0.001***
	No	21	193	214		
Compost manure use	Yes	17	76	93	3.366	0.067
	No	15	134	149		
Access to extension services	Yes	32	0	32	---	---
	No	0	210	210		
SLMPs implementation	Yes	9	95	104	3.318	0.069
	No	23	115	138		

Significant p-values denoted as: ***$p < 0.01$ or **$p < 0.05$.

SLMPs compared to those that did not (71.9%). SLMP implementation (43%) was very low among farmers who accessed extension services (8.7%) compared to their counterparts (91.3%). Other factors such as farmers' age, gender, household size, residency period, cropped area, and farming type showed no significant differences. Most farmers were females and adults aged between 36 and 60 without formal education. At least 70% of the farmers had lived more than 20 years in the study area. Most households had between 1–4 and 5–9 members and produced crops on less than one hectare.

3.2 Seemingly unrelated bivariate probit regression results

Table 3 shows the results of the SUBP regression of how access to extension services influenced SLMP implementation. The Wald Chi^2 statistic of 76.47 ($p < 0.001$) confirms the overall significance of the model. The Wald test of rho = 0 with a Chi^2 value of 3.684 ($p = 0.054$) indicates that the correlation between the error terms is not significant at the 5% level. In other words, no direct link existed between access

TABLE 3 Seemingly unrelated probit model for access to extension services and SLMP implementation.

Variables	Access to extension services			Implement SLMPs			dy/dx
	Coefficient	Z	P > |z|	Coefficient	z	P > |z|	
Age	0.143	0.84	0.403	0.122	0.84	0.399	0.012
Gender	−0.130	−0.59	0.553	---	---	---	−0.006
Formal education	−0.614	−1.65	0.098	0.258	0.99	0.323	−0.023
Household size	−0.245	−1.42	0.156	−0.007	−0.08	0.938	−0.013
Residency period	0.045	0.37	0.713	0.176	2.03	0.043**	0.009
Cropped area	---	---	---	−0.155	−1.16	0.245	−0.005
Fertilizer type used	---	---	---	0.258	1.92	0.054	0.009
Farming type	---	---	---	0.743	3.77	0.000***	0.027
Formal employment	0.757	2.42	0.015**	---	---	---	0.040
Awareness of degradation	1.267	4.26	0.000***	0.035	0.14	0.886	0.068
Degradation signs observed	0.375	2.99	0.003***	−0.423	−4.23	0.000***	0.004
Compost manure use	---	---	---	−0.326	−1.48	0.139	−0.012
_cons	−3.025	−4.37	0.000***	0.467	0.93	0.352	
/athrho	−0.311	−1.92	0.055				
rho	−0.301						
Number of observations	242						
Wald $Chi^2(19)$	76.47						
Log pseudolikelihood	−216.47						
Prob > Chi^2	0.000						

Wald test of rho = 0: $Chi^2(1) = 3.684$; Prob > $Chi^2 = 0.054$; Significant p-values denoted as: ***$p < 0.01$ or **$p < 0.05$.

to extension services and SLMP implementation. Therefore, the relationship between the two outcomes was driven more by unobserved factors than by the observed ones.

The SUBP model results reveal key drivers of access to extension services and SLMP implementation. Only the number of degradation signs observed jointly influenced access to extension services and SLMP implementation. An increase in the number of land degradation signs observed by farmers had a statistically significant positive effect on the likelihood of accessing extension services (coefficient = 0.375, $p = 0.003$). The marginal effect (dy/dx = 0.004) indicates that each additional degradation sign increased the probability of accessing extension services by 0.4%. Conversely, observing more signs of land degradation had a statistically significant negative effect on SLMP implementation (coefficient = −0.423, $p < 0.001$). The marginal effect (dy/dx = −0.004) suggests a 0.4% decrease in the probability of implementing SLMPs for each additional land degradation sign observed by farmers. Formal employment (coefficient = 0.757, $p = 0.015$) and awareness of land degradation (coefficient = 1.267, $p < 0.001$) significantly increased the likelihood of seeking extension services. Marginal effects (dy/dx) show that awareness of degradation increased the probability of accessing extension services by 6.8%, while formal employment increased access to extension services by 4%. For SLMP implementation, longer residency periods (coefficient = 0.176, $p = 0.043$) and irrigation use (coefficient = 0.743, $p < 0.001$) had a significant positive influence, and the marginal effects (dy/dx) suggest an increase in the chances of SLMP implementation by 0.9% (dy/dx = 0.009) and 2.7% (dy/dx = 0.027), respectively.

3.3 Recursive bivariate probit regression results

Table 4 shows the RBP regression results of the effect of access to extension services on SLMP implementation. The Wald Chi^2 value of 186.52 ($p < 0.001$) confirms that the model is statistically significant. This implies that at least one independent variable significantly influences the outcome. A Wald test of rho = 0 produced a Chi^2 value of 40.674 ($p < 0.001$). This indicates that the correlation between the error terms of access to extension services and SLMP implementation is significant and that some unobserved factors jointly influenced both outcomes. In this case, the recursive structure of the model confirms a direct causal relationship, where access to extension services encourages SLMP implementation.

The recursive bivariate probit model reveals a statistically robust relationship between extension service access and SLMP implementation. Awareness of degradation and the number of degradation signs observed on farms jointly influenced access to extension services and SLMP implementation. Awareness of degradation significantly increased the chances of access to extension services (coefficient = 1.268, $p < 0.001$) and implementation of SLMP

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TABLE 4 Recursive bivariate probit model for access to extension services and SLMP implementation.

Variables	Access to extension services			Implement SLMPs			dy/dx
	Coefficient	Z	P > |z|	Coefficient	z	P > |z|	
Access to extension services	---	---	---	−1.997	−10.57	0.000***	−0.048
Age	0.224	1.43	0.153	0.165	1.34	0.179	0.033
Gender	−0.269	−1.71	0.088	---	---	---	−0.036
Formal education	−0.840	−2.28	0.023**	0.002	0.01	0.991	−0.112
Household size	−0.119	−0.97	0.331	−0.084	−0.95	0.343	−0.018
Residency period	0.017	0.16	0.873	0.160	1.91	0.056	0.006
Cropped area	---	---	---	−0.136	−2.51	0.012**	−0.003
Fertilizer type used	---	---	---	0.223	2.44	0.015**	0.005
Farming type	---	---	---	0.644	4.72	0.000***	0.015
Formal employment	0.697	2.72	0.007***	---	---	---	0.093
Awareness of degradation	1.268	4.38	0.000***	0.758	2.91	0.004***	0.187
Degradation signs observed	0.382	3.34	0.001***	−0.245	−2.72	0.007***	0.045
Compost manure use	---	---	---	−0.259	−1.61	0.108	−0.006
_cons	−3.052	−5.00	0.000***	0.094	0.22	0.828	
/athrho	12.914	6.38	0.000***				
Rho	1						
Number of observations	242						
Wald $Chi^2(19)$	186.52						
Log pseudolikelihood	−212.83						
Prob > Chi^2	0.00						

Wald test of Rho = 0: $Chi^2(1) = 40.67$; Prob > $Chi^2 = 0.000$; Significant p-values denoted as: ***$p < 0.01$ or **$p < 0.05$.

(coefficient = 0.758, $p = 0.004$) by 18.7% (dy/dx = 0.187). More intense degradation observed by farmers had a significant positive effect on access to extension services (coefficient = 0.382, $p = 0.001$) but had a significant adverse effect on SLMP implementation (coefficient = −0.245, $p = 0.007$). Marginal effects (dy/dx) show that a unit increase in land degradation intensity encouraged farmers to seek extension services while discouraging SLMP implementation by 4.5% (dy/dx = −0.045).

Other key drivers of extension access mirror the SUBP model. Being formally employed improved the likelihood of access to extension services (coefficient = 0.697, p = 0.007) by a probability of 9.3% (dy/dx = 0.093), while formal education had an unexpected negative influence on access to extension services (coefficient = −0.840, $p = 0.023$). Formal education reduced the chances of access to extension services by 11.2% (dy/dx = −0.112). For SLMP implementation, irrigation farming (coefficient = 0.644, $p < 0.001$) and fertilizer use (coefficient = 0.223, $p = 0.015$) slightly increased the likelihood of adoption as shown by the marginal effects (dy/dx) of less than 2%, whereas larger cropped areas discouraged SLMP implementation (coefficient = −0.136, $p = 0.012$) where the marginal effect indicates a 0.3% less chances (dy/dx = −0.003). Contrary to expectations, access to extension services significantly reduced the chances of SLMP implementation (coefficient = −1.997, $p < 0.001$). The marginal effect (dy/dx = −0.048) suggests a decline of 4.8% in the probability of SLMP implementation. The perfect error correlation ($\rho = 1$) and strongly significant Wald test ($\chi^2 = 40.674$, $p < 0.001$) confirm that access to extension services and implementation of sustainable practices were intertwined. This implies that standard single-equation probit models would severely distort estimates of the impact of public extension services and validates the use of a recursive bivariate probit model.

3.4 Insights from key informant interviews and triangulation of survey findings

Table 5 summarizes the qualitative insights and themes from key informant interviews, triangulated with the quantitative survey findings and the associated implications. KIIs contextualized the survey results, revealing systemic barriers stemming from input inaccessibility, a top-down approach, and irrelevant training. Several themes emerged, which are consistent with the negative influence of extension services on SLMP implementation (Table 5). For example, the negative influence of extension services on SLMP implementation was attributed to a lack of required inputs. One farmer noted that they could not apply compost because they did not have the manure since they lost their cattle (Table 5). KIIs also revealed systemic mismatches

TABLE 5 Triangulation of quantitative findings and key informant interview (KII) insights.

Key informants (n = 10)	KII insights	Theme	Linked survey results (n = 242)	Implication
Male farmer (Mphanama)	*"Extension officers teach us composting, but I lost all my cattle in 2018. No manure, no compost."*	Input inaccessibility	Negative extension access influence on SLMP implementation ($p < 0.001$)	Explains why access to extension services did not translate to adoption
Female farmer (Ga-Matlala)	*"They promote practices needing inputs that we do not have or cannot afford."*	Resource misalignment		
Male irrigated farmer (Ga-Radingwana)	*"Drip irrigation lets me test cover crops. My neighbors with no irrigation cannot risk it."*	Structural advantage	Irrigation drove SLMPs ($p < 0.001$)	Highlights the role of irrigation in SLMP adoption and risk mitigation.
Extension Officer 2	*"Farmers with drip systems can afford to experiment with new practices. Rainfed farmers cannot"*			
Female large-land holder (Maseleseleng)	*"5 hectares of mulching? I'm 70 years old. Who will do the work? Managing compost on 5 hectares is impossible without hired labor."*	Labor/resource constraints	Larger land discouraged SLMPs ($p = 0.012$)	Contextualizes the inverse relationship between land size and SLMP adoption and challenges scale-efficiency assumptions.
Formally employed male farmer (Ga-Matlala)	*"I can take time off my salaried job to attend training. I can also afford to call or visit the extension officers for advice. Others cannot."*	Socioeconomic privilege	Formal employment aids extension access ($p = 0.007$)	Clarifies why employed farmers accessed extension services more.
Elderly male farmer (Mphanama)	*"After my soil eroded, I sought help from the extension officer."*	Crisis-driven demand	Land degradation awareness increases extension access ($p < 0.001$)	Shows how degradation awareness motivates help-seeking behavior.
Young female farmer (Ga-Matlala)	*"They often show us YouTube videos, but not everyone in our community has internet or smartphones."*	Digital exclusion		Exposes gaps in digital extension approaches.
Female farmer (Mphanama)	*"Extension officers are all men. They ignore our indigenous soil amendment tricks."*	Gender bias/ Exclusion of local knowledge	Gendered disparities among households that adopted SLMPs	Suggests gendered knowledge hierarchies.
	"Officers lecture us; they never ask what we have tried before."	Exclusion of local knowledge	Modern SLMPs were mostly promoted	Critiques top-down extension mandates.
Extension Officer 1	*"We're trained to promote inorganic fertilizers, but farmers cannot afford them."*	Policy-reality mismatch		Critiques top-down extension mandates.
Extension Officer 1	*"I know drip irrigation is irrelevant here, but it's what we are monitored on."*	Misaligned incentives		Explains low adoption despite high training attendance.
Extension Officer 2	*"In the 1990s, farmers were given seeds and tools. Now it's just training."*	Resource withdrawal		Historical context for current failures.

between advice from extension officers and farmer realities. For example, extension programs often promoted irrigation-dependent SLMPs in contexts where farmers lacked irrigation, as one Extension Officer reported that they trained farmers on drip irrigation. However, most farmers had no access to water for irrigation or funds to acquire drip kits.

4 Discussion

The recursive bivariate probit model reveals several significant findings that challenge conventional assumptions about the relationship between extension services and SLMP implementation. However, the contrasting results between the SUBP and RBP models warrant careful interpretation. While the SUBP model found no significant correlation between access to extension services and SLMP implementation (Wald test of rho = 0.054), the RBP model indicated a significant and negative influence, with a perfect error correlation ($\rho = 1$, $p < 0.001$). This discrepancy reflects the underlying assumptions and treatment of endogeneity in each model. The SUBP model estimates the two decisions (access to extension services and SLMP implementation) as simultaneous but independent. Therefore, the SUBP model does not explicitly control for endogeneity, and this potentially underestimates the influence of unobserved variables (Filippini et al., 2018). In contrast, the RBP model adopts a recursive framework that captures the causal pathway from extension access to SLMP implementation while accounting for any shared unobserved factors, such as farmer motivation, preferences, access to social capital, or perceived risk. The significance of the RBP model structure indicates that it is more appropriate in the current study's context and suggests that smallholder decisions were rarely made in isolation but were influenced by complex, interrelated factors (Ngigi and Muange, 2022; Oduniyi and Tekana, 2021). However, the negative relationship between extension access and SLMP implementation in the RBP model supports the argument that systemic barriers constrain the effectiveness of extension services. Although not empirically tested, constructs of certain theories were used to augment the key informant interviews in explaining the survey findings on the factors influencing extension access and SLMP implementation.

The significantly negative influence of extension services on SLMP implementation in the RBP model, where farmers who accessed formal agricultural extension services were less likely to implement SLMPs by 4.8% ($p < 0.001$), emerges from three key systemic failures as validated by key informant interviews, i.e., input inaccessibility, top-down dissemination, and irrelevant training. Firstly, KIIs revealed that this counterintuitive result stemmed from systemic mismatches, i.e., extension officers promoted SLMPs or inputs (e.g., inorganic fertilizers, drip irrigation, manure for composting) that were inaccessible to most low-resource farmers, consistent with recent findings (Oduniyi, 2022). Survey data also shows that some farmers who accessed formal extension services lacked the recommended inputs, which rendered extension advice impractical. Resource withdrawal and historical contexts where farmers received inputs further explain the current ineffectiveness of extension services. This aligns with recent studies highlighting significant bottlenecks of extension services in developing contexts (Kibrom et al., 2025) and the Political Ecology framework's emphasis on structural barriers since extension programs ignored local resource constraints (Yemadje et al., 2012). Formal agricultural extension programs must move beyond information dissemination to providing resources that reduce systemic and structural barriers, similar to providing extension services, seeds, manure, irrigation infrastructure, and farm fencing in Msinga local municipality, South Africa (Mbatha, 2024; Shushu et al., 2024). This would enhance the effectiveness of extension services and the adoption of sustainable practices. However, this must target deserving low-resource farmers with the requisite farming knowledge, such as those who successfully complete a farmer training program or participatory learning action, since they may be more confident to implement such innovations (Jellason et al., 2021).

Secondly, the insights from KII revealed policy-reality mismatches. The top-down extension models evident in the study area resulted in the low adoption of SLMPs, since they often impose irrelevant or impractical practices. KIIs revealed that farmers often dismissed advice when it ignored local realities and knowledge. The finding further suggests that formal agricultural extension programs in the study area were misaligned with farmers' needs or indicate gaps between agricultural extension officers' training and farmers' needs to the extent of discouraging sustainable practices, indicating a need for participatory extension approaches (Rogers, 2003; Manzeke-Kangara et al., 2024). For example, despite high awareness of land degradation ($p < 0.001$), adoption remained low not only because inputs were inaccessible and/or unaffordable, but also because the practices failed to integrate farmers' local knowledge. This further critiques the top-down extension approaches. Several studies have attributed the ineffectiveness of public extension services to the top-down approach, poor functioning of farmer training centers, inadequate extension skills, high farmer-to-extension worker ratio, inadequate information and/or inappropriate recommendations, and lack of information sharing among actors (Manzeke-Kangara et al., 2024; Kibrom et al., 2025; Chanza and Mgalamadzi, 2025). This aligns with the Political Ecology framework, as systemic barriers outweighed knowledge transfer challenges (Yemadje et al., 2012). Top-down approaches, therefore, exclude some farmers as the methods or practices are not consistent with the local realities. Digital extension services in the study area, such as YouTube videos, expose gaps in digital extension approaches in rural areas where field demonstrations by leading farmers work better. Consistent with the Social Practice Theory, extension officers' top-down approaches often neglect local knowledge and realities, exacerbating adoption gaps (Sharifzadeh et al., 2023).

Thirdly, our study findings suggest that the training received by farmers was irrelevant, despite several studies showing that public extension services were a key driver of SLMP implementation (Mdiya et al., 2023; Bontsa et al., 2023a). Contrary to the Diffusion of Innovations theory (Rogers, 2003), compatibility of SLMPs was low due to resource gaps, a pattern echoed in KIIs. Therefore, farmers dismissed extension advice as 'theoretical and irrelevant' since they lacked the required resources, inputs, or infrastructure, underscoring Political Ecology's emphasis on structural barriers (Yemadje et al., 2012). This is further supported by the high proportion of farmers who implemented SLMPs without accessing public extension services, although farmers could have accessed alternative extension information through social networks, e.g., counterparts, farmer groups, and social media (Zondo and Ndoro, 2024). However, it is also possible that some farmers implemented SLMPs unknowingly, as shown elsewhere (Oduniyi, 2022; Oduniyi et al., 2023). While this highlights challenges with current formal extension services, it also supports the argument that the practices promoted through formal extension programs were incompatible with farmers' contexts or preferences. Nonetheless, this highlights an urgent need to examine the current extension content, including exploring alternative extension approaches, extension service delivery mechanisms, and the intrinsic factors to address smallholder farmers' emerging needs effectively (Kunzekweguta et al., 2017; Afful and Mabena, 2024; Manzeke-Kangara et al., 2024; Chanza and Mgalamadzi, 2025; Teele

and Nkoane, 2024). For instance, formal agricultural extension programs could be transformed by integrating participatory and in-person advisory services with digital platform extension services while prioritizing local knowledge and realities in addressing farmers' needs (Antwi-Agyei and Stringer, 2021; Mapiye et al., 2025; Kibrom et al., 2025; Hansen et al., 2021; Ramaraj et al., 2023).

Despite the systemic barriers, it is also possible that existing formal agricultural extension programs in the study area attracted farmers facing systemic adoption barriers. For instance, farmers' awareness of the land degradation problem compelled them to seek extension services, as noted in one of the KII. However, in many cases, farmers often lack the resources to implement the recommended SLMPs (Oduniyi and Tekana, 2021; Shushu et al., 2024; Dube et al., 2025). The perfect correlation of error terms indicates a strong dependence between extension access and SLMP implementation, suggesting unmeasured or unobserved behavioral control factors (e.g., risk aversion, perceived costs and benefits, cultural perspectives) mediate extension access and SLMP implementation as suggested by the Theory of Planned Behavior (Ajzen, 1991). Since the current study did not empirically test any perceived behavioral controls, future studies should examine how these could be influencing access to formal extension services and SLMP implementation, given that farmers in this study shared identical unmeasured characteristics that simultaneously increased their access to extension services but limited SLMP implementation (Filippini et al., 2018).

Key determinants of formal agricultural extension access reveal several important implications. Formal employment increased the likelihood of accessing extension services by 9.3%, indicating that it enabled extension access. Thus, farmers with resources can visit even distant extension officers and seek information, compared to resource-constrained farmers, as indicated by a formally employed key informant (Oduniyi and Tekana, 2021). The shortage of extension officers in rural areas has been highlighted in many developing countries (Manzeke-Kangara et al., 2024; Kibrom et al., 2025; Chanza and Mgalamadzi, 2025). Surprisingly, the negative effect of formal education indicates a detrimental impact of discouraging farmers from accessing public extension services. The finding suggests a lesser preference for formal extension services, delivery mechanisms, or extension content. Some key informants indicated that extension officers ignored their knowledge and previous practices, suggesting that farmers had alternative extension services, for instance, from their counterparts, social networks, or digital platforms (Zondo and Ndoro, 2024). This view is consistent with studies showing that educated farmers independently sought and acquired information on sustainable practices from diverse sources, including digital technologies, due to their literacy (Bontsa et al., 2023b; Zondo and Ndoro, 2024). Shunning formal extension services by educated farmers could indicate their ineffectiveness in addressing their challenges. At the same time, the findings from this study are contrary to those that found a positive influence of formal education on extension services information due to perceived benefits (Oduniyi and Tekana, 2021). The difference with such studies is that those farmers had the resources and the capacity to implement sustainable practices. Our findings further highlight the structural inequalities in resource allocation, consistent with key tenets of the Political Ecology framework (Yemadje et al., 2012).

Farmers observing more intense land degradation and those aware of land degradation problems on their farms were significantly more inclined to seek public extension services. The intensity of land degradation, therefore, compelled farmers to seek ameliorative action, starting with seeking extension information (Irwin et al., 2023). While this indicates a crisis-driven demand and explains how degradation awareness often motivates farmers to seek help, usually, farmers often fail to implement recommended practices, as the land degradation would be too intense to reverse. For instance, some farmers reported that public extension services were sought to gain information on the appropriate action, while others wanted to understand the resources required to address the problem. These findings may suggest that intrinsic factors, such as farmers' knowledge, perceptions, and attitudes about their agricultural landscape, also motivated farmers to seek public extension services (Meijer et al., 2015). Accessing relevant and adequate information from extension services usually translates to action, in this case, SLMP implementation (Oduniyi and Tekana, 2021; Oduniyi et al., 2023). However, despite the significant positive influence of land degradation awareness on SLMP implementation, more signs of land degradation observed had a significant negative influence on SLMP implementation. This contrasts with the reasoning that more severe land degradation would encourage farmers to implement multiple sustainable practices, as is the case in some studies (Kolapo et al., 2022). However, this further suggests the incompatibility of SLMPs with farmers' needs or contexts, i.e., information acquired was insufficient or inappropriate to address more intense land degradation, or farmers lacked the economic or financial resources to implement sustainable practices (Emerton and Snyder, 2018; Hayden et al., 2021; Olumba et al., 2025). It may also indicate the risk aversion of farmers, similar to small-scale farmers in Ethiopia who resisted soil organic carbon-enhancing amendments, fearing they would be diminished by soil erosion (Nguru et al., 2021). However, the lack of resources among smallholder farmers can also make public extension services appear less effective despite providing sufficient information indicating a need for material or financial support for low-resource farmers beyond extension information (Kolapo et al., 2022; Nguru et al., 2021; Shushu et al., 2024; Olumba et al., 2025).

The strong positive influence of irrigation on SLMP implementation ($p < 0.001$) was driven by risk perception, not just technology access, as it allowed some farmers to experiment with innovations. One of the extension officers attributed this to irrigation's role in mitigating risks such as climate change, allowing farmers to try out new innovations. These findings mirror the structural inequalities in resource allocation as observed in South Africa's Eastern Cape province, consistent with the key tenets of the Political Ecology framework (Irwin et al., 2023; Jiba et al., 2024). Access to irrigation encourages farmers to implement sustainable practices as part of investments to enhance agricultural productivity. This is different from those farmers who only depend on rainfed conditions. The positive influence of access to irrigation on SLMP implementation underscores the importance of water availability in sustaining conservation agriculture (Bekele et al., 2021). Investing in irrigation infrastructure would be critical for smallholder farmers in the study villages, given the increasing precarity of rainfed agriculture due to unpredictable rainfall. However, in areas where there is no access to water for irrigation or irrigation infrastructure, training farmers on such practices was irrelevant. Therefore, farmers with access to irrigation had a structural advantage compared to their counterparts without access. As a semi-arid area, developing small-scale irrigation

schemes in the study area would significantly improve the adoption of sustainable practices, agricultural productivity, incomes, and livelihoods among smallholder farmers (Jiba et al., 2024; Dube, 2023). This underscores the role of infrastructure and contextualization of training, not just innovation traits, in enabling adoption.

The strong positive effect of fertilizer use on SLMP implementation in this study aligns with recent studies on the benefits of improved soil fertility amendments (Chander et al., 2023; Nzanza Bombiti et al., 2025). The findings suggest that fertilizer application and SLMP implementation were complementary practices. For instance, farmers applied compost and organic manure as soil fertility amendments, yet these form part of SLMPs. The application of compost manure improves soil health, fertility, structure, drainage, and microbial activity. These benefits can reduce land degradation and enhance crop productivity (Jahangir et al., 2021). Using inorganic fertilizers is often associated with farmers who intend to address soil nutrient deficiencies and improve crop yields urgently. Thus, applying organic and inorganic soil fertility amendments yields the same outcomes as SLMP implementation (Nafi et al., 2020). However, the cost of inorganic fertilizers and the unavailability of adequate organic fertilizers among low-income farmers in semi-arid rural areas, such as the Mphanama area, are a major concern, as corroborated by key informant interviews (Nguru et al., 2021). This is consistent with the negative influence of larger cropped areas on the adoption of SLMPs. While the Diffusion of Innovations theory predicts economies of scale advantages, our findings show that farmers with larger landholdings resisted SLMPs implementation ($p = 0.012$), reflecting the surveyed farmers' resource constraints. Insights from KII revealed that it was more difficult for farmers with larger cropped areas to implement SLMPs than those with smaller cropped areas due to labor bottlenecks and a lack of inputs such as manure. This challenges Diffusion of Innovations' compatibility principle, as labor costs, not practice complexity, drive resistance (Rogers, 2003). Therefore, despite the positive influence of fertilizer use on SLMP implementation, there are limitations to how low-resource farmers can utilize soil fertility amendments and SLMPs (Yemadje et al., 2012). These challenges and the erratic rainfall have long contributed to the low productivity of rainfed, small-holder farming systems in Sub-Saharan Africa. This underscores the importance of addressing these limitations to improve the sustainability and productivity of smallholder agriculture.

The perfect error correlation has critical methodological and practical implications. Statistically, it validates the recursive approach over single-equation models, as standard probit analysis would erroneously estimate the effect (Ngigi and Muange, 2022; Oduniyi and Tekana, 2021). A perfect error correlation reveals that the unobserved factors of this model simultaneously drove farmers toward extension services while preventing them from implementing SLMPs. This finding supports the call for integrated interventions addressing information gaps, risk perceptions, and structural barriers (Emerton and Snyder, 2018; Manzeke-Kangara et al., 2024; Oduniyi et al., 2023). This study has several important implications for policy and practice. The negative influence of formal agricultural extension services on SMLP implementation indicates an urgent need to transform formal agricultural extension approaches and content, possibly integrating in-person advisory services and digital platforms while incorporating more indigenous knowledge (Ngigi and Muange, 2022; Bontsa et al., 2023b; Bontsa et al., 2023a; Ramaraj et al., 2023; Baffour-Ata et al., 2022). A multimodal extension delivery would reduce the exclusion of certain groups of farmers. There is also a need to address the unobserved constraints, such as resource limitations and risk perceptions, that drive farmers toward extension services but prevent them from implementing sustainable practices (Oduniyi, 2022; Emerton and Snyder, 2018; Oduniyi and Tekana, 2021; Oduniyi et al., 2023). Extension programs must also pair knowledge dissemination with resource provision to address a gap highlighted in Political Ecology (Yemadje et al., 2012) but overlooked in Diffusion of Innovations (Rogers, 2003). Furthermore, the study highlights the critical role of irrigation and irrigation infrastructure development on the sustainability of smallholder agriculture in semi-arid areas. These insights directly inform South Africa's Agriculture and Agro-processing Master Plan implementation, particularly its extension service modernization components (FAO, 2022).

5 Limitations

While this study provides critical insights into the role of public extension services in SLMP adoption, we acknowledge some key limitations. Firstly, the study relied on cross-sectional data, which limits the ability to infer causality or temporal changes in farmer behavior as would longitudinal data over time. Secondly, while the study focused on four villages, the findings may limit the generalizability beyond the semi-arid context of Fetakgomo Tubatse Local Municipality. Thirdly, the measurement of variables such as "awareness of degradation," "degradation signs observed," and "extension access" relied on farmer self-reporting, which may be subject to recall bias or subjective interpretation. Similarly, the study did not directly assess perceived behavioral control measures (e.g., attitudes, norms) through structured surveys, and hence, they were not empirically tested in this study. Although the recursive bivariate probit model accounts for endogeneity, it does not identify the specific unobserved variables, such as farmer risk preferences, trust in extension agents, cultural attitudes, or traditional knowledge systems, which may jointly influence extension access and SLMP implementation. Finally, the study did not evaluate the quality or content of extension services, which could explain the negative correlation observed in the RBP model. Future research should integrate mixed methods (e.g., participant observation, extension program audits), longitudinal designs, and expand qualitative inquiry to address these gaps. Future studies should also investigate the unobserved factors and mechanisms behind the perfect correlation ($\rho = 1$). Despite these limitations, the findings offer actionable policy implications for South Africa's Agriculture and Agro-processing Master Plan.

6 Conclusion

This study used a recursive bivariate probit regression model to examine the conventional assumptions about formal agricultural extension services on adopting agricultural innovations and interventions using a case of four villages (Mphanama, Ga-Radingwana, Ga-Matlala, Maseleseleng) in the Fetakgomo Tubatse Local Municipality, South Africa. The results revealed a negative relationship between access to formal agricultural extension services and on-farm sustainable land management practices (SLMPs) implementation. Farmers with access to formal agricultural extension services were 4.8% less likely to implement SLMPs. Although contrary to expectations, this finding stemmed from three systemic mismatches validated by key informants, i.e., input inaccessibility, top-down dissemination, and irrelevant training. The

findings also revealed systemic gaps where farmers observing intense land degradation sought extension advice but failed to implement SLMPs. This suggests that current extension services lack actionable solutions for more intense land degradation or attract farmers facing structural barriers (e.g., resource limitations and risk perceptions) to access extension services while impeding them from implementing SLMPs due to resource limitations or incompatibility with their needs. This suggests that extension programs targeted at low-resource farmers in rural areas must pair knowledge dissemination with resource provision to address a gap highlighted in Political Ecology but overlooked in the Diffusion of Innovations. The findings further suggest that the formal extension service program (i.e., top-down approach, content, and/or delivery mechanism) discouraged farmers from accessing extension services, resulting in some implementing SLMPs without accessing formal extension services. Key informant interviews suggest that Political Ecology best explains SLMP implementation barriers, as resource access outweighed attitudes, and that extension programs failed at compatibility by not adapting to local economies. This indicates an urgent need to transform formal agricultural extension approaches, content, and delivery mechanisms to be inclusive and effective in addressing the low access to extension services and subsequent SLMP implementation. A hybrid model blending in-person advisory services, digital platforms, and indigenous knowledge could enhance relevance and address farmers' needs. The perfect error correlation suggests that some unobserved factors, including inadequate extension services or farmers' inability to act on acquired extension information, essentially linked the two decisions, i.e., extension access and SLMP implementation. This finding validated the need for recursive bivariate modeling over single-equation approaches. Findings from this study have critical policy implications that extend beyond the four villages in the Fetakgomo Tubatse Local Municipality. There is an urgent need to transform public extension programs targeted at low-resource farmers from merely disseminating information to providing bundled support, such as input subsidies and credit access, to enhance their effectiveness. Prioritizing small-scale irrigation investments can be a crucial strategy to incentivize SLMP implementation among smallholder farmers in semi-arid regions. Furthermore, leveraging alternative networks and knowledge systems, including digital tools and farmer-to-farmer exchanges, can help reach excluded groups more effectively. This study concludes that improving SLMP adoption goes beyond information access to systemic reforms that remove the structural and systemic barriers limiting smallholder farmers' capacity to implement sustainable practices. However, addressing these multiple challenges requires the active engagement of smallholder farmers in co-designing effective extension services and SLMP practices that address farmers' challenges.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of the University of Limpopo under Project Number TREC/1634/2024:IR.

Author contributions

EpM: Visualization, Methodology, Conceptualization, Writing – original draft, Formal analysis, Writing – review & editing. NM: Writing – review & editing. TM: Writing – review & editing, Project administration. EmM: Validation, Writing – review & editing. MM: Writing – review & editing. KM: Writing – review & editing, Validation. KA: Project administration, Funding acquisition, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Afful, D. B., and Mabena, P. P. (2024). Agricultural extension practitioners' use of information communication tools in the Capricorn District, Limpopo, South Africa: a perception study. *South African J. Agricultural Extension (SAJAE)* 52, 175–196. doi: 10.17159/2413-3221/2024/v52n3a15904

Ajzen, I. (1991). The theory of planned behavior. *Organ. Behav. Hum. Decis. Process.* 50, 179–211.

Alemu, T., Tolossa, D., Senbeta, F., and Zeleke, T. (2023). The effects of continuous sustainable land management practices on agricultural land productivity in Central Ethiopia. *J. Degraded Min. Lands Manage.* 10, 4389–4403. doi: 10.15243/jdmlm.2023.103.4389

Antwi-Agyei, P., and Stringer, L. C. (2021). Improving the effectiveness of agricultural extension Services in Supporting Farmers to adapt to climate change: insights from northeastern Ghana. *Clim. Risk Manag.* 32:100304. doi: 10.1016/J.CRM.2021.100304

Badolo, F., Kotu, B. H., Oyinbo, O., Sanogo, K., and Birhanu, B. Z. (2022). Farmers' preferences for sustainable intensification attributes in sorghum-based cropping systems: evidence from Mali. *Renew. Agric. Food Syst.* 37, 695–706. doi: 10.1017/S1742170522000345

Baffour-Ata, F., Antwi-Agyei, P., Nkiaka, E., Dougill, A. J., Anning, A. K., and Kwakye, S. O. (2022). Climate information services available to farming households in northern region, Ghana. *Weather Clim. Soc.* 14, 467–480. doi: 10.1175/WCAS-D-21-0075.1

Bayisa, H., Kebede, B., and Benti, F. (2024). Factors influencing the implementation and adoption of sustainable land management practices on Wacaca Mountain in central highlands of Ethiopia. *Environ. Model. Assess.* 30, 53–70. doi: 10.1007/s10666-024-09993-7

Bekele, R. D., Mirzabaev, A., and Mekonnen, D. (2021). Adoption of multiple sustainable land management practices among irrigator rural farm households of Ethiopia. *Land Degrad. Dev.* 32, 5052–5068. doi: 10.1002/LDR.4091

Bontsa, N. V., Gwala, L., Ngarava, S., Mdiya, L., and Zhou, L. (2023a). Quality of climate change extension services provided to smallholder farmers in Raymond Mhlaba local municipality, eastern Cape Province, South Africa. *South African J. Agricultural Extension (SAJAE)* 51, 114–127. doi: 10.17159/2413-3221/2023/v51n2a15717

Bontsa, N. V., Mushunje, A., Ngarava, S., and Zhou, L. (2023b). Utilisation of digital technologies by smallholder farmers in South Africa. *South African J. Agricultural Extension (SAJAE)* 51, 104–146. doi: 10.17159/2413-3221/2023/v51n4a15337

Chander, G., Singh, A., Abbhishek, K., Whitbread, A. M., Jat, M. L., Mequanint, M. B., et al. (2023). Consortium of management practices in long-run improves soil fertility and carbon sequestration in drylands of semi-arid tropics. *Int. J. Plant Prod.* 17, 477–490. doi: 10.1007/s42106-023-00249-0

Chanza, C., and Mgalamadzi, L. M. (2025). Market orientation in agricultural extension and advisory services approaches: experiences from service providers and farmers in Central Malawi. *South African J. Agricultural Extension (SAJAE)* 53, 39–60. doi: 10.17159/2413-3221/2025/v53n1a17211

Dube, S. V. (2023). Institutional arrangements and support systems for independent smallholder irrigators in the Msinga local municipality, South Africa. *South African J. Agricultural Extension (SAJAE)* 51, 66–81. doi: 10.17159/2413-3221/2023/v51n1a11977

Dube, P. I., Olorunfemi, O. D., and Nyawo, P. H. (2025). Perception and utilisation of organic farming practices among smallholder farmers: evidence from a micro-level survey in Ehlanzeni District, South Africa. *South African J. Agricultural Extension (SAJAE)* 53, 169–192. doi: 10.17159/2413-3221/2025/v53n1a18444

Elias, A., Nohmi, M., Yasunobu, K., and Ishida, A. (2013). Effect of agricultural extension program on smallholders' farm productivity: evidence from three peasant associations in the highlands of Ethiopia. *J. Agric. Sci.* 5:8P163. doi: 10.5539/JAS.V5N8P163

Emerton, L., and Snyder, K. A. (2018). Rethinking sustainable land management planning: understanding the social and economic drivers of farmer decision-making in Africa. *Land Use Policy* 79, 684–694. doi: 10.1016/J.LANDUSEPOL.2018.08.041

Engelbrecht, C. J., and Engelbrecht, F. A. (2016). Shifts in Köppen-Geiger climate zones over southern Africa in relation to key global temperature goals. *Theor. Appl. Climatol.* 123, 247–261. doi: 10.1007/S00704-014-1354-1

Etsay, H., Negash, T., and Aregay, M. (2019). Factors that influence the implementation of sustainable land management practices by rural households in Tigrai region, Ethiopia. *Ecol. Process.* 8:14. doi: 10.1186/s13717-019-0166-8

FAO. (2022). Agriculture and Agro-Processing Master Plan "Social Compact". Available online at: https://www.fao.org/faolex/results/details/en/c/LEX-FAOC214490/ (accessed on 8 April 2025).

Filippini, M., Greene, W. H., Kumar, N., and Martinez-Cruz, A. L. (2018). A note on the different interpretation of the correlation parameters in the bivariate probit and the recursive bivariate probit. *Econ. Lett.* 167, 104–107. doi: 10.1016/J.ECONLET.2018.03.018

Gwala, L., Yusuf, F. S. G., Loki, O., Bontsa, N. V., Mdiya, L., and Rani, Z. T. (2024). Perceptions of communal farmers on extension support services accessibility in the Port St Johns, eastern Cape Province. *South African J. Agricultural Extension (SAJAE)* 52, 83–96. doi: 10.17159/2413-3221/2024/v52n4a18365

Hansen, J., Kagabo, D., Clarkson, G., Furlow, J., and Fiondella, F. Climate Services for Agriculture: Empowering farmers to manage risk and adapt to a changing climate in Rwanda; Kigali, CGIAR (2021).

Haregeweyn, N., Tsunekawa, A., Tsubo, M., Fenta, A. A., Ebabu, K., Vanmaercke, M., et al. (2023). Progress and challenges in sustainable land management initiatives: a global review. *Sci. Total Environ.* 858:160027. doi: 10.1016/J.SCITOTENV.2022.160027

Hayden, M. T., Mattimoe, R., and Jack, L. (2021). Sensemaking and the influencing factors on farmer decision-making. *J. Rural. Stud.* 84, 31–44. doi: 10.1016/J.JRURSTUD.2021.03.007

Hazrana, J., and Mishra, A. K. (2024). Effect of input subsidies and extension services: evidence from rice productivity in Bangladesh. *Food Policy* 125:102628. doi: 10.1016/J.FOODPOL.2024.102628

Irwin, R., Short, I., Mohammadrezaei, M., and Dhubhain, A. N. (2023). Increasing tree cover on Irish dairy and drystock farms: the main attitudes, influential bodies and barriers that affect agroforestry uptake. *Environ. Sci. Pol.* 146, 76–89. doi: 10.1016/j.envsci.2023.03.022

IUCN. (2021). IUCN Mainstreaming Sustainable Land Management for Large-Scale Impact in the Grazing Lands of Limpopo and Northern Cape Provinces in South Africa – Project. Available online at: https://iucn.org/our-work/projects/mainstreaming-sustainable-land-management-large-scale-impact-grazing-lands (accessed on 14 April 2025).

Jahangir, M. M. R., Islam, S., Nitu, T. T., Uddin, S., Kabir, A. M. A., Meah, M. B., et al. (2021). Bio-compost-based integrated soil fertility management improves post-harvest soil structural and elemental quality in a two-year conservation agriculture practice. *Agronomy-Basel* 11:2101. doi: 10.3390/agronomy11112101

Jellason, N. P., Conway, J. S., and Baines, R. N. (2021). Understanding impacts and barriers to adoption of climate-smart agriculture (CSA) practices in North-Western Nigerian drylands. *J. Agric. Educ. Ext.* 27, 55–72. doi: 10.1080/1389224X.2020.1793787

Jha, C. K., and Gupta, V. (2021a). Farmer's perception and factors determining the adaptation decisions to cope with climate change: an evidence from rural India. *Environ. Sustain. Indic.* 10:100112. doi: 10.1016/J.INDIC.2021.100112

Jha, C. K., and Gupta, V. (2021b). Do better agricultural extension and climate information sources enhance adaptive capacity? A micro-level assessment of farm households in rural India. *Ecofeminism Climate Change* 2, 83–102. doi: 10.1108/efcc-10-2020-0032

Jiba, P., Obi, A., Mdoda, L., and Mzuyanda, C. (2024). The impact of smallholder irrigation scheme on household welfare in farm-managed irrigation scheme communities in the eastern cape province, South Africa. *South African J. Agricultural Extension (SAJAE)* 52, 48–72. doi: 10.17159/2413-3221/2024/v52n1a13953

Kaiser, A., and Burger, P. (2022). Understanding diversity in farmers' routinized crop protection practices. *J. Rural. Stud.* 89, 149–160. doi: 10.1016/J.JRURSTUD.2021.12.002

Kgaphola, M. J., Ramoelo, A., Odindi, J., Mwenge Kahinda, J. M., Seetal, A. R., and Musvoto, C. (2023a). Impact of land use and land cover change on land degradation in rural semi-arid South Africa: case of the greater Sekhukhune District municipality. *Environ. Monit. Assess.* 195:710. doi: 10.1007/S10661-023-11104-0

Kgaphola, M. J., Ramoelo, A., Odindi, J., Mwenge Kahinda, J. M., Seetal, A., and Musvoto, C. (2023b). Social–ecological system understanding of land degradation in response to land use and cover changes in the greater Sekhukhune District municipality. *Sustainability* 15:3850. doi: 10.3390/SU15043850

Khwidzhili, R. H., and Worth, S. H. (2016). The sustainable agriculture imperative: implications for south African agricultural extension. *S. Afr. J. Agric. Ext.* 44, 19–29. doi: 10.17159/2413-3221/2016/V44N2A367

Kibrom, A. A., Haimanot, A. B., Tigist, P., and Beyene, D. B. (2025). The challenges of extension service delivery and its determinants in the agricultural extension system: an insight from a study in North-Western Ethiopia. *South African J. Agricultural Extension (SAJAE)* 53, 16–38. doi: 10.17159/2413-3221/2025/v53n1a17189

Kolapo, A., Didunyemi, A. J., Aniyi, O. J., and Obembe, O. E. (2022). Adoption of multiple sustainable land management practices and its effects on productivity of smallholder maize farmers in Nigeria. *Resour. Environ. Sustain.* 10:100084. doi: 10.1016/J.RESENV.2022.100084

Kunzekweguta, M., Rich, K. M., and Lyne, M. C. (2017). Factors affecting adoption and intensity of conservation agriculture techniques applied by smallholders in Masvingo district, Zimbabwe. *Agrekon* 56, 330–346. doi: 10.1080/03031853.2017.1371616

Lasway, J. A., Selejio, O., and Temba, G. R. (2020). Modeling multiple adoption decisions on agricultural technologies in Tanzania: a multinomial probit analysis. *Tanzan. Econ. Rev.* 10, 1–16.

LDARD. (2025). LDARD Programme 2 - Sustainable Resource Use And Management Available online at: https://www.ldard.gov.za/index.php/about-us/overview-of-the-department/programme-2-sustainable-resource-use-and-management (accessed on 14 April 2025).

Lian, J. S., Wang, H. Y., Deng, Y., Xu, M. G., Liu, S. T., Zhou, B. K., et al. (2022). Impact of long-term application of manure and inorganic fertilizers on common soil bacteria in different soil types. *Agric. Ecosyst. Environ.* 337:8044. doi: 10.1016/j.agee.2022.108044

Ludwig, D., and Poliseli, L. (2018). Relating traditional and academic ecological knowledge: mechanistic and holistic epistemologies across cultures. *Biol. Philos.* 33:43. doi: 10.1007/S10539-018-9655-X

Manganyi, B., Sotsha, K., Rambau, K., and Chiloane, D. (2024). Improving Market Access for Smallholder Farmers in South Africa. Available online at: https://www.namc.co.za/wp-content/uploads/2024/10/Policy-Brief-Improving-Market-Access-for-Smallholder-Farmers-in-South-Africa.pdf (accessed on 9 April 2025).

Manzeke-Kangara, M. G., Muwaniki, C., Siziba, S., Chamboko, T., Mtambanengwe, F., and Wedekind, V. (2024). Evolution of agricultural extension in Zimbabwe: emerging technologies, training needs and future possibilities. *South African J. Agricultural Extension (SAJAE)* 52, 21–55. doi: 10.17159/2413-3221/2024/v52n2a14969

Mapiye, O., Makombe, G., Molotsi, A. H., Dzama, K., and Mapiye, C. (2025). Revolutionising the public extension system for smallholder livestock farmers: user experiences and the prospects of using information and communication technologies in north West Province, South Africa. *South African J. Agricultural Extension (SAJAE)* 53, 120–138. doi: 10.17159/2413-3221/2025/v53n1a18044

Mbatha, M. W. (2024). The provision of agricultural extension services to rural farmers as a strategy to improve agricultural practices in South Africa. *South African J. Agricultural Extension (SAJAE)* 52, 1–19. doi: 10.17159/2413-3221/2024/v52n1a12717

Mdiya, L., Aliber, M., Ngarava, S., Bontsa, N. V., and Zhou, L. (2023). Impact of extension services on the use of climate change coping strategies for smallholder ruminant livestock farmers in Raymond local municipality, eastern Cape Province, South Africa. *South African J. Agricultural Extension (SAJAE)* 51, 150–166. doi: 10.17159/2413-3221/2023/v51n2a15725

Meijer, S. S., Catacutan, D., Ajayi, O. C., Sileshi, G. W., and Nieuwenhuis, M. (2015). The role of knowledge, attitudes and perceptions in the uptake of agricultural and agroforestry innovations among smallholder farmers in sub-Saharan Africa. *Int. J. Agric. Sustain.* 13, 40–54. doi: 10.1080/14735903.2014.912493

Mokgolo, M. J., and Mzezewa, J. (2023). Baseline study of soil nutrient status in smallholder farms in Limpopo Province of South Africa. *South African J. Agricultural Extension (SAJAE)* 51, 51–65. doi: 10.17159/2413-3221/2023/v51n1a11914

Mpandeli, S., and Maponya, P. (2014). Constraints and challenges facing the small scale farmers in Limpopo Province, South Africa. *J. Agric. Sci.* 6:135. doi: 10.5539/JAS.V6N4P135

Mpandeli, S., Nesamvuni, E., and Maponya, P. (2015). Adapting to the impacts of drought by smallholder farmers in Sekhukhune District in Limpopo Province, South Africa. *J. Agric. Sci.* 7, 115–124. doi: 10.5539/jas.v7n2p115

Nafi, E., Webber, H., Danso, I., Naab, J. B., Frei, M., and Gaiser, T. (2020). Interactive effects of conservation tillage, residue management, and nitrogen fertilizer application on soil properties under maize-cotton rotation system on highly weathered soils of West Africa. *Soil Tillage Res.* 196:4473. doi: 10.1016/j.still.2019.104473

Ngigi, M. W., and Muange, E. N. (2022). Access to climate information services and climate-smart agriculture in Kenya: a gender-based analysis. *Clim. Chang.* 174:21. doi: 10.1007/s10584-022-03445-5

Nguru, W. M., Gachene, C. K., Onyango, C. M., Ng'ang'a, S. K., and Girvetz, E. H. (2021). Factors constraining the adoption of soil organic carbon enhancing technologies among small-scale farmers in Ethiopia. *Heliyon* 7:e08497. doi: 10.1016/j.heliyon.2021.e08497

Nzanza Bombiti, J.-R., Taurayi, S., Mugari, E., Tatsvarei, S., Pontain Zvinavashe, A., Musakwa, W., et al. (2025). Household and farm-level drivers of the use and intensity of soil fertility amendments in smallholder farming systems: a case of Masvingo District, Zimbabwe, and Mopani District, South Africa. *Front. Agron.* 7:1471052. doi: 10.3389/FAGRO.2025.1471052

Oduniyi, O. S. (2022). Factors driving the adoption and use extent of sustainable land management practices in South Africa. *Circ. Econ. Sustain.* 2, 589–608. doi: 10.1007/S43615-021-00119-9

Oduniyi, O. S., and Chagwiza, C. (2022). Impact of adoption of sustainable land management practices on food security of smallholder farmers in Mpumalanga Province of South Africa. *GeoJournal* 87, 4203–4217. doi: 10.1007/S10708-021-10497-0

Oduniyi, O. S., Ojo, T. O., and Nyam, Y. S. (2023). Awareness and adoption of sustainable land management practices among smallholder maize farmers in Mpumalanga Province of South Africa. *Afr. Geogr. Rev.* 42, 217–231. doi: 10.1080/19376812.2021.2018661

Oduniyi, O. S., and Tekana, S. S. (2021). Does information acquisition influence the adoption of sustainable land management practices? Evidence from Mpumalanga Province, South Africa. *Front. Sustain. Food Syst.* 5, 1–8. doi: 10.3389/fsufs.2021.769094

Olumba, C. N., Garrod, G., and Areal, F. (2025). Investigating the constraints and mitigation strategies for the adoption of sustainable land management practices in erosion-prone areas of Southeast Nigeria. *Environ. Manag.* 75, 1504–1519. doi: 10.1007/S00267-024-02104-Y

Oyinbo, O., Chamberlin, J., Abdoulaye, T., and Maertens, M. (2022). Digital extension, price risk, and farm performance: experimental evidence from NigeriaJEL codes. *Am. J. Agric. Econ.* 104, 831–852. doi: 10.1111/ajae.12242

Oyinbo, O., Chamberlin, J., and Maertens, M. (2020). Design of Digital Agricultural Extension Tools: perspectives from extension agents in Nigeria. *J. Agric. Econ.* 71, 798–815. doi: 10.1111/1477-9552.12371

Pasara, M. T., and Mhlanga, D. (2022). Accelerating sustainable development goals in the wake of COVID-19: the role of higher education institutions in South Africa. *Emer. Open Res.* 1, 1–16. doi: 10.1108/EOR-03-2023-0017

Qwabe, Q. N., and Khapayi, M. (2025). Investigating the influence of agricultural extension service providers (AESPS) on building inclusive food systems through underutilised indigenous foods education: a case study. *South African J. Agricultural Extension (SAJAE)* 53, 1–15. doi: 10.17159/2413-3221/2025/v53n1a16943

Qwabe, Q. N., Swanepoel, J. W., Zwane, E. M., and van Niekerk, J. A. (2022). Nexus between the invisibility of agricultural extension services and rural livelihoods development: assertions from rural farming communities. *South Afr. J. Agric. Ext.* 50, 26–41. doi: 10.17159/2413-3221/2022/v50n1a14407

Ramaraj, A. P., Rao, K. P. C., Kumar, G. K., Ugalechumi, K., Sujatha, P., Rao, S. A., et al. (2023). Delivering context specific, climate informed agro-advisories at scale: a case study of ISAT, an ICT linked platform piloted with rainfed groundnut farmers in a semi-arid environment. *Clim. Serv.* 31:100403. doi: 10.1016/j.cliser.2023.100403

Rogers, E. M. (2003). Diffusion of innovations. *5th* Edn. New York: Free Press.

Salla, A. (2019). Weather and Climate Information Services in Subsistence Agriculture-Farmers' Experiences on the Adequacy of These Services in the Taita Hills, Kenya. Kenya: University of Helsinki.

Sharifzadeh, M. S., Abdollahzadeh, G., and Damalas, C. A. (2023). Farmers' behaviour in the use of integrated pest management (IPM) practices: perspectives through the social practice theory. *Int. J. Pest Manag.* 71, 406–419. doi: 10.1080/09670874.2023.2227607

Shiba, W. T., Mdiya, L., Aliber, M., and Zantsi, S. (2024). Institutional factors affecting smallholder farmers' decision to adopt climate change adaptation strategies: evidence from Raymond Mhlaba local municipality, eastern cape, South Africa. *South African J. Agricultural Extension (SAJAE)* 52, 185–206. doi: 10.17159/2413-3221/2024/v52n4a18423

Shushu, G. N. J., Mmbengwa, V. M., Swanepoel, J. W., and Manasoe, B. (2024). Impact assessment of government funding for subsistence, smallholder farmers, communities, and households on food security: an advice for extension services. *South African J. Agricultural Extension (SAJAE)* 52, 107–119. doi: 10.17159/2413-3221/2024/v52n2a15759

Teele, T., and Nkoane, M. M. (2024). Reimagining agricultural advisors and educators as agricultural bricoleurs towards enhanced skills transfer: an adult learning perspective. *South African J. Agricultural Extension (SAJAE)* 52, 16–35. doi: 10.17159/2413-3221/2024/v52n3a13288

Von Maltitz, L., Van Niekerk, J. A., and Davis, K. (2024). The digital readiness of agricultural advisory professionals: a south African case study. *South African J. Agricultural Extension (SAJAE)* 52, 47–65. doi: 10.17159/2413-3221/2024/v52n4a16851

Wadduwage, S. (2021). Drivers of peri-urban farmers' land-use decisions: an analysis of factors and characteristics. *J. Land Use Sci.* 16, 273–290. doi: 10.1080/1747423X.2021.1922525

Yemadje, R. H., Crane, T. A., Vissoh, P. V., Mongbo, R. L., Richards, P., Kossou, D. K., et al. (2012). The political ecology of land management in the oil palm based cropping system on the Adja plateau in Benin. *NJAS Wageningen J. Life Sci.* 60, 91–99. doi: 10.1016/J.NJAS.2012.06.007

Zondo, W. N. S., and Ndoro, J. T. (2024). Evaluating the influence of socioeconomic factors on smallholder farmer's social media adoption in the Nkomazi local municipality, Mpumalanga Province. *S. Afr. J. Agric. Ext.* 52, 20–47. doi: 10.17159/2413-3221/2024/v52n1a13764