frontiers | Frontiers in Agronomy

TYPE Original Research
PUBLISHED 19 June 2025
DOI 10.3389/fagro.2025.1471052

Check for updates

OPEN ACCESS

EDITED BY
Tajamul Hussain,
Oregon State University, United States

REVIEWED BY
Issaka Abdulai,
University of Göttingen, Germany
Muhammad Tahir Shehzad,
University of Agriculture, Faisalabad, Pakistan

*CORRESPONDENCE
Ephias Mugari
mapfori.mugari@ul.ac.za;
mugarie@gmail.com

RECEIVED 26 July 2024
ACCEPTED 26 May 2025
PUBLISHED 19 June 2025

CITATION
Bombiti J-RN, Taurayi S, Mugari E, Tatsvarei S, Zvinavashe AP and Musakwa W (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

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

Jean-Robert Nzanza Bombiti[1], Silent Taurayi[2], Ephias Mugari[3]*, Simbarashe Tatsvarei[4], Augustine Pontain Zvinavashe[4] and Walter Musakwa[2]

[1]Department of Water and Forests, University of Uele, Bas Uele, Democratic Republic of Congo, [2]Geography, Environmental Management & Energy Studies, Faculty of Science, University of Johannesburg, Johannesburg, South Africa, [3]Centre for Global Change, University of Limpopo, Polokwane, South Africa, [4]Department of Agricultural Business Development and Economics, University of Zimbabwe, Harare, Zimbabwe

Introduction: Smallholder farming systems critically secure livelihoods and significantly contribute towards household food security in Sub-Saharan Africa (SSA). Sustainable soil fertility management is, however, essential for improving crop and livestock productivity and resilience in smallholder farming systems.

Methods: Using the integrated soil fertility management (ISFM) approach, an investigation into the intricate relationship between socio-economic and farm-level factors and agricultural practices on the use and intensity of use of quantities of organic soil amendments (OSA) and inorganic soil amendments (ISA) among smallholder farmers in Masvingo, Zimbabwe and Mopani, South Africa, which remains poorly understood among rural farming communities, revealed complex relationships among these factors and issues.

Results and discussion: The ISFM approach employing binary and ordered logistic regression models on household survey data (n=378) found that the farmer's location (i.e. district), years of formal education, literacy, household labor, income sources and monthly income, total landholding, main crop grown, livestock ownership, soil type and soil testing significantly affected fertilizer adoption and fertilizer application intensity. Farmers in Masvingo, Zimbabwe, were more inclined to use and apply higher quantities of OSA and ISA than those in Mopani, South Africa, highlighting the role of regional agroecological and socio-economic differences. Cattle ownership significantly increased OSA use while negatively influencing ISA use, reinforcing the importance of crop-livestock integration. Additionally, soil testing encouraged ISA application but discouraged OSA use, suggesting that farmers perceived ISA as a more immediate response to soil fertility deficiencies.

Conclusion: The contrasting influence of some socio-economic factors indicates the intricate nature of smallholder farming systems and how household characteristics are intertwined with ISFM decisions. Therefore, there is a need for context-specific farmer education programs, tailored soil testing programs, financial support for fertilizer access, and location-specific extension services to address the unique differences among smallholder farmers in rural areas to enhance soil fertility, improve crop and livestock productivity, and increase overall resilience in smallholder farming systems.

KEYWORDS

organic soil amendments, inorganic soil amendments, small-scale farming, soil fertility amendments, Southern Africa, sub-Saharan Africa, sustainable agriculture

1 Introduction

Poor soil fertility threatens sustainable crop and livestock productivity and household food security of smallholder farming communities in the greater part of SSA (Mutsamba et al., 2020; Namatsheve et al., 2021). Inherent poor soil properties, continuous cropping without adequate nutrient inputs, removal of crop residues, and inappropriate production practices have led to poor soil fertility status in these farming communities (Asante et al., 2020; Laekemariam and Kibret, 2020). Efficient utilization of soil nutrients underpins the integrated soil fertility management (ISFM) approach (Mugwe et al., 2019). The ISFM approach envisions a collection of soil fertility management techniques that invariably involve the use of inorganic fertilizers, organic fertilizers, improved germplasm, and adapting these techniques to local conditions, aiming to maximize agronomic use efficiency and improve crop and livestock productivity. It is an approach that can be adopted by any institution or farming community promoting it, and is based on a set of aforementioned principles. There are drawbacks to using only mineral fertilizers prior to the ISFM approach conceptualization, including high costs, unavailability, and adverse effects of inorganic inputs on the environment and human health (Mugwe et al., 2019). An important research focus is on ensuring that the ISFM approach, or its components, can adjust to the specific conditions that farmers face in their area, utilizing the proper ratio of inorganic and organic inputs, together with other soil fertility amendments (Mugwe et al., 2019). The strength of the ISFM approach is that it is farmer-focused, adaptable, and sustainable, compared to other approaches such as ecological intensification, the soil food web approach, and biodynamic farming (Mugwe and Otieno, 2021). The ISFM approach fits with international agricultural sustainability initiatives toward sustainable intensification, climate-wise farming methods, and ecosystem-based agriculture. Considered the pillar of sustainable intensification, the ISFM approach seeks to maximize agricultural output and productivity while reducing environmental effects. The approach necessarily implies efficiently utilizing scarce water, fixed land, and diminishing natural resources to maximize agricultural outputs and productivity (Vanlauwe et al., 2010). The ISFM approach is strongly related to climate-smart agriculture, which aims to improve organic matter and, in the process, lower greenhouse gas emissions, boost agricultural output and productivity, and strengthen resilience to climate change (Lipper et al., 2014).

Therefore, soil fertility and nutrient management become functions of diverse institutional arrangements, biophysical factors, socio-economic processes, and household organization. Smallholder farming systems in SSA are complex due to the intricate interactions between crop and livestock production systems, soil and climate within a diverse range of unfavorable socio-economic factors, biophysical environments, and cultural diversity (Mkuhlani et al., 2020; Mutsamba et al., 2020; Ndlovu et al., 2020). Consequently, soil fertility management becomes highly complex due to a set of interacting factors that dictate the extent of household investment in soil fertility management. To understand the farmer's role in soil fertility and nutrient management, there is a need to understand farmers' characteristics, including the interacting factors that influence household decision-making psychology, farming practices, and cultural practices (Laekemariam and Kibret, 2020; Mogaka et al., 2021). Household categorization becomes critical in targeting agricultural innovations, adoption, and understanding how different farming objectives and resource endowments affect resource allocation, leading to soil fertility heterogeneity (Azuka, 2020; Laekemariam and Kibret, 2020).

The adoption of sustainable practices and technology in SSA smallholder farming systems is strongly constrained by the limited availability of key resources such as land, technology, plant nutrients, finance, and labor. Resource allocation and use efficiency are constrained by the interaction of these limited resources, threatening the livelihoods of farming households (Cornish et al., 2020; Lewoyehu et al., 2020; Amede et al., 2022; Wawire et al., 2023). Resource limitation forces farmers to allocate available labor and nutrient resources to certain fields (Laekemariam and Kibret, 2020). For example, limited availability of organic resources often leads to the occurrence of soil fertility gradients within smallholder farming systems, which strongly affect the resource use efficiency of organic and inorganic fertilizers (Gunarathne et al., 2020; Chipomho et al., 2022). The soil fertility status within smallholder farms is likely to vary between households of different social status, cattle ownership, and/or long-term market-oriented objectives versus subsistence objectives. Mogaka et al (Mogaka et al., 2021). argues that land use systems of wealthier farmers in SSA have higher nitrogen and phosphorus balances than plots of poorer farmers, which also vary inversely with the distance of the fields relative to the homestead's location.

Lack of adequate nutrient resources and shortage of labor are among the key factors that limit the productivity of African smallholder farming systems. Livestock contributes significantly to crop production by providing manure and draft power (Mkuhlani et al., 2020; Mwakidoshi et al., 2023). Healthy soils are often regularly amended with organic nutrients such as animal manure and composts, and are the most common sources of soil nutrients among smallholder farming systems in SSA (Adem et al., 2023). Livestock owners use animal manure more often than non-owners, who usually rely on picking livestock droppings from common grazing lands or barter trade with crop residues or provision of labor. The bulk nature of organic amendments increases labor demand for handling and application in the field. Labor is commonly in short supply during the farming season. It is a major factor in determining farmers' choice of crops and production methods. Wealthy farmers can hire the casual labor necessary to improve management of their farms, while poor farmers are often forced to sell their labor, leading to poor nutrient management (Zingore et al., 2011).

Smallholder farmers in Southern Africa have limited means to increase the availability and accessibility of resources. Improving the use efficiency of nutrients, land, and labor is imperative to sustain high crop and livestock productivity (Zingore et al., 2011). Socioeconomic factors that influence the nutrient management strategies determining the spatial and temporal soil fertility variability have not been fully explored (Mogaka et al., 2021; Asule et al., 2022; Heidenreich et al., 2022). Technological interventions improving the productivity of smallholder agriculture must recognize the social and cultural diversity and spatial heterogeneity of farms and farming systems (Kiprotich et al., 2023). Stöckle et al (Stöckle et al., 2003). reckons that using crop-livestock simulation models offers opportunities to explore and optimize crop-livestock interactions and enhance resource-use efficiencies, including designing sustainable farming systems.

Laub et al (Laub et al., 2023). contend that models to understand constraints and potential development pathways should have limited complexity so that users are able to control model behavior and understand why certain outcomes arise. There are drawbacks associated with the use of detailed process models. Their computational and mathematical complexity, arising from coupling multiple modules, results in unrealistic behavior. Also, increased data input demand for parameterization and deriving variables for calibration and validation is difficult since many variables have not been measured. Furthermore, the extensive data demand and construction of models for specific cases from scratch is expensive to countenance, and there is a partial understanding of the underlying processes influencing African smallholder farming systems, which are mostly generalized.

It is clear that understanding the characteristics of the farm household, the environmental context, and decision-making psychic are critical to how farm soil properties develop. This study aimed to analyze the household characteristics and farm-level drivers of soil fertility amendments in smallholder farming systems among smallholder farmers in Masvinog District, Zimbabwe, and Mopani District, South Africa. The two sites were selected due to their similar climate characteristics, yet contrasting smallholder socio-economic and agroecological characteristics. The study primarily focuses on organic and inorganic fertility amendments due to their widespread adoption in the study areas and their immediate impact on soil productivity in smallholder farming systems compared to other aspects of the ISFM approach, such as agroforestry, improved germplasm, and crop rotation (Laub et al., 2023). This study was undertaken at a time when several corporates in South Africa have been experimenting with the combined use of organic fertilizers such as compost and livestock manure, and inorganic fertilizers such as chemical fertilizers as soil fertility amendments to improve soil health and crop productivity while reducing inputs costs and environmental damage. Recent studies suggest that smallholder farmers in Southern Africa tend to adopt incremental, rather than holistic ISFM approaches, often prioritizing organic and inorganic fertility amendments due to their immediate soil fertility needs (Mponela et al., 2016; Kihara et al., 2022; Ndengu et al., 2022). Concentrating on these two soil fertility amendment choices allowed the current study to effectively assess the farmer and farm-level characteristics that influence the use of soil fertility amendments and the intensity of use.

The study aligns with government efforts and policies, and practices to improve soil fertility management in South Africa and Zimbabwe, which emphasize fertilizer subsidies and organic soil fertility amendments as the primary soil fertility management options in smallholder farming areas (Mponela et al., 2016; Kunzekweguta et al., 2017; Khonje et al., 2022). Direct application of organic and inorganic soil fertility amendments allows for immediate and measurable impacts on soil nutrient availability and crop productivity (Kihara et al., 2022). While we acknowledge the different components of the ISFM approach, the focus of this study is limited to quantifying the likelihood and intensity of use of these two soil fertility management practices that do not require complex, extensive, and long-term trials like the other components of the ISFM approach.

2 Materials and methods

2.1 Site description

A comparative case study was conducted in two smallholder farming areas of Mopani District, South Africa, and Masvingo District, Zimbabwe (Figure 1). The results of this comparative study are limited to these two areas, given that further experimental studies are expected. These two districts, while from different countries, share the same agroecological region, Natural Region III, allowing comparisons of practices and outcomes (Manatsa et al., 2020). Mopani district is in Limpopo Province and 470km north-east of Johannesburg at 23.3089° S, and 30.7160° E, with a subtropical climate where the rainfall summer season extends from September to March, while the dry winter season usually extends from April to August. The district is characterized by hot, semi-arid conditions with average annual rainfall fluctuating between 400 and 900 mm. The economy is agro-based, revolving around cattle ranching and the production of maize, peanuts, tomatoes, potatoes, mangoes, and bananas. On the other hand, Masvingo district is located at the center of Masvingo Province and south-east of Zimbabwe at 20.2527° S, and 30.9876° E. The district has three notable seasons: a hot, wet summer season from mid-November to March, a cold, dry winter season from April to July, and a hot, dry spring season from August to mid-November. The district falls into three natural regions, i.e., III, IV, and V, receiving 650–800 mm, 450–650 mm, and <450 mm of rainfall, respectively (Manatsa et al., 2020). The dominant crops grown are maize, groundnuts, and Bambara nuts, while minor crops include finger millet, cowpeas, sorghum, sugar beans, and sunflowers (Kunzekweguta et al., 2017). Dominant crops under irrigation include maize, vegetables such as brassicas, onions, and tomatoes, which are grown mainly for the market. These climatic, agroecological, and agronomic similarities and differences at the two sites provided suitable conditions for analyzing smallholder farmers' use and intensity of organic and inorganic soil amendments in South Africa and Zimbabwe.

2.2 Sample size and sampling procedure

Mzilela village under Giyani Local Municipality and Ward 23 were selected purposefully to represent Mopani and Masvingo districts, respectively. They were purposively chosen because of two running projects in these areas and the convenience of having complete access to the areas on a regular basis, which also enabled participatory observation research. While we acknowledge that the purposive selection of the two sites may have excluded villages with divergent socio-economic or agroecological conditions and potentially limited the generalizability of the findings, the selected sites represent typical smallholder systems in their respective districts, as confirmed by local extension officers. The sample sizes were calculated on the assumption that the target population in Mopani and Masvingo districts was normally distributed. The sample sizes were determined using a sample size calculator presented by Creative Research Systems Survey Software (http://www.surveysystem.com/resource.htm). A sample size of 135 households for Mzilela village in Mopani district and 243 for Ward 23 in Masvingo district was established. Due to the bigger size of Ward 23, the sample size was further disaggregated into villages, and respondents were chosen using a two-stage simple random sampling from the villages. About 25% of the villages were randomly selected from the ward, and proportionate samples were drawn from these villages.

2.3 Data collection

Multiple data collection methods were used to allow data triangulation to enhance the validity and reliability of information gathered. A household/farmer survey was conducted in the two areas using a structured questionnaire (Myeni and Moeletsi, 2020). Three focus group discussions were conducted using a guided checklist, one for Mzilela village and two for Ward 23. Interviews were conducted with key informants who were mainly agricultural extension personnel and some knowledgeable farmers using snowball sampling. Observation was also used during the course of the study to support results from the other two methods.

2.4 Data analysis

Data collected from households were captured and cleaned in the Statistical Package for Social Sciences version 28 and analyzed using STATA version 17. The survey highlighted frequencies, proportions, standard deviations, t-tests, and chi-square tests of issues related to demographics and socio-economic characteristics, crop production and related practices, and soil fertility management practices for both Mopani and Masvingo districts. Analysis followed the use of a Probit model on survey data from 381 households assessing the adoption of soil organic carbon enhancing technologies, such as the use of manure, fertilizer, and crop residue management among smallholder farmers in two watersheds in Ethiopia (Nguru et al., 2021). For this study, Generalized Linear Models (GLM), which were either Binary Logistic Models (BLM) for use of the two soil fertility amendments, and Ordinal Logistic Models (OLM) for the intensity of quantity or intensification of soil fertility amendments, were used to examine the effect of selected socioeconomic factors and farmer practices on the use of ISA and OSA, in line with the conceptual ISFM approach. We checked for multicollinearity using the Variance Inflation Factor (VIF) for the binary logistic regression model, ensuring all values were below 10. We computed the Hosmer-Lemeshow test of goodness of fit, which was non-significant ($p>0.05$), indicating that the model was fit for the data (Archer and Lemeshow, 2006). For the ordinal logistic regression model, we tested the proportional odds assumption using the Brant test. The test results indicated that the assumption holds ($p>0.05$), implying that the proportional odds assumption was not violated, supporting the use of the Ordered Logit Model (Williams, 2006).

The variables used in developing the models are described in Table 1 below and are based on the equation:

$$\mathrm{Logit(pi)} = \mathrm{Y} + \mathrm{C_oX}$$

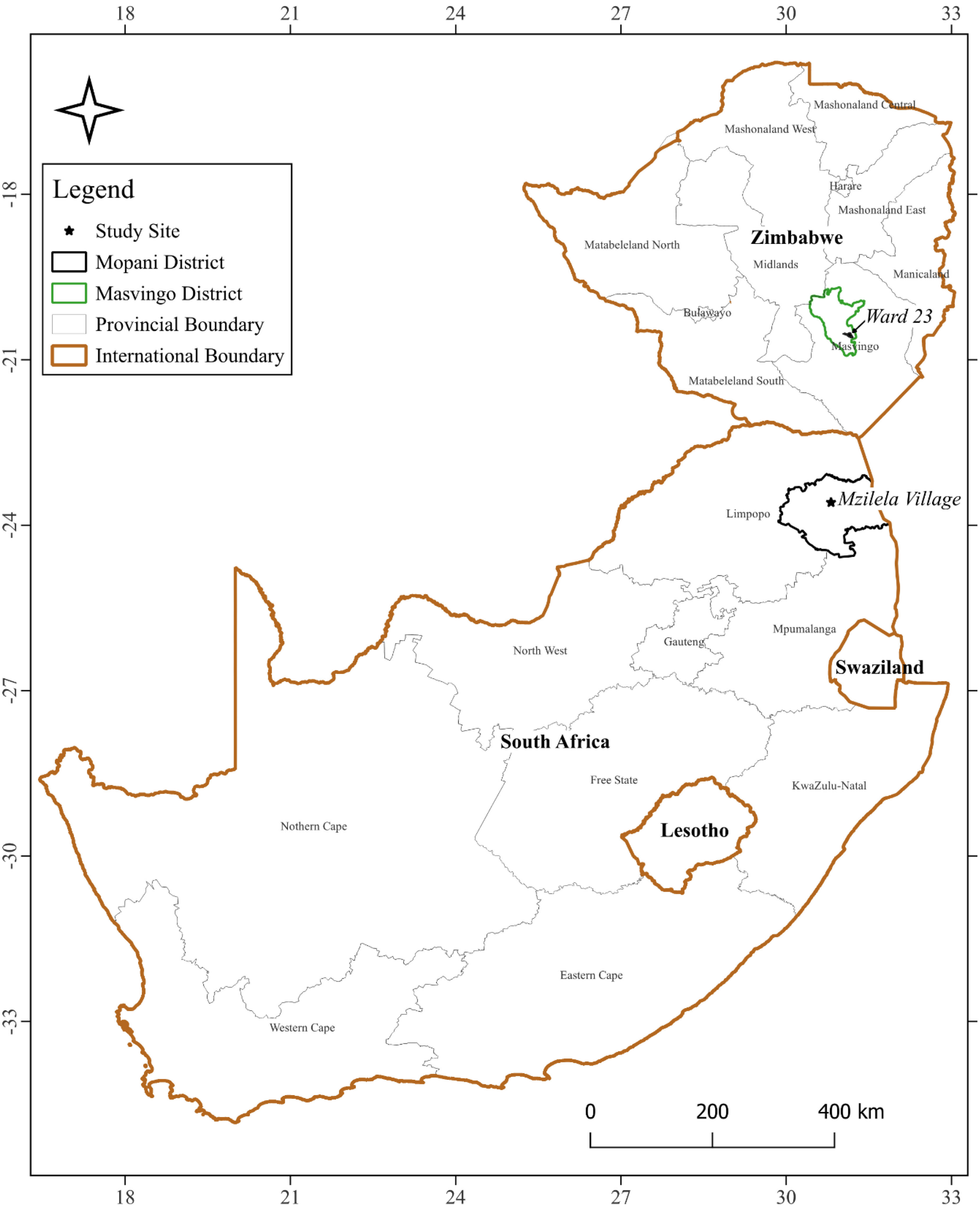

FIGURE 1
Locations of Mzilela Village in Mopani District, South Africa, and Ward 23 of Masvingo, Zimbabwe.

TABLE 1 Description of study variables.

Dependent Variables	Responses/Codes
Use of organic soil amendments	0 = No; 1 = Yes
Quantity of organic soil amendments	0 =None; 1 =<200kg; 2 = 201-500kg; 3 = 501-1000kg; 4 = 1001-3000; 5 = >3000
Use of inorganic fertilizers	0 = No; 1 = Yes
Quantity of inorganic fertilizers	0 = None; 1 =<50kg; 2 = 51-100kg; 3 = 101-150kg; 4 = 151-250kg 5 = >250kg
Predictor Variables	**Responses/Codes**
Sex	0 = Female; 1 = Male
Age of the head of household	Continuous variable
Years spent in formal Education	Continuous variable
Ability to read and write	0 = No; 1 = Yes
Household labor	Continuous variable
Main livelihood source	0 = Farming; 1 = Formal employment; 2 = Other
Main income source	0 = Crops and livestock sales; 1 = Other
Average Monthly Income US$	0 =<100; 1 = 101-250; 2 = 251-500; 3 = >501
Number of scotch carts	Continuous variable
Total land holding (ha)	Continuous variable
Cattle ownership	Continuous variable
Total Livestock Units	Continuous variable
Main crop grown	0 = Cereals; 1 = Vegetables; 2 = Cash crops
Dominant soil type on the farm	0 = Sandy; 1 = Clay; 2 = Loam; 3 = Sandy loam; 4 = Clay loam
Prior soil testing	0 = No; 1 = Yes
District located	0=Mopane (South Africa); 1= Masvingo (Zimbabwe)

Where: Logit (p_i) = log $(p_i)/(1-p_i)$, p_i = probability of event occurring, Y = intercept, C_0 = Coefficient of independent/predictor variable (Factor or Covariate), and X = independent/predictor variable.

The household and farm-level characteristics in Table 1 were chosen based on their influence on soil fertility management decisions in smallholder farming systems in most rural areas in Southern Africa. Socio-economic factors like gender, age, education, literacy, household labor, and income sources affect access to resources and decision-making psychic regarding organic soil amendments (OSA) and inorganic soil amendments (ISA) (Mponela et al., 2016; Mango et al., 2018; Kiprotich et al., 2023). Farm characteristics, such as landholding, livestock ownership, soil type, and prior soil testing, shape input choices and fertilizer use intensity (Quaye et al., 2021; Kihara et al., 2022). Location of farmer accounts for regional variations in climate, market access, and policy interventions influencing soil fertility practices (Quaye et al., 2021; Amede et al., 2022). These variables, therefore, delineate the economic, institutional, and biophysical drivers of soil fertility management in smallholder farming systems in Mopani and Masvingo districts.

3 Results

3.1 Demographic and socio-economic characteristics of farming households

Table 2 below compares the demographic and socioeconomic characteristics of households surveyed in Masvingo and Mopani districts. Mopani District had more female-headed households (58.5%), while Masvingo District had more male-headed households (61.7%). The literacy rate was higher for Masvingo (92.6%) compared to that of Mopani (62.2%), as shown in Table 2. Most of the household heads in Mopani and Masvingo were more than 51 years old. There were more household heads with no formal education in Mopani compared to Masvingo.

The average household size and the mean number of household members providing farm labor were significantly higher for Masvingo (6.02 and 4.11) than in Mopani (5.36 and 1.29). Table 2 indicates that more than half of the households were in the categories 2 to 5 household members for Mopani (51.8%) and 6 to 10 members for Masvingo (55.2%). In Mopani, most farmers (69.7%) earned below US$250 per month, while Masvingo had a significantly higher proportion (84.8%) (Table 2). Farming was the primary source of livelihood and income for Masvingo. In Mopani, there was a high dependence on other livelihood and income sources such as child and elderly grants, remittances, and informal employment (Table 2).

Land in both areas was held by the state, with traditional leaders acting as custodians who allocated land for establishing homesteads, fields, and grazing. The average landholding per household in Masvingo was significantly higher (2.1 ha) than in Mopani (0.75 ha) (Table 2). Table 2 also shows significant differences between Masvingo and Mopani districts in household farm assets such as scotch cart, water cart, water pump, cultivator, etc. ownership. Generally, the trend shows that farmers in Mopani district had more farm assets than those in Masvingo district, except for hoes and shovels, which were significantly higher in Masvingo. On average, households owned more chickens than any other livestock, followed by cattle in both Mopani and Masvingo (Table 2). Significant differences were only observed in the ownership of chickens and cattle, i.e., households in Mopani owned significantly more cattle than those in Masvingo, who owned significantly more chickens than those in Mopani. There were various uses of livestock mentioned in Mopane and Masvingo, respectively – source of income through sale (27.6% and 25.4%), draught power (1.1% and 31.5%), meat (39.7% and 31.7%), prestige (31.7% and 8%) and manure (0% and 3.3%).

3.2 Agronomic attributes and practices of farming households

Table 3 below summarizes the results of agronomic attributes and practices of farming households in Mopani and Masvingo

 10.3389/fagro.2025.1471052

TABLE 2 Demographic and socio-economic characteristics of households in Masvingo and Mopani.

Household (head) characteristics	Parameter	Masvingo (n=243)		Mopane (n=135)		χ2/t-stats	p-value
		Observed (%)	SD	Observed (%)	SD		
Age (years)	Mean 19-30 31-40 41-50 >51	51.39 80 (3.3) 41 (17.2) 73 (29.6) 122 (50.2)	12.27	52.33 – 36 (26.7) 36 (26.7) 63 (46.6)	15.53	0.645	0.518
Gender	Female Male	93 (38.3) 150 (61.7)		79 (58.5) 56 (41.5)		14.096	0.000***
Ability to read and write	Yes No	225 (92.6) 18 (7.4)		84 (62.2) 51 (37.8)		53.050	0.000***
Formal education (years)	Mean None 1-7 8-13 >13	8.09 8 (3.3) 100 (41.2) 129 (53.0) 6 (2.5)	3.15	8.07 30 (22.2) 13 (9.6) 80 (59.3) 12 (8.9)	5.05	0.033	0.973
Household size	Mean 1 2-5 6-10 >10	6.02 1 (0.4) 99 (40.8) 134 (55.1) 9 (3.7)	2.05	5.36 1 (0.7) 70 (51.9) 64 (47.4) –	1.94	3.042	0.002**
Household labor – members providing farm labor	Mean 0 1-5 6-10 >10	4.11 – 201 (82.7) 41 (16.9) 1 (0.4)	1.69	1.29 32 (23.7) 102 (75.6) 1 (0.7) –	1.12	15.784	0.000***
Average number of livestock and poultry ownership	Cattle Donkeys Goats Pigs Sheep Chickens	7.08 (75.3) 3.52 (8.6) 6.54 (50.2) 3.67 (6.17) 3.33 (1.23) 13.29 (39.9)	3.68 2.20 4.16 2.29 1.53 5.46	9.33 (42.2) 5.33 (2.2) 5.55 (21.5) 4.21 (21.5) – 10.91 (40.7)	6.62 0.58 2.08 2.85 – 6.29	3.271 1.389 1.241 0.635 – 2.441	0.001** 0.178 0.216 0.528 – 0.015***
Main livelihood source	Farming Formal employment Other	227 (93.4) 3 (1.2) 13 (5.3)		11 (8.1) 42 (31.1) 82 (60.7)		271.233	0.000***
Main income source	Crops and livestock Other	105 (43.2) 138 (56.8)		16 (11.9) 119 (88.1)		39.211	0.000***
Household monthly income (US$)	<100 101-250 251-500 >500	110 (45.3) 96 (39.5) 33 (13.6) 4 (1.6)		48 (35.6) 46 (34.1) 25 (18.5) 16 (11.9)		23.389	0.000***
House ownership	None Brick cottage Brick thatched huts Big house – tiles, asbestos, or zinc roof Pole and dagga	2 (0.8) 51 (21.0) 137 (56.4) 35 (14.4) 18 (7.4)		48 (35.6) 32 (23.7) 42 (31.1) 12 (8.9) 1 (0.7)		11.454	0.010**
Landholding (ha)	Arable land	2.10 (99.2)	1.57	0.76 (90.4)	3.63	4.893	0.000***
Average number of agricultural farm assets owned	Tractor Scotch cart Water cart Water pump Plough Cultivator Hoes Shovel Knapsack sprayers	0.00 (60.1) 0.65 (83.1) 0.33 (63.4) 0.03 (61.7) 0.89 (92.6) 0.26 (68.3) 6.46 (99.2) 1.99 (96.7) 0.68 (74.9)	0.00 0.52 0.48 0.16 0.54 0.44 2.97 1.00 0.79	1.20 (3.7) 1.33 (2.2) 1.00 (2.2) 1.00 (7.4) 1.00 (3.7) 1.00 (3.7) 2.71 (94.1) 1.53 (91.1) 1.44 (6.6)	0.45 0.58 0.00 0.00 0.00 0.00 2.96 1.00 1.01	36.008 2.257 2.411 18.985 0.456 3.759 11.519 4.113 2.823	0.000*** 0.025** 0.017** 0.000*** 0.648 0.000*** 0.000*** 0.000*** 0.005***

Figures in parentheses are percentages in that category. Significance levels *< 0.10, **< 0.05, ***< 0.01

TABLE 3 Agronomic attributes and practices of farming households in Masvingo and Mopani.

Variable	Parameter	Masvingo (n=243)	Mopane (n=135)	χ2 stats	p-value
		Observed (%)	Observed (%)		
Main crop grown	Cereals Vegetables Cash crops	225 (92.6) 4 (1.6) 14 (5.8)	107 (79.3) 28 (20.7) –	46.912	0.000***
Dominant soil type on the farm	Sandy Clay Loam Sandy loam Clay loam	26 (10.7) 8 (3.3) 38 (15.6) 127 (52.3) 44 (18.1)	– – 36 (26.7) 87 (64.4) 12 (8.9)	31.533	0.000***
Soil fertility indicators	Soil color Soil texture/structure Crop condition Response to inputs Good drainage Crop yield	68 (28.0) 20 (8.2) 18 (7.4) – – –	15 (11.1) 39 (28.9) 102 (75.6) 18 (13.3) 9 (6.7) 34 (25.2)	339.000	0.000***
Prior soil testing	Yes No	13 (5.3) 230 (94.7)	9 (6.7) 126 (93.3)	0.274	0.600
Types of organic soil amendments (OSA) used	Livestock manure Compost Vermicompost Leaf litter Green manure Anthill soil Biochar Ash	157 (64.6) 75 (30.9) 13 (5.3) 20 (8.2) 1 (0.4) 2 (0.8) 1 (0.4) 1 (0.4)	31 (23.0) – – 3 (2.2) 1 (0.7) – – –	26.872	0.006***
Types of inorganic soil amendments (ISA) used	Compound AN Liquid AN Urea	201 (82.3) 207 (85.2) 5 (2.1) 5 (2.1)	7 (5.2) – 10 (7.4) 2 (1.5)	20.591	0.001***
Quantities of organic soil amendments (OSA) applied per hectare	=<200 kg 201–500 kg 501–1000 kg 1001–3000 kg >3000 kg	16 (6.6) 126 (51.9) 41 (16.9) 31 (12.8) 20 (8.2)	20 (14.8) 6 (4.4) 4 (3.0) 3 (2.2) 2 (1.5)	209.297	0.000***
Quantities of inorganic soil amendments (ISA) applied	=<50 kg 51–100 kg 101–150 kg 151–250 kg >250 kg	4 (1.6) 42 (17.3) 86 (35.4) 78 (32.1) 22 (9.1)	41 (30.4) 52 (38.5) 2 (1.5) 1 (0.7) 1 (0.7)	288.899	0.000***

Figures in parentheses are percentages in that category. Significance levels *< 0.10, **< 0.05, ***< 0.01

districts. A significantly higher proportion of farmers in Masvingo (92.6%) grew cereals as their main crop compared to those in Mopani (79.3%) ($p<0.05$). At the same time, a significantly higher proportion of farmers in Mopani (20.7%) grew vegetables as their main crop than those in Masvingo (1.6%). Most farmers in Mopani grew vegetables (98.5%) and field crops (94.4%) on less than one hectare. In Masvingo, 84.1% and 40.4% of farmers grew vegetables and field crops on less than one hectare, respectively. In comparison, 14.2% and 31.2% grew vegetables and field crops between one and two hectares, and 1.7% and 10.4% grew between two and three hectares, respectively. Almost 18% of the farmers grew field crops on at least three hectares. Farmers in both Masvingo (52.3%) and Mopani (64.4%) districts reported sandy loam as the most dominant soil type. Though there were no significant differences between Masvingo and Mopani, at least 90% of the farmers surveyed in both districts had never conducted soil tests to determine the soil fertility status of their fields (Table 3). However, farmers used certain indicators to determine the fertility or productive capacity of their soils. Farmers in Masvingo district nonetheless identified fewer soil fertility indicators than those in Mopani district. The observed differences in the soil fertility indicators, such as soil color, soil texture, soil structure, and crop yields, were significantly different between the two sites ($p<0.05$).

A range of OSAs were applied for field and vegetable crops, with livestock manure being popular in both areas and among field crops. There was no use of biochar, compost, vermi-compost, ashes,

TABLE 4 Binary logistic regression model results of the determinants of the use of organic and inorganic soil amendments.

Variable	Use of organic soil amendments				Use of inorganic soil amendments			
	Coefficient	Odds ratio	SE	p>|z|	Coefficient	Odds ratio	SE	p>|z|
District located	2.15	8.62	0.562	0.000 ***	5.08	160.55	0.988	0.000 ***
Gender	0.13	1.14	0.319	0.689	-0.26	0.77	0.545	0.634
Age	-0.01	0.99	0.015	0.802	-0.02	0.98	0.026	0.466
Years of formal education	-0.11	0.89	0.061	0.077 *	0.05	1.05	0.102	0.629
Ability to read and write	0.15	1.16	0.593	0.805	0.10	1.11	0.992	0.917
Household labor	-0.08	0.92	0.095	0.400	0.34	1.41	0.174	0.050 *
Main livelihood source	-0.98	0.37	0.246	0.000 ***	-0.38	0.69	0.419	0.371
Main income source	0.50	1.64	0.183	0.007 ***	0.41	1.50	0.340	0.232
Monthly income	0.26	1.30	0.205	0.200	0.39	1.48	0.322	0.226
Scotch carts owned	0.44	1.56	0.391	0.256	0.19	1.21	0.670	0.775
Total landholding	-0.04	0.96	0.057	0.454	0.45	1.56	0.287	0.121
Main crop grown	-0.66	0.52	0.323	0.042 **	-1.49	0.23	0.643	0.020 **
Cattle owned	0.52	1.68	0.169	0.002 ***	-0.53	0.59	0.308	0.087 *
Total Livestock Units	-0.39	0.68	0.153	0.010 **	0.57	1.77	0.286	0.047 **
Dominant soil type	-0.15	0.86	0.173	0.391	0.56	1.76	0.272	0.039 **
Prior soil testing	-0.63	0.53	0.624	0.311	1.88	6.54	1.172	0.109
_cons	0.46	1.58	1.346	0.733	-5.27	0.01	2.296	0.022 **
Number of obs LR $chi^2(16)$ Prob > chi^2 Log-likelihood Pseudo R^2	377 184.21 0.0000 -152.624 0.376				377 355.06 0.0000 -63.347 0.737			

Significance levels > 0.10 not significant, *< 0.10 **< 0.05, ***< 0.01; Odds ratio< 1 indicates negative relationship, while ≥ 1 indicates positive relationship.

and anthill soil as OSA in the Mopani district. Table 3 reveals that the quantity of OSA used by most farmers in Mopani district was less than 200 kg per year. For Masvingo district, most OSA users were in the 201–500 kg application category.

In terms of inorganic fertilizers (ISA), about 54% of the farmers in Masvingo district used quantities below 150 kg (Table 3). At the same time, in Mopani district, the quantities of ISA used were significantly lower than in Masvingo district (p<0.05). In Masvingo district, 32.1% of the farmers applied between 150 and 250 kgs per year on field crops, and 9.1% used more than 250 kgs. In Mopani district, 30.4% and 38.5% of farmers used less than 50 kgs and between 50 and 100 kgs of fertilizer on field crops per year, while for vegetable crops, it was 50% and 33.3% of the farmers, respectively. Side dressing or banding was the most popular application method on both field and vegetable crops in Mopani district (54.5% and 66.7%, respectively) and Masvingo district (64.1% and 73%, respectively). Broadcasting in Mopani district was 45.5% and 13.3% for field and vegetable crops, respectively, and in Masvingo district was 31.4% and 21%. Fertigation through drip irrigation and foliar sprays was not common and only attained maximum frequencies of 13.3% and 6.7% in vegetable crops in Mopani district and Masvingo district, respectively.

3.3 Key household and farm-level drivers influencing farmers' use of organic and inorganic soil fertility amendments

The binary logistic regression model results in Table 4 reveal key household and farm-level factors influencing the use (non-use) of inorganic and organic soil fertility amendments (ISA and OSA). The overall model was highly significant (p< 0.0001) for both soil amendments, with pseudo R^2 values of 0.737 for ISA and 0.376 for OSA models, indicating strong explanatory power for both models. In addition, the Hosmer-Lemeshow goodness of fit test was non-significant (p>0.05), indicating that the model was a good fit for the data. The results indicate that 6 and 4 out of the 16 variables used in the binary logistic regression significantly influenced the use of OSA and ISA at the 95% confidence interval, respectively.

The results reveal that farmers' location or district significantly affected the use of both ISA and OSA (p< 0.01), with farmers in Masvingo district more likely to adopt soil amendments than in Mopani district. Farmers with more cattle were 1.68 times more likely to use OSA (p< 0.01) and 0.59 times more likely to use ISA. Households with more total livestock units (TLU) were 1.77 times more likely to use ISA and 0.68 times more likely to use OSA

TABLE 5 Ordered logistic regression results of the determinants of the quantity of inorganic and organic soil amendments used.

Variable	Quantity of organic soil amendments				Quantity of inorganic soil amendments			
	Coefficient	Odds ratio	SE	p>|z|	Coefficient	Odds ratio	SE	p>|z|
District located	2.52	12.40	0.478	0.000 ***	5.11	165.23	0.614	0.000 ***
Gender	0.25	1.28	0.223	0.268	0.34	1.41	0.250	0.169
Age	0.01	1.01	0.010	0.184	0.02	1.02	0.011	0.162
Years of formal education	0.03	1.03	0.042	0.511	0.05	1.05	0.045	0.250
Ability to read and write	0.42	1.52	0.423	0.322	1.08	2.95	0.500	0.030 **
Household labor	-0.08	0.92	0.066	0.216	0.02	1.02	0.075	0.782
Main livelihood source	-0.66	0.52	0.222	0.003 ***	-0.40	0.67	0.247	0.105
Main income source	0.17	1.18	0.119	0.163	0.23	1.26	0.129	0.070 *
Monthly income	-0.27	0.76	0.150	0.070 *	0.60	1.83	0.178	0.001 ***
Scotch carts owned	0.61	1.85	0.247	0.013 **	0.07	1.07	0.255	0.799
Total landholding	-0.01	0.99	0.048	0.861	0.36	1.43	0.098	0.000 ***
Main crop grown	0.49	1.64	0.257	0.055 *	-0.36	0.70	0.279	0.195
Cattle owned	0.32	1.38	0.122	0.009 ***	-0.37	0.69	0.130	0.004 ***
Total Livestock Units	-0.19	0.83	0.110	0.090 *	0.38	1.46	0.118	0.001 ***
Dominant soil type	-0.25	0.78	0.107	0.018 **	0.27	1.31	0.116	0.019 **
Prior soil testing	-0.12	0.88	0.476	0.793	1.19	3.28	0.510	0.020 **
Number of obs LR $chi^2(16)$ Prob > chi^2 Log-likelihood Pseudo R^2	377 281.99 0.0000 -453.988 0.237				377 444.82 0.0000 -360.617 0.382			

Significance levels > 0.10 not significant, *< 0.10 **< 0.05, ***< 0.01; Odds ratio< 1 indicates negative relationship, while ≥ 1 indicates positive relationship.

(p<0.05). The number of household members providing farm labor had a significant positive effect on using ISA. The primary income source (crop and livestock sales) was 1.64 times likely to encourage the use of OSA. The main crop grown was 0.23 times and 0.52 times more likely to discourage the use of ISA and OSA, respectively. Years of formal education had a marginally significant negative effect on the use of OSA (p< 0.10), with additional years of schooling reducing chances of OSA by 11%. Nonetheless, education did not significantly impact the use of ISA. The primary livelihood source had a significant negative influence on OSA use only (p< 0.01) and limited the chances of OSA use by 63%. Soil types other than sandy soils significantly encouraged the use of ISA by 76% (p<0.05).

3.4 Key household and farm-level drivers of intensity of quantities of organic and inorganic soil fertility amendments used

The ordered logistic regression results in Table 5 show the determinants of the quantity of inorganic (ISA) and organic soil amendments (OSA) used. The overall model was very significant (p< 0.0001), with pseudo-R^2 values of 0.237 for ISA and 0.382 for OSA, indicating moderate explanatory power. The Brant test, which checks the proportional odds assumption, was not significant (p>0.05). This shows that the proportional odds assumption was not violated and that the model was fit for the data. The results show that 5 and 8 out of the 16 variables used in the ordered logistic regression significantly influenced the quantity of OSA and ISA used at the 95% confidence interval, respectively.

Similar to the binary logistic regression results, the farmer's district or location significantly influenced the quantity of ISA and OSA used (p< 0.01). Thus, farmers in Masvingo were more likely to use more quantities of both ISA and OSA than those in Mopani. The monthly income of farmers significantly enhanced their use of more ISA quantities by 83% despite limiting the OSA quantities used by a factor of 0.76. The primary income source (crop and livestock sales) was positively and significantly associated with the use of larger quantities of ISA. The number of cattle owned, similar to the ownership of scotch carts, had a significant positive influence on OSA quantities used by farmers. However, the number of cattle owned had a significant negative influence on ISA quantities used. In other words, farmers with more cattle were 1.38 times more likely to use more OSA quantities but 31% less likely to use more ISA quantities. Larger total landholding significantly encouraged farmers to use more ISA by 43%, but limited the quantities of OSA by 1% (not significant). Farmers with more cattle applied significantly (1.38 times) more quantities of OSA (p< 0.01). However, larger total livestock units significantly enhanced the quantities of ISA used by 46% (p< 0.05).

Farmers who had tested their soils had significantly more chances (3.28 times) of using more ISA quantities, but were less likely to use more OSA quantities, though this was not significant. The ability to read and write significantly encouraged farmers to use more quantities of ISA. The dominant soil type on the farm had a significant negative influence on OSA quantities used and a significant positive influence on ISA quantities used by farmers. Therefore, soil types other than sandy soils discouraged the use of OSA by 22% while they encouraged the use of ISA by 31% ($p< 0.05$). The primary livelihood source (farming) limited the quantity of ISA and OSA used, but the effect was only significant for OSA ($p< 0.01$). The results suggest that households depending on farming were 48% less likely to use more quantities of OSA. The other significantly positive factors are the farmer's district, primary income source, monthly income, total holding, total livestock units for ISA, the farmer's location, scotch carts owned, and the number of cattle owned for OSA. Significant negative drivers are the main crop grown and cattle owned for ISA and total land holding and total livestock units for OSA.

4 Discussion

Smallholder farming systems play a critical role in enhancing the food security and livelihoods of many rural communities in southern Africa, where the majority of the people depend on agriculture as a primary source of income and sustenance (Shikuku et al., 2017; Musokwa and Mafongoya, 2021; Khonje et al., 2022). This study investigated the complex interplay of socio-economic factors and farmer practices in influencing the adoption of soil fertility amendments among smallholder farming communities in Mopani district, South Africa, and Masvingo district, Zimbabwe. The results of the binary and ordered logistic regression models provide valuable insights into the barriers and enablers of adopting and intensifying organic and inorganic soil fertility amendments among smallholder farmers in Masvingo and Mopani districts, particularly, and smallholder farming areas in SSA generally. The findings underscore the critical role of socio-economic characteristics, farm attributes, and institutional factors in shaping smallholder farmers' decision-making psychic regarding soil fertility management. They also align with the principles of Integrated Soil Fertility Management (ISFM), which emphasizes a combination of organic and inorganic inputs to improve soil health and crop productivity (Gnahoua et al., 2023). A discussion of the major drivers of use and intensity of soil fertility amendments provides critical insights that inform policies and farmer support initiatives aimed at promoting sustainable soil fertility management.

4.1 Household and farm-level determinants of the use of organic and inorganic soil fertility amendments

The binary logistic regression model results indicate that the farmer's location, that is, the district, significantly influences the use of both organic and inorganic soil fertility amendments. This suggests that regional differences in agroecological conditions, infrastructure such as roads, communication networks, markets, etc, and the availability of extension services play a critical role in determining farmers' soil fertility management decisions as observed in other studies in Sub-Saharan Africa (Pretty and Bharucha, 2014). The increase in local-level studies in recent years shows the importance of location and context in sustainability studies. For instance, Gnahoua et al. suggest a wide variation of soil fertility management practices across regions (Gnahoua et al., 2023). This was attributed to differences in land degradation severity, market access, and government support programs. In this study, Masvingo district in Zimbabwe and Mopani district in South Africa, though agroecologically similar, also vary in terms of prevailing government policies and programs aimed at smallholder farmers. In Masvingo district, and Zimbabwe in general, smallholder farmers' support programs have mostly focused on improving the staple maize crop productivity (Kaponda and Chiwaridzo, 2024). This contrasts with the Mopani district, where the thrust of smallholder farmers was on vegetable production. The significant negative influence of crops grown on the use of both organic and inorganic fertilizers supports the above arguments, considering that the main crops grown in Mopani and Masvingo districts differed. In addition, this could either be a highlight of the challenges of input affordability and/or reliance on other practices of the ISFM approach, such as crop rotation and/or intercropping with legumes to manage soil fertility (Vanlauwe et al., 2010).

Years of formal education had a significant negative effect on the use of OSA. Smallholder farmers with more years of formal education were less likely to use organic fertilizers, potentially indicating a preference for alternative soil fertility management practices, consistent with findings by (Marenya and Barrett, 2007). While these findings are consistent with those of Mugari et al (Mugari et al., 2020). who attributed the negative influence of formal education on the implementation of on-farm conservation measures to the acquisition of irrelevant or insufficient knowledge, this study offers a different insight. Educated individuals benefit from wider access to knowledge and better comprehension of soil fertility management information, better schooling, and the ability to read as well as comprehend and choose from wider soil fertility amendments at their disposal. Given the diverse practices in the ISFM approach, it is possible that smallholder farmers implement alternative soil fertility amendments, potentially reducing reliance on conventional inorganic fertilizers (Marenya and Barrett, 2007). Kiprotich et al. also argues that adoption of integrated soil fertility management technologies, including those not considered in this study, is significantly intensified by formal agricultural training (Kiprotich et al., 2023). Nonetheless, targeted agricultural education remains critical to enhance the holistic implementation of ISFM practices and other climate-smart agricultural practices (Lipper et al., 2014).

The negative influence of the main livelihood source on the use of OSA suggests that households whose primary livelihood is non-agricultural were less likely to invest in organic fertilizers. This aligns with studies by Lobley and Potter (2004), which found that part-time farmers often allocated fewer resources to intensive soil fertility management. Considering that most of the participants in this study were full-time smallholder farmers, this implies that they would invest more in practices that enhance soil health and, consequently, the productivity of their main livelihood source than their counterparts. When the actual income was considered, households earning more income were more inclined to use both organic and inorganic soil fertility amendments. This indicates that farmers could leverage their additional incomes and financial capacity to procure inorganic fertilizers. It is also possible that they invested their off-farm incomes in farming by improving their livestock herds, particularly cattle, a sign of wealth in many rural areas, thus having more access to livestock and organic manure (Pretty and Bharucha, 2014). The study shows a positive impact of household members providing farm labor on the use of ISA. Laekemariam and Kibret (2020) also contend that smallholder farmers regard the use of ISA as associated with higher returns and are therefore inclined to use more labor in their production activities, as the return per unit labor is expected to be high.

Studies have attributed low usage of chemical fertilizers among smallholder farmers to financial constraints and smaller livestock herds (Gnahoua et al., 2023). The findings of this research underscore the need for policies, programs, and projects that improve smallholder farm incomes and livestock herds to enhance their freedom to use their preferred soil fertility amendments. This can also allow them to explore other components of the ISFM approach, such as improved germplasm or implementing it holistically, as this would require financial capacity.

The significant positive influence of cattle ownership on the use of organic fertilizers is linked to the increased availability of manure as the cattle herd increases, while the negative preference for inorganic fertilizers is attributed to the availability of inexpensive cattle manure. Owning cattle is critical to improving household access to manure, a major component of organic soil fertility management in rural areas, and an alternative to chemical fertilizers, a trend supported by studies in mixed crop-livestock systems (Pretty and Bharucha, 2014; Gowing et al., 2020). Crop-livestock farming systems, particularly in Masvingo district, offered smallholder farmers animal manure and crop residues, which are critical components of OSA. As the total livestock units grew, the increased preference for inorganic fertilizers was mainly attributed to improved financial resources for affording expensive chemical fertilizers. Higher total livestock units, driven by more livestock ownership, have been linked to wealth and financial stability in many rural areas as farmers commercialize. This also necessitates higher nutrient inputs, such as inorganic fertilizers (Kassie et al., 2013). The smaller cattle herds owned by smallholder farmers in this study imply that chickens and goats considerably contributed to total livestock units. These, however, produce less manure compared to cattle, a similar concern raised by Tan et al (Tan et al., 2023). who reported that the use of livestock manure is intricately tied to the livestock density, which is a function of herd size and type of livestock owned. Nonetheless, surveyed farmers generated sufficient income from selling goats and chickens, which enabled them to purchase chemical fertilizers. The significant positive influence of cattle ownership and TLU on the use of OSA and ISA was consistent with ownership of scotch carts, which are critical as carrying devices for transporting manure and chemical fertilizers to the fields.

The adverse effect of prior soil testing on the use of organic soil amendments suggests that farmers who conducted soil tests perceived organic inputs as insufficient in addressing soil fertility deficiencies. This is supported by the very high odds of using inorganic fertilizers associated with prior soil testing. Farmers who tested their soil were more inclined to use inorganic fertilizers to supplement the specific deficient nutrients. Generally, soil testing is sporadic among smallholder farmers in Southern Africa (Nezomba et al., 2017). In order to effectively contribute to the holistic implementation of ISFM practices, smallholder farmers need to be educated on the importance of soil testing by initiating soil health programs and providing subsidies that allow farmers to improve soil fertility. However, farmers with larger landholdings were less likely to use OSA and more likely to use ISA. Firstly, larger landholdings require significant quantities of OSA compared to ISA, yet farmers usually do not have enough OSA, partly due to smaller cattle herds and limited throughput. Secondly, applying OSA is very labor-intensive, cumbersome, and time-consuming. Surveyed smallholder farmers preferred using ISA despite it being relatively expensive compared to OSA. Several studies have shown that farmers are rational and usually make decisions to maximize resources at their disposal (Nezomba et al., 2017). Results further showed that the dominant soil type had a significant positive impact on the use of ISA. Smallholder farmers often applied inorganic fertilizers in response to their perception of the nutrient content of their soils. They often applied organic fertilizer where soils were weak and sandy, and minimal inorganic fertilizer where soils were heavy, such as loamy and clay soils (Vanlauwe et al., 2010).

4.2 Household and farm-level determinants of the intensity of quantities of inorganic and organic soil fertility amendments used

The ordered logistic regression model results revealed that the farmer's location (district) played a significant role in determining the quantity of both organic and inorganic amendments used. Regional variations in soil quality, extension support, and market access explain this variation (Tittonell and Giller, 2013). Soil quality was very diverse among smallholder farmers due to their varied soil fertility management regimes, including challenges of accessing suitable and quality soil fertility amendments (Namatsheve et al., 2021; Singh et al., 2022; Wawire et al., 2023). Access to extension services is critical for farmers in rural areas, particularly in Zimbabwe. Households in Zimbabwe's rural farming areas are sparsely located, limiting frequent access to regular extension services, unlike in South Africa (Chipomho et al., 2022). Farmers in Mopani district mainly grew vegetables, which are in high demand, while farmers in Zimbabwe mostly focused on the staple maize. South Africa's rural areas have better infrastructure and are more accessible than Zimbabwe's rural farming areas, presenting market access challenges. These differences underscore the importance of the location of farmers, even within the same study area, in determining the quantities of organic and inorganic amendments used, and the actual decision to use them.

Estimation results further showed that the ability to read and write positively impacted the use of ISA. With information readily accessible, high literacy rates, and significant usage of internet services, smallholder farmers were able to read some of the results of intense inorganic fertilizer use worldwide (Tan et al., 2023). Consequently, farmers became more inclined to want to intensify the use of inorganic fertilizers. The negative influence of the main livelihood source on the quantity of organic soil amendments used suggests that where returns are higher, farmers tend to reduce the quantity of OSA used. Hailu and Mazegebo (Hailu and Mezegebo, 2021) have shown that the more returns and livelihood sources, the less reliance on OSA, as it is scarce and labor-intensive. This does not imply that full-time smallholder farmers invested adequately in soil fertility amendments and other inputs that enhanced smallholder crop and livestock productivity. Despite persistent government initiatives and programs supporting smallholder farmers, their productivity has remained very low (Quaye et al., 2021). Progress has, however, been registered in some cases, such as the *Pfumvudza/Intwasa* program in Zimbabwe (Tanyanyiwa et al., 2022). These gains, however, are not sustained. This indicates several underlying challenges facing smallholder farming systems in SSA that need a holistic approach. There is a need to go beyond just focusing on the farmer and farm level issues and consider institutional factors limiting smallholder farming systems' sustainability.

Farmers with off-farm income as the primary source of income were likely using more quantities of organic and inorganic soil amendments. It was, however, the actual monthly income that made the difference as it significantly enhanced the intensity of inorganic soil amendments at the expense of organic amendments, suggesting that inorganic inputs require more financial investments. In contrast, organic inputs depend mainly on the availability of livestock manure. Despite the sources, as farmers' income increases, it enhances their financial stability and enables them to apply more chemical fertilizers (Adem et al., 2023). The use of inorganic amendments is consistent with the significant influence of prior soil testing, which increased the use of inorganic fertilizers. Soil testing allowed farmers to know the actual soil nutrient deficiency and the quantities of chemical fertilizers they should apply. The negative influence of prior soil testing on the use of organic fertilizers suggests that farmers were not sure of the nutrient content and the quantities required to address the deficiencies. While the use of organic soil amendments is being promoted as a sustainable practice compared to chemical fertilizers, the poor quality of organic soil amendments in most rural areas limits their effectiveness (Epper et al., 2020). Ownership of scotch carts, an indicator of asset wealth and transport capacity, was positively associated with organic amendment quantities. Farmers with scotch carts could carry bulky livestock manure to their fields. Hailu and Mazegebo (Hailu and Mezegebo, 2021) also revealed that access to farm equipment enhanced soil fertility management efforts.

Livestock ownership remained a key determinant, with cattle and total livestock units significantly influencing the quantity of organic and inorganic fertilizers. As the number of cattle and quantity of cattle manure increased, farmers could apply more OSA. The negative influence on OSA quantities used as total livestock units increases, suggesting that as TLU increases, farmers become financially stable to afford chemical fertilizers. The significant positive influence of TLU on the use of ISA is consistent with these findings. There is an obvious association between TLU and the wealth status of households. This underscores the role of livestock in farm nutrient cycling (Gowing et al., 2020). The dominant soil type had opposite effects on organic and inorganic amendments, suggesting that farmers tailor their soil fertility strategies based on perceived soil characteristics (Chipomho et al., 2022). This is consistent with the positive influence of farmers' literacy, which allows them to acquire farming information and make rational and sustainable decisions to enhance their productivity. Finally, prior soil testing had a positive impact on intensifying ISA and reducing the use of OSA. Heidenreich et al (Heidenreich et al., 2022). argue that soil testing is associated with commercial farming and reduced reliance on OSA.

5 Conclusions and implications

This study investigated the complex interplay of socio-economic factors, agricultural practices, and the adoption of soil fertility amendments among smallholder farmers in Masvingo District, Zimbabwe, and Mopani District, South Africa. The influence of factors analyzed varied between the two districts, underscoring the importance of localized strategies and interventions to promote sustainable agricultural practices. Socio-economic factors, including income levels, livelihood sources, and total land holdings, emerged as key determinants of OSA and ISA utilization. These factors were found to significantly impact smallholder farmers' use and the intensification of these soil amendments. Farm-level characteristics and farmer practices relating to crops grown, livestock ownership, and soil testing influenced the use of specific soil amendments. These findings underscore the multifaceted nature of smallholder farming systems, where crop and livestock management are intricately linked to soil fertility management decisions.

The findings of this study have several important implications. The findings reveal a need for targeted policy interventions to promote balanced soil fertility management strategies among smallholder farmers. The strong influence of the farmer's location on soil fertility amendment decisions suggests that region-specific programs tailored to local contexts and farming practices would be more effective than blanket policies. This is also true for farmers and farms in the same locality, which may also be diverse. The positive influence of farmers' ability to read and write needs to be leveraged by strengthening farmer training programs on integrated soil fertility management techniques. Once farmers understand the "why", rather than the "what", of integrated soil fertility management, it would influence its holistic implementation in smallholder farming communities. Thereafter, it would be critical to improve smallholder farmers' financial stability through subsidies, microcredit schemes, and input voucher programs to enable them to invest in the different components of the ISFM approach.

Lastly, the negative effect of soil testing on the use of organic soil fertility amendments suggests a need to integrate soil fertility assessments with extension services that promote both organic and inorganic options. In this regard, livestock integration programs could also be expanded to improve manure availability and utilization, particularly among farmers with smaller herd sizes. Overall, the results emphasize the importance of holistic approaches that combine financial, educational, and institutional support to enhance sustainable soil fertility management in smallholder farming systems. Addressing these limitations and research gaps could help design more effective policies and strategies for improving soil fertility management and sustainable agricultural productivity in smallholder farming systems.

6 Limitations of the study and future research directions

This study has some limitations, particularly focusing only on some components of the ISFM approach and leaving others, such as crop rotation, agroforestry, residue management, and improved germplasm. The study was, however, informed by the prevailing farmer practices at the two study sites. The other components of the ISFM approach presented serious data availability and collection challenges. The cross-sectional study and nature of the data presented challenges, including the inability to capture seasonal dynamics and long-term changes in soil fertility management. Future research needs to scale up this study to other agroecological regions and expand the ISFM approach's scope beyond just organic and inorganic soil fertility amendments considered in this study. Future studies could also consider incorporating longitudinal studies, integrating biophysical data from field trials, assessing policy interventions, and examining farmer decision-making processes to comprehend smallholder farmers' soil fertility management decisions fully. The study also lacked a rigorous economic evaluation to quantify the benefits of using and intensifying OSA and ISA systems. The study showed the substitution effects between ISA and OSA but did not quantify these substitution effects.

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 studies involving humans were approved by University of Limpopo Ethics Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JB: Conceptualization, Formal Analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing, Project administration. STau: Conceptualization, Formal Analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing, Investigation, Software, Supervision. EM: Conceptualization, Formal Analysis, Methodology, Software, Visualization, Writing – review & editing, Validation. STat: Conceptualization, Formal Analysis, Investigation, Supervision, Validation, Visualization, Writing – review & editing, Methodology, Software. AZ: Formal analysis, Visualization, Writing – review & editing, Validation. WM: Formal analysis, Validation, Visualization, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The article processing charges were partly paid by the University of Limpopo.

Acknowledgments

We acknowledge the contribution of the extension workers and farmers in Mopani (South Africa) and Masvingo (Zimbabwe) districts who made this research a success with limited funding.

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.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Adem, M., Azadi, H., Spalevic, V., Pietrzykowski, M., and Scheffran, J. (2023). Impact of integrated soil fertility management practices on maize yield in Ethiopia. *Soil Tillage Res.* 227, 1–10. doi: 10.1016/j.still.2022.105595

Amede, T., Gashaw, T., Legesse, G., Tamene, L., Mekonen, K., Thorne, P., et al. (2022). Landscape positions dictating crop fertilizer responses in wheat-based farming systems of east african highlands. *Renew. Agric. Food Syst.* 37, S4–S16. doi: 10.1017/S1742170519000504

Archer, K. J., and Lemeshow, S. (2006). Goodness-of-fit test for a logistic regression model fitted using survey sample data. *Stata. J.* 6, 97–105. doi: 10.1177/1536867X0600600106

Asante, M., Ahiabor, B. D. K., and Atakora, W. K. (2020). Growth, nodulation, and yield responses of groundnut (Arachis hypogaea L.) as influenced by combined application of rhizobium inoculant and phosphorus in the Guinea savanna zone of Ghana. *Int. J. Agron.* 2020, 1–7. doi: 10.1155/2020/8691757

Asule, P. A., Musafiri, C. M., Nyabuga, G., Kiai, W., Ngetich, F. K., and Spurk, C. (2022). Determinants of soil fertility information needs and access among smallholder farmers in the central highlands of Kenya. *Commun. Soil Sci. Plant Anal.* 53, 1979–1998. doi: 10.1080/00103624.2022.2070190

Azuka, C. (2020). V; igue, A.M. Spatial variability of soil properties under different land uses in the koupendri catchment, Benin. *Spanish. J. Soil Sci.* 10, 45–64. doi: 10.3232/SJSS.2020.V10.N1.04

Chipomho, J., Tatsvarei, S., Parwada, C., Mashingaidze, A. B., Rugare, J. T., Mabasa, S., et al. (2022). Weed types and dynamics associations with catena landscape positions: smallholder farmers' Knowledge and perception in Zimbabwe. *Int. J. Agron.* 2022, 1–10. doi: 10.1155/2022/2743090

Cornish, P. S., Kumar, A., and Das, S. (2020). Soil fertility along toposequences of the east India plateau and implications for productivity, fertilizer use, and sustainability. *Soil* 6, 325–336. doi: 10.5194/soil-6-325–2020

Epper, C. A., Paul, B., Burra, D., Phengsavanh, P., Ritzema, R., Syfongxay, C., et al. (2020). Nutrient flows and intensification options for smallholder farmers of the lao uplands. *Agric. Syst.* 177, 1–13. doi: 10.1016/j.agsy.2019.102694

Gnahoua, J.-B. G., Ouattara, M. L. M. S., Coulibali, Z., Diomandé, L. B., and Soro, Y. R. (2023). Integrated soil fertility management: A promising pathway for sustainable intensification of smallholder cotton farming systems in côte d'Ivoire. *Asian J. Res. Crop Sci.* 8, 51–58. doi: 10.9734/AJRCS/2023/V8I1157

Gowing, J. W., Golicha, D. D., and Sanderson, R. A. (2020). Integrated crop-livestock farming offers a solution to soil fertility mining in semi-arid Kenya: evidence from marsabit county. *Int. J. Agric. Sustain.* 18, 492–504. doi: 10.1080/14735903.2020.1793646

Gunarathne, V., Senadeera, A., Gunarathne, U., Biswas, J. K., Almaroai, Y. A., and Vithanage, M. (2020). Potential of biochar and organic amendments for reclamation of coastal acidic-salt affected soil. *Biochar* 2, 107–120. doi: 10.1007/s42773-020-00036–4

Hailu, H. G., and Mezegebo, G. K. (2021). Estimating the impact of inorganic fertilizer adoption on sesame productivity: evidence from humera, tigray, Ethiopia. *Cogent. Food Agric.* 7, 1–14. doi: 10.1080/23311932.2021.1933798

Heidenreich, A., Grovermann, C., Kadzere, I., Egyir, I. S., Muriuki, A., Bandanaa, J., et al. (2022). Sustainable intensification pathways in sub-saharan africa: assessing eco-efficiency of smallholder perennial cash crop production. *Agric. Syst.* 195, 1–12. doi: 10.1016/j.agsy.2021.103304

Kaponda, T., and Chiwaridzo, O. T. (2024). "Enhancing food security through sustainable agriculture: A case study of the pfumvudza/intwasa program in Zimbabwe," in *Sustainable practices for agriculture and marketing convergence* (IGI Global, New York), 251–280, ISBN: .

Kassie, M., Jaleta, M., Shiferaw, B., Mmbando, F., and Mekuria, M. (2013). Adoption of interrelated sustainable agricultural practices in smallholder systems: evidence from rural Tanzania. *Technol. Forecast. Soc Change* 80, 525–540. doi: 10.1016/J.TECHFORE.2012.08.007

Khonje, M. G., Nyondo, C., Chilora, L., Mangisoni, J. H., Ricker-Gilbert, J., and Burke, W. J. (2022). Exploring adoption effects of subsidies and soil fertility management in Malawi. *J. Agric. Econ.* 73, 874–892. doi: 10.1111/1477-9552.12486

Kihara, J., Manda, J., Kimaro, A., Swai, E., Mutungi, C., Kinyua, M., et al. (2022). Contributions of integrated soil fertility management (ISFM) to various sustainable intensification impact domains in Tanzania. *Agric. Syst.* 203, 103496. doi: 10.1016/j.agsy.2022.103496

Kiprotich, S., Mogaka, H., Ndirangu, S. N., and Onyari, C. N. (2023). Determinants of adoption and adoption intensity of integrated soil fertility management technologies among sorghum farmers in upper eastern Kenya. *Soil Use Manage.* 40 (1), 1–17. doi: 10.1111/sum.12958

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

Laekemariam, F., and Kibret, K. (2020). Explaining soil fertility heterogeneity in smallholder farms of southern Ethiopia. *Appl. Environ. Sci.* 2020, 1–16. doi: 10.1155/2020/6161059

Laub, M., Corbeels, M., Ndungu, S. M., Mucheru-Muna, M. W., Mugendi, D., Necpalova, M., et al. (2023). Combining manure with mineral N fertilizer maintains maize yields: evidence from four long-term experiments in Kenya. *F. Crop Res.* 291, 1–15. doi: 10.1016/j.fcr.2022.108788

Lewoyehu, M., Alemu, Z., and Adgo, E. (2020). The effects of land management on soil fertility and nutrient balance in kecha and laguna micro watersheds, amhara region, northwestern, Ethiopia. *Cogent. Food Agric.* 6 (1), 1–16. doi: 10.1080/23311932.2020.1853996

Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., et al. (2014). Climate-smart agriculture for food security. *Nat. Clim. Change* 4, 1068–1072. doi: 10.1038/nclimate2437

Lobley, M., and Potter, C. (2004). Agricultural change and restructuring: recent evidence from a survey of agricultural households in england. *J. Rural Stud.* 20, 499–510. doi: 10.1016/J.JRURSTUD.2004.07.001

Manatsa, D., Mushore, T. D., Gwitira, I., Wuta, M., Chemura, A., Shekede, M. D., et al. (2020). *Revision of Zimbabwe's agro-ecological zones* (Zimbabwe Government Printers: Harare).

Mango, N., Makate, C., Tamene, L., Mponela, P., Ndengu, G., Mango, N., et al. (2018). Adoption of small-scale irrigation farming as a climate-smart agriculture practice and its influence on household income in the chinyanja triangle, southern africa. *Land* 7, 49. doi: 10.3390/land7020049

Marenya, P. P., and Barrett, C. B. (2007). Household-level determinants of adoption of improved natural resources management practices among smallholder farmers in western Kenya. *Food Policy* 32, 515–536. doi: 10.1016/J.FOODPOL.2006.10.002

Mkuhlani, S., Mupangwa, W., MacLeod, N., Gwiriri, L., Nyagumbo, I., Manyawu, G., et al. (2020). Crop-livestock integration in smallholder farming systems of goromonzi and murehwa, Zimbabwe. *Renew. Agric. Food Syst.* 35, 249–260. doi: 10.1017/S1742170518000558

Mogaka, B. O., Bett, H. K., and Ng'ang'a, S. K. (2021). Socioeconomic factors influencing the choice of climate-smart soil practices among farmers in western Kenya. *J. Agric. Food Res.* 5, 1–12. doi: 10.1016/j.jafr.2021.100168

Mponela, P., Tamene, L., Ndengu, G., Magreta, R., Kihara, J., and Mango, N. (2016). Determinants of integrated soil fertility management technologies adoption by smallholder farmers in the chinyanja triangle of southern africa. *Land. Use Policy* 59, 38–48. doi: 10.1016/J.LANDUSEPOL.2016.08.029

Mugari, E., Masundire, H., and Bolaane, M. (2020). Adapting to climate change in semi-arid rural areas: A case of the limpopo basin part of Botswana. *Sustainability* 12, 8292. doi: 10.3390/su12208292

Mugwe, J., Ngetich, F., and Otieno, E. O. (2019). Integrated soil fertility management in sub-saharan africa: evolving paradigms toward integration. In: Leal Filho, W., Azul, A., Brandli, L., Özuyar, P., and Wall, T. (eds) *Zero Hunger Encyclopedia of the UN Sustainable Development Goals*, Springer, Cham. doi: 10.1007/978-3-319-69626-3_71-1

Mugwe, J., and Otieno, E. O. (2021). Integrated Soil Fertility Management Approaches for Climate Change Adaptation, Mitigation, and Enhanced Crop Productivity. In: Leal Filho, W., Luetz, J., Ayal, D. (eds). *Handbook of Climate Change Management.* Springer, Cham. 1–22. doi: 10.1007/978-3-030-22759-3_325-1

Musokwa, M., and Mafongoya, P. (2021). Pigeonpea yield and water use efficiency: A savior under climate change-induced water stress. *Agronomy-Basel* 11, 1–14. doi: 10.3390/agronomy11010005

Mutsamba, E. F., Nyagumbo, I., and Mupangwa, W. (2020). Forage and maize yields in mixed crop-livestock farming systems enhancing forage and maize yields in mixed crop-livestock systems under conservation agriculture in sub-humid Zimbabwe. *NJAS-Wageningen. J. Life Sci.* 92, 1–10. doi: 10.1016/j.njas.2019.100317

Mwakidoshi, E. R., Gitari, H. H., Muindi, E. M., Wamukota, A., Seleiman, M. F., and Maitra, S. (2023). Smallholder farmers' Knowledge on the use of bioslurry as a soil fertility amendment input for potato production in Kenya. *L. Degrad. Dev.* 34 (8), 2214–2227. doi: 10.1002/ldr.4601

Myeni, L., and Moeletsi, M. E. (2020). Factors determining the adoption of strategies used by smallholder farmers to cope with climate variability in the eastern free state, South Africa. *Agriculture-Basel.* 10 (9), 1–16. doi: 10.3390/agriculture10090410)

Namatsheve, T., Chikowo, R., Corbeels, M., Mouquet-Rivier, C., Icard-Verniere, C., and Cardinael, R. (2021). Maize-cowpea intercropping as an ecological intensification option for low input systems in sub-humid Zimbabwe: productivity, biological N-2-fixation and grain mineral content. *F. Crop Res.* 263, 1–12. doi: 10.1016/j.fcr.2020.108052

Ndengu, G., Mponela, P., Chataika, B., Desta, L. T., Chirwa, R., and Sileshi, G. G. (2022). Effect of combining organic manure and inorganic fertilizers on maize-bush bean intercropping. *Exp. Agric.* 58, 1–12. doi: 10.1017/S0014479722000102

Ndlovu, E., Prinsloo, B., and le Roux, T. (2020). Impact of climate change and variability on traditional farming systems: farmers' Perceptions from south-west, semi-arid Zimbabwe. *Jàmbá J. Disaster. Risk Stud.* 12, 2072–2845. doi: 10.4102/JAMBA.V12I1.742

Nezomba, H., Mtambanengwe, F., Tittonell, P., and Mapfumo, P. (2017). Practical assessment of soil degradation on smallholder farmers' Fields in Zimbabwe: integrating local knowledge and scientific diagnostic indicators. *CATENA* 156, 216–227. doi: 10.1016/J.CATENA.2017.04.014

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

Pretty, J., and Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. *Ann. Bot.* 114, 1571–1596. doi: 10.1093/AOB/MCU205

Quaye, A. K., Doe, E. K., Amon-Armah, F., Arthur, A., Dogbatse, J. A., and Konlan, S. (2021). Predictors of integrated soil fertility management practice among cocoa farmers in Ghana. *J. Agric. Food Res.* 5, 100174. doi: 10.1016/j.jafr.2021.100174

Shikuku, K. M., Winowiecki, L., Twyman, J., Eitzinger, A., Perez, J. G., Mwongera, C., et al. (2017). Smallholder farmers' Attitudes and determinants of adaptation to climate risks in east africa. *Clim. Risk Manage.* 16, 234–245. doi: 10.1016/J.CRM.2017.03.001

Singh, U., Choudhary, A. K., Varatharajan, T., and Sharma, S. (2022). Agricultural management practices affect the abundance of markers of phosphorus cycle in soil: case study with pigeonpea and soybean. *J. Soil Sci. Plant Nutr.* 22, 3012–3020. doi: 10.1007/s42729-022-00863-3

Stöckle, C. O., Donatelli, M., and Nelson, R. (2003). CropSyst, a cropping systems simulation model. *Eur. J. Agron.* 18, 289–307. doi: 10.1016/S1161-0301(02)00109-0

Tan, M., Hou, Y., Zhang, T., Ma, Y., Long, W., Gao, C., et al. (2023). Relationships between livestock density and soil phosphorus contents – county and farm level analyses. *Catena* 222, 106817. doi: 10.1016/j.catena.2022.106817

Tanyanyiwa, V. I., Kanyepi, T., and Katanha, A. (2022). Zimbabwe's pfumvudza agriculture programme—Reality or rhetoric? In: Leal Filho, W., Kovaleva, M., and Popkova, E. (eds) *Sustainable Agriculture and Food Security*. Springer, Cham. doi: 10.1007/978-3-030-98617-9_19

Tittonell, P., and Giller, K. E. (2013). When yield gaps are poverty traps: the paradigm of ecological intensification in african smallholder agriculture. *F. Crop Res.* 143, 76–90. doi: 10.1016/J.FCR.2012.10.007

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K. E., Merckx, R., Mokwunye, U., et al. (2010). Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook Agric.* 39 (1), 17–24. doi: 10.5367/000000010791169998

Wawire, A., Csorba, A., Zein, M., Rotich, B., Phenson, J., Szegi, T., et al. (2023). Farm household typology based on soil quality and influenced by socio-economic characteristics and fertility management practices in eastern Kenya. *Agronomy-Basel.* 13 (4), 1–22. doi: 10.3390/agronomy13041101

Williams, R. (2006). Generalized ordered logit/partial proportional odds models for ordinal dependent variables. *Stata. J.* 6 (1), 58–82. doi: 10.1177/1536867X0600600104

Zingore, S., Tittonell, P., Corbeels, M., van Wijk, M. T., and Giller, K. E. (2011). Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: A case from murewa district, Zimbabwe. *Nutr. Cycl. Agroecosystems.* 90, 87–103. doi: 10.1007/s10705-010-9414-0