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Research article

Determinants of land management technology adoptions by rural households in the Goyrie watershed of southern Ethiopia: Multivariate probit modeling estimation

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ABSTRACT

Land management technology (LMT) adoption is one of Ethiopia's crucial strategies to combat soil depletion and promote agricultural production. However, there is scant information concerning the intensity, interdependent nature, and households' decision to adopt multiple LMTs. Thus, the purpose of this study is to identify factors influencing households' decisions to adopt multiple LMTs and the intensity and interdependency of the technologies in the Goyrie watershed of southern Ethiopia. The data was collected from 291 randomly selected household heads, focus group discussion participants, and key informant interview respondents. The quantitative data was analyzed using descriptive statistics and econometric methods like multivariate probit and ordered probit modeling, while the qualitative data was presented through content analysis. The result indicated that more than half of respondents (67 %) applied one or two LMTs. The highest complementary effects were observed in mixed soil bunds with *desho* grasses and manure applications. However, soil bunds and fanya-juu, manure application and agroforestry showed interchangeability with one another. Sex, education, family size, landholding size, access to development agents and credit institutions, training, and village membership increased the probability of adopting multiple LMTs, whereas age, land rent, and crop sharing discouraged the likelihood of households' decisions to adopt LMT. The results of the ordered probit model revealed that village membership and contact with extension agents highly encouraged the intensity of LMT adoptions. Thus, policymakers and planners should consider social, institutional, human asset, and technological related factors to increase adoption rates and intensity of land management technologies.

1. Introduction

Despite increasing global attention to the threat on land degradation, the potential effects of sustainable integrated land management technologies have been discernible, especially in Sub-Saharan African countries [1]. Its effective application is crucial for attaining the United Nations (UN's) Sustainable Development Goals (SDGs), such as preventing desertification, rehabilitating eroded

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lands, reducing soil erosion, addressing climate change, and preserving land productivity for future generations [2–5]. According to Refs. [5,6] reported that adoptions of integrated land management technology (ILMT) could help to reduce soil erosion, preserve land resources and their associated ecosystem services, improve soil health by increasing soil organic matter, improve soil structure, and water infiltration, which in turn sustain yield production and income. Furthermore, widespread application of ILMTs improve food security, provide positive ecosystem services, conserve biodiversity, and support community livelihoods [7]. However, the integration of environmental and human components on land influences landowners' ability to accept good practices in land management, and socioeconomic constraints also determine the adoption decisions of land management technologies [6,8].

According to the current study report of the Soil Reference and Information Groups, globally, 9 million hectares of land are eroded, impacting 1.5 billion people and 124 million on the African continent alone [4,9]. Similarly, in Ethiopia, land degradation, particularly soil erosion is one of the most socioeconomic and environmental issues that are exacerbated by poor resource endowment, topography, population growth, deforestation activities, land tenure, and inappropriate land management technology adoptions [5,10–12]. In response to the risk of land degradation, Ethiopian farmers have employed a number of indigenous land management practices in their locality for several years [13,14]. Additionally, soil and stone bunds, biological measures (multipurpose fodder species), improved seed, agronomic practices, afforestation, terrace buildings, and hillside area closures are widely implemented with the help of development agents, experts, training, resource conservation, and restoration intervention programs, including the Productive Safety Net Program (PSFP), Food for Work, MERET, and MERET PLUS Program, as well as foreign donors [15–17]. Since 2008, sustainable land management technology adoptions has been prioritized to restore degraded farmlands, enhance agricultural yields, minimize environmental impact in the first phase (2008–2013) and addresses poor farmland management practices, rapid vegetation loss, secure land tenure, improve livelihoods, and promote adoptions in the second phase (2013–2018) [13,16,18].

Consequently, encouraging results have been documented in different places of the country. For instance application of physical land management technologies minimize the rate of soil erosion in Tigray [19,20], terrace building on farmlands improve soil depth and nutrients in *Wollo* areas [14]; stabilization of stone bunds reduce soil erosion, maintain soil moisture, improve soil attributes [21]; integration of physical and biological measures reduce soil loss and maintain soil health and vegetation varieties [22,23]; ameliorate livelihoods [24–26]. Although land management technologies (LMTs) offer benefits, adoption rates remain below expectations, and soil depletion persists. For instance, nearly 50 % of the highland has significant soil depletion, with 4 % beyond reclamation [4]. Over 33.7t $ha^{-1}yr^{-1}$ of topsoil has been lost in the northern Ethiopian highlands alone [27]. The situation of soil depletion is also severe in the southern highlands due to population growth, high rainfall, rugged terrain, inappropriate agricultural practices, and rapid deforestation [28]. Lack of integration of the physical and biological measures [29]; lack of maintenance and inappropriate technology design [30]; low farmer motivation for long-term benefits of technologies [13]; farmers perceived physical structures occupying productive lands, making it difficult to oxen plough and requiring labor as constraints of technology implementations [31].

Past studies have shown that the adoption of LMTs are determined by factors such as demographic, socioeconomic, institutional and physical related factors [10,14,32,33]. However, currently determinant variables such as technology profitability [34]; social asset endowment variables such as local membership [35]; development agent workload and land certification [36]; traditional land law [37]; land rent and sharing [38]; manure and improve seeds [32] were not widely assessed even if these variables influence the adoption of LMTs. Moreover, most past studies have used binary logistic regression models to identify factors influencing the adoptions LMTs, but these models have limited explanatory power and do not show a potential correlation between different technologies and their intensity [39–41]. Besides, identifying of determinants using single-phase models has biases and limited policy relevance [42]. Similarly, in the study area [43], tried to identify determinants of households decisions to adopt LMTs. However, most of the determinant variables deployed in the study were related to soil erosion and land degradation risks, but failed to assess the current recommended adoption determinant variables and use simple descriptive tool analysis rather than multivariate modeling approaches. Thus, to fill such variable and methodological gaps, as well as analyze households' choices for multiple uses of land management technologies and simultaneous adoption decisions, and assess the potential correlation between unobserved disturbances in the adoption equations, the current study deployed multivariate probit modeling approaches. Thus, the purpose of this study was 1) to analyze factors influencing households' decisions to adopt land management technologies and 2) to evaluate the intensity of the applied land management technologies in the Goyrie watersheds of southern Ethiopia.

Therefore, assessing the main determinants of households adopting various land management practices in the Goyrie watershed could be used to mitigate the risk of flooding and sediment loading in the *Koyisha* dam, as well as generate new information on ecological and socioeconomic issues. Despite a well-organized review of research documents on the determinants of household decisions to adopt land management technologies, the study analysis also contributes to providing new information on policy-related variables such as the effectiveness of development agents (access to extension services), social asset variables (membership), technology benefits, and land-related variables (land rent and sharing) in the study area. This information can be used to develop more effective land management technologies that can benefit both communities and sustainable environment. Studies that treat the adoption of LMTs as independent may ignore the importance of interdependency among technologies and may be biased in policy estimates. As a result, this research can also reveal the interdependency of selected LMTs, which may have important policy implications for developing strategies for supporting LMTs.

2. Materials and methods

2.1. Biophysical conditions of the study area

The study was conducted in the Goyrie watershed in *Demba Gofa* district, southern Ethiopia. The *Goyrie* watershed is situated between 6°22′ 00″ and 6° 26′ 00″ N latitude and 36° 57′ 00″ and 37° 01′ 00″ E longitude (Fig. 1). The location is 510 km southwest of Addis Ababa (the capital city of Ethiopia) and 23 km northeast of Sawla town (the center of *Gofa* Zone) [44]. The Goyrie watershed covers a total area of nearly 2616.25 ha. The landscape feature covers mountains, undulating terrains, plains, and rugged surfaces [45]. The Goyrie watershed's altitude ranges from 1086 to 2381 m above sea level, averaging at around 1731 m (Fig. 1). The peak and the outlet of the watershed, *Alba* and *Baysa-Zenti* respectively, mark the highest and lowest elevation points within the watershed.

Rainfall and temperature data from the Ethiopian National Meteorological Agency (ENMA) of *Sawula* station from 1993 to 2022 depicted that the mean annual rainfall in the Goyrie watershed was 1324.8 mm, observed in 1996 (Fig. 2).The maximum (1578 mm) and minimum (1064 mm) rainfall were observed in the years 2019 and 2022, respectively (Fig. 2). Mean annual temperature was 21.6 °C, recorded in 2010. The maximum yearly mean temperature (29.5 °C) and the minimum mean annual temperature (14 °C) were observed in 2009 and 2001, respectively (Figure, 2). The distribution of rainfall throughout the year is categorized into two rainy seasons known as *Belg* (March–May) and the rainy season or summer (June–September). The dominant soil types in the study watershed is dystric nitoisols, which are dominant in the southern and eastern parts of the watershed. Orthic acrisols, the second dominant soils are widespread in the northern and the central parts of the watershed, while dystric fluvisols are found in the western parts of the watershed [46].

2.2. Socioeconomic conditions of the study area

Based on [47] and projected total population for July 2017 [48] data, the total population of *Demba Gofa* district was 81,158 (male = 40,335, female = 40, 823) in 2007 and 91,412 (male = 45,486, female = 45,926) for July 2017. The population is steadily increasing. According to the *Demba Gofa* District Finance Office (DGDFO) annual report for June 2023, almost 1210 household heads are living in the Goyrie watershed. This total includes 1118 male household heads and 92 female household heads. Crop and livestock mixed subsistence farming system is the principal means of income for the majority of the population. The principal grain yields grown in the watershed are maize (*Zea mays*), teff (*Eragrostis teff*), sorghum (*Sorghum biocolr*), and groundnut (*Arachis hypogaea)*. Other crops, such as sweet potatoes (*Ipomoea-batatas*), enset (*Ensete venter cosum*), cassava (*Manihot esculenta*), moringa (*Moringaceae)*, coffee (*Coffee arabica*) and chat (*Catha edulis*) are also grown in various locations within the watershed [49]. Furthermore, small irrigation systems are being used around homesteads to cultivate vegetables and fruits such as oranges (*Citrus sinensis*), mangos (*Mangifera indica*), papaya (*Carica papaya*), guavas (*Psidium guajava*), tomatoes (*Solanum lycopersicum*), and lemons (*Citrus limon*). People in the area also raise domestic animals such as cattle, sheep, goats, donkeys, poultry, as well as bee keeping are significant occupation. Additionally, residents of the watershed earn their living through off-farm activities, petty trade, and handicrafts [49].

2.3. Concepts of land management technology adoptions

In the context of this study, LMTs are farming practices and methods that can be adopted at the local level to maintain and enhance the ability of land to produce crop, rehabilitate degraded lands and maintain ecological balance [50]. These include physical LMTs (primarily stone and soil bunds, fanya-juu, and terrace construction), biological measures (the use of multipurpose grass species), and agronomic methods (such as manure application, crop rotation, and mulching) [6,34]. Recognizing the challenges of land degradation, farmers in the Ethiopian highlands adopted a variety of LMTs and their combinations [4,16,30]. Although more priority was given to physical LMT adoptions, currently Ethiopian government encourage and recommended rural farmers to adopt different LMTs to improve soil properties, increase yield grain and improve rural livelihoods [21,25,51]. Similarly, in the Goyrie watershed, commonly adopted LMTs include soil bund plus desho grass (*Pennisetum pedicellatum trin*), stone bund, fanya-juu, soil bund alone and stone face

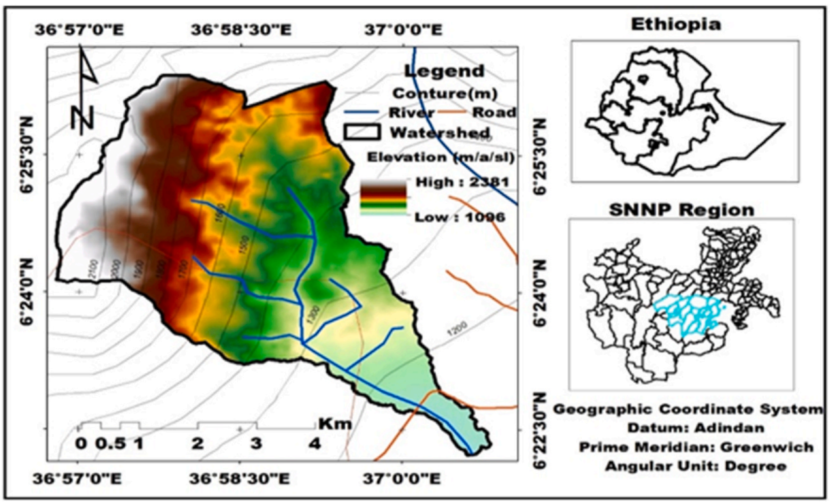

Fig. 1. A location of map of the study watershed.

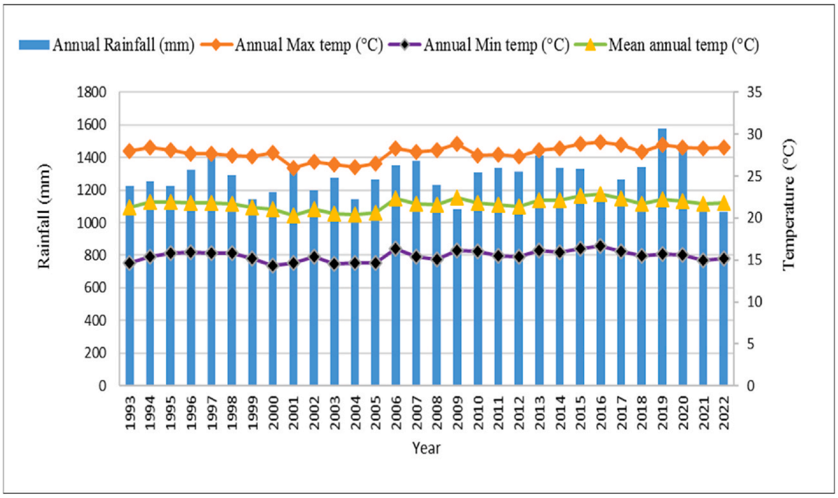

Fig. 2. Mean annual temperature and total rainfall of the Goyrie watershed (1993–2022).

soil bunds (Fig. 3 a, b, c, d and e respectively). Additionally, agroforestry practices have been adopted on and around farmlands in the study watershed (Fig. 3 f). Soil bunds combined with desho grass were adopted on farmlands since 2008, while others embraced both individual and communal lands through individual and community mobilization.

During the focus group discussion (FGD), development agents and agricultural experts confirmed that, in response to national and regional government recommendations, farmers have adopted a variety of LMTs, including stone and soil bunds, fanya-juu and soil bunds, and multipurpose fodder species, rather than relying on single technology. Adoption of various LMTs provides ecological, economic, and socio-cultural benefits (Table 1). For example, the use of stone and soil bunds, fanya-juu bunds, and desho grass conserves and rehabilitates degraded areas, improves soil qualities, and uses grass for animal feed via cut and carry systems. According to current studies, the single LMT adoption approach has not met social, economic, or environmental needs [25,52,53] thus, rural farmers should implement a variety of land management technologies and their combinations. Manure application and agroforestry are also some of the LMTs adopted in the Goyrie watershed of southern Ethiopia. Table 1and Fig. 3 provides a full summary of LMTs as well as their benefits.

During the FGDs and key informant interviews (KII), participants explained that, although the adopted LMTs have economic and environmental benefits, some of the physical LMTs have disadvantages. The majority of them stated that physical LMTs such as the adoption of stone and soil bunds and fanya-juu require lots of labor and material to construct, and made them costly investment. More than half of the FGD participants also stated that these physical LMT adoptions require constant maintenance, are difficult to plough with oxen, and produce rats and termites. According to development agents and agricultural experts, manure might be difficult to carry and store, especially if the farmlands are far from homes. Manure, if not adequately managed, can contaminate water supplies.

2.4. Research design and approach

According to Ref. [65], the type of research approach is chosen depending on the philosophical basis of the study. Therefore, the study deployed a mixed-methods (quantitative-qualitative) approach because the philosophical base of this research is a pragmatic worldview and concurrent triangulation design, i.e., both the quantitative and qualitative data were collected and analyzed simultaneously at a particular time. However in terms of weight, the quantitative approach was prioritized over the qualitative approach due to the need for statistical tools based on generalizations of the problem. The concurrent triangulation design captures the benefits of both quantitative and qualitative approaches while minimizing their drawbacks. Furthermore, the primary benefit of this design is that one form of data gathering compensates for the weaknesses of the others, resulting in a more complete understanding of the study subjects [65].The quantitative approach enabled us to collect data on all quantifiable associations between adopted land management technologies and adoption determinants. In contrast, a qualitative approach was used to collect and analyze qualitative information that triangulates and strengthens the quantitative data.

2.5. Sample and sampling procedure

According to Ref. [66], suggested that researchers must consider factors like, accuracy, cost, population homogeneity, sampling techniques and study types when selecting appropriate sample size of the study. Thus, for the purpose of this objective, a multistage sampling method was utilized to draw representative sample units. At the first stage, *Demba-Gofa* district was chosen from the six rural

Fig. 3. a- Soil bunds plus desho grass, b- Stone bund, c- Fanya-juu, d- Soil bund, e− Stone face soil bunds, f-agroforestery

districts in *Gofa* Zone based on specific criteria: discernible evidence of different land management technology adoptions, accessibility of well maintain practices and availability of integrated land management technology adoptions. With similar criteria among the 5 milli[1] watersheds found in Demba-Gofa district, the Goyrie watershed was selected. The selection process was held with natural resource development experts through desk top discussion in December 2022. There are six rural villages found in the watershed, and households that reside in the watershed are considered the survey population of this study. A total of 1210 household heads with their respective villages were listed in the kebele[2] administration office (Table 2). At the final stage 291 sample respondents were drawn through simple random sampling techniques with proportional to the size allocation techniques Equation (1) (Eq. (1)). The required sample size was calculated based on a mathematical formula developed by Ref. [67]:

[1] Milli watershed (1000 ha–10,000 ha, or 10–100 km).
[2] The smallest administration unit of Ethiopia.

Table 1
Description of LMTs adopted in the Goyrie watershed.

Type of LMTs	Description and their benefits
Soil bund	An embankment is built over the contour and formed of soil or mud. It is used to prevent runoff erosion, boost infiltration, improve soil fertility, and increase yield production and income, thereby reducing food insecurity [20,21].
Stone bund	Embankment-like structure of stone with a basin at its upper side and built across the slope. It is constructed when stones are available. It protects soil against erosion by trapping sediment and water and improving soil fertility and grain production [54–56].
Stone face soil bund	Stone-faced soil bunds are soil bunds with stone facing on the upstream sides. This facing protects the bund from erosion and stabilizes the soil. This application is used to reduce flooding, modify terrain through changing slope length and angle, and reduce the risk of crop failure due to drought [43,57–59]
Soil bund with desho grass	It is one of the LMTs that entails building a soil bund along the slope counter and growing desho grass (a fodder species) on it. It reduces soil erosion, lets water permeate the soil, and increases soil fertility and yield production. Grass facilitates animal feeding through a cut-and-carry technique and various domestic needs (home, beds, and energy). It reduces the cost of agricultural production, such as soil fertilizer [22,23,25,26].
Fanya-juu	Soil bund that involves digging a trench and throwing the soil uphill to form an embarkment. It is used to minimize soil erosion, revitalize degraded areas, improve soil quality, and improve crop production [25,58,60]
Manure	Is the process of spreading manure on farmlands (mainly around homesteads) to improve soil properties and crop yields. Manure is a natural fertilizer that consists of nutrients like nitrogen, phosphorus, and potassium that are essential for plant growth. It helps to reduce the risk of soil nutrient loss, improve soil structure, and ameliorate agricultural production [30,59,60]
Agroforestry	It is a land management system that involves the growing of trees for timber, fruits and herbs that are used for food and medicine, and habitat for a variety of species. Application of agroforestry can reduce greenhouse gas emissions by absorbing carbon dioxide from the atmosphere and increase resilience to climate change by providing shade, shelter, and food [61–64]

Table 2
Distribution of sample household heads based on villages in Goyrie watershed.

Villages name	Village location	Total number of HHH[a]	Total sample
Daniza	Upper	256	62
Selo	Upper	204	49
Zada,	Middle	202	49
Gayila-Chalbie	Middle	241	57
Dolo	Lower	161	39
Baysa	Lower	146	35
Total		1210	291

[a] Source: Rural *kebele* administration office documentation, 2023; HHH, household heads.

Table 3
Multi-collinearity of independent variables.

Variables	VIF	1/VIF
Sex	1.14	0.87
Age	1.16	0.86
Education	1.38	0.72
Family size	1.42	0.70
Land holding size	1.33	0.75
TLU	1.41	0.71
Off-farm activity	1.20	0.83
Access to extension	1.12	0.89
Access to credit	1.22	0.81
Training	1.36	0.73
Farm distance	1.06	0.94
Perception on SE	1.24	0.80
Village membership	1.52	0.65
Perception on BLMTs	1.16	0.85
Land rent	1.20	0.83
Crop sharing	1.24	0.80
Mean VIF	1.28	

VIF-variance inflation factor, 1/VIF, tolerance, BLMTs-benefits of land management technologies, SE-soil erosion, and TLU- tropical livestock unit.

Table 4
Descriptive and summary statistics for the variables used in MVP and ordered probit models.

Independent variables	Description/Specification	ES	Mean	Std.dev
Sex of HHH	Household heads 1 = male, 0 = female; Dummy	+	0.83	0.37
Age of HHH	Age of household heads in year; Continuous	±	48.14	10.14
Education level	Educational status of household heads in years; Continuous	±	2.00	0.68
Family size of HHH	Number of family members of house hold heads; Continuous	±	5.16	1.76
Land size of HHH	Land holding size of household heads in hectares; Continuous		2.91	0.68
TLU	Total livestock of household heads in TLU, Continuous	±	5.17	1.41
Land rent	Household heads who rent his/her land = 1, otherwise = 0; Dummy	–	0.47	0.50
Crop sharing	Household heads who gave land for crop sharing = 1 otherwise = 0; Dummy	+	0.44	0.49
Off-farm activity	Household heads involved off-farm = 1, otherwise = 0, Dummy	–	0.52	0.50
Access to extension	Household heads contact with experts = 1, otherwise = 0; Dummy		0.518	0.50
Access to credit	Households gained credit for LMTs = 1, otherwise = 0; Dummy	±	0.55	0.49
Village membership	Household heads involved in local membership = 1,otherwise = 0; Dummy	+	0.57	0.49
Training	Household heads receive training = 1, otherwise = 0; Dummy	+	0.54	0.49
Farm distance	Distance of households farm from his/her home in km; continuous	+	1.98	0.98
Perception of SE	Households perceive soil erosion severity = 1, otherwise = 0; Dummy	+	0.56	0.49
Perception BLMTs	Households perceive the benefits of LMTs = 1, otherwise = 0, Dummy	–	0.52	0.50
Dependent variable				
SOB	Household adopt **soil bund** = 1, otherwise = 0		Fig. 3 and Table 1	
STB	Households adopt **stone bund** = 1, otherwise = 0			
STFSOB	Households adopt **stone-face soil bund** = 1, otherwise = 0			
SOBIDG	Households adopt mixed **soil bund plus desho grasses** = 1, otherwise = 0			
MANURE	Households applied **manure** = 1, otherwise = 0			
AG	Households practice **agroforestry** = 1, otherwise = 0			

HHH, household heads; TLU, tropical livestock unit; SE, soil erosion; BLMT, benefits of land management technologies; ES, expected sign; km, kilometers.

$$n = \frac{Z^2 * p * q * N}{e^2\ (N-1) + Z^2\ * p * q} \tag{1}$$

Where; n is the necessary sample size, N denotes the total household heads in the watershed, Z is the value found in statistical tables that cuts an area α at the tails (1- α equals the required confidence level 95 % or 1.96); p is estimated proportional in the population (0.5), q is 1-p and e represents the desire level of precision (0.05) (Eq. (1)). Therefore, the total required sample size is:

$$n = \frac{1.96^2 * 0.5 * 0.5 * 1210}{0.05^2\ (1210-1) + 1.96^2\ * 0.5 * 0.5} = 291$$

Thus, the required sample size for each village was calculated as follow:

$$n_i = \frac{Ni}{\sum Ni} * N$$

Where n_i is the available sample size of each respective villages; Ni is the total household heads for each village; N represents the total sample household heads (291) and ΣNi, total head of households in the *Goyrie* watershed (1210).

2.6. Data source and data collection methods

A household survey was conducted to collect cross-sectional data from 291 household heads using semi-structured questionnaire (open and closed ended) formats. To make communication easier with respondents, the questionnaire was developed in English and then translated into Amharic, which is the official language of the country. To check the consistency and validity of the questionnaire, a pilot test was conducted with 30 randomly selected household heads (five from each village), who were not members of the sample respondents but had similar backgrounds. Finally, the questionnaire has been modified and revised depending on the pilot tests. Then, six enumerators (agricultural experts working in the watershed) were purposefully selected and trained on data collection and interviewing techniques for two days at the end of May 2023. Consequently, the required demographic, socio-economic, institutional, and social asset characteristics of households, their perceptions of land management technologies, and technology-related variable responses were collected from June to July 2023 using face-to-face interview approaches.

To triangulate and cross-checked the quantitative data collected via questionnaire, three focus group discussions (in the upper, middle, and lower villages) of the watershed have been conducted, each with a total of 10 participants. Totally 30 focus group participants (21 males and 9 females), including development agents working in the watershed, elders, model farmers, and youths, were purposefully drawn and involved in the discussions in June 2023.to July 2023. A checklist was developed to guide a focus group discussion (FGD) about the adoption of land management technologies in the watershed, the role of communities, and the factors that impact rural households' adoption of the technologies. Outcomes of FGDs was helped to substantiate the household survey results.

Besides, 15 key informant interviews (9 males and 6 females) consisting of natural resource management experts, land management and use experts, crop production and animal resource development experts, and local elders were purposefully identified to obtain detailed information on the determinants of land management technology adoption by households in the study watershed.

2.7. Statistical data analysis

Both descriptive statistics and econometric models were deployed for data analysis. Descriptive statistics such as percent, mean, and standard deviation) were used to analyze and compared the demographic, socio-economic, institutional, and social asset characteristics of households, their perceptions on soil erosion, perception on the benefits of LMTs and technology related variables. An independent *t*-test was utilized to evaluate the mean difference of continuous independent variables via STATA 14.2 software. Multivariate probit (MVP) model was deployed to analyze the causal relationship between various LMTs and factors influencing households' decisions to adopt LMTs. Although the MVP modeling approach cannot distinguish between the two causes of correlation, it was preferred when the number of selected dependent variables exceeded two and were non-continuous [4,53,54]. Furthermore, we used the MVP modeling approach, which investigates the correlation between a collection of covariates and each of the distinct technologies while allowing error terms to be correlated. Besides, the MVP model depicts the existence of interdependence and the complementary nature of land management technology adoptions. In this case study, we used an order probit modeling approach to assess the factors that influence the intensity (number) of land management technology adoption in the study watershed. This means that the intensity of adoptions is quantified using count variables that represent the number of technologies embraced. Furthermore, the qualitative data gathered from FGDs and KII participants was examined using content analysis to supplement the quantitative findings.

2.8. Empirical model specification

2.8.1. Multivariate probit modelling approach

Rural households are likely to have multiple decisions when choosing land management technology adoptions, and it is crucial to encourage them to make multiple concurrent choices rather than relying on single technology adoptions. Single technology adoption (bivariate modeling) approaches do not show any potential correlation, interdependence, or inter-linkages of error terms among various land management practices and their intensity [39,41]. Therefore, being unable to capture the correlation (interdependence) of the error terms among different LMTs in the adoption equation model, leads to limited policy recommendations [40]. Thus, we used the MVP modeling approach, which allows for the simultaneous investigation of potential correlations between unobserved disturbances (error terms) and correlations between the adoption of each LMT [68,69]. The household's adoption of different land management technologies and their combinations were based on the benefits of the technologies [68]. As a result, adoption of combined technologies, as well as adoption decisions, are multivariate [39,40]. Therefore, the MVP modeling approach is used to demonstrate the interdependence of dependent variables, estimate a set of binary probit models simultaneously, and consistently estimate the probabilities of individual and joint LMT adoptions, as well as the premises of households that use a combination of any LMTs to reduce soil erosion [4,10,56]. The MVP modeling analysis in terms of the anticipated utility maximization theory that advocates individual household i will adopt a particular LMTs on his/her land if the anticipated utility from adoption (U^*_{ij}) is greater than the anticipated utility from other alternative measures (U_{ij}), i.e., $Y^*_{im} = U^*_{ij} - U_{ij} > 0$, where Y^*_{im} is the net benefit that household gained from adopting jth technologies [39]. For our purpose the MVP modeling including seven binary questions (Eq. (2) &3) that addresses: SOB (soil bund), STB (stone bund), STFSOB (stone-face soil bund), MANURE (manure), and SBIDG (soil bund integrated with desho grasses), FANYAJU (fanya-juu) and AG (agro-forestry).

$$Y^*_{im} = \beta_m X_{im} + \varepsilon_{im\,;}\ (m = 1, 2, 3, 4, 5, 6, 7 \tag{2}$$

$$Y_{im} = 1 \text{ if } \quad Y^*_{im} > 0 \text{ and } 0 \text{ otherwise} \tag{3}$$

Based on this assumption that a rational ith farmer has a latent variable Y^*_{im} represents unobserved preferences associated with the choice of technologies (m = 1,2,3,4,5,6,7 LMTs used in this study); X_{im} represents the vector of independent variables that are expected to predict each type of LMTs; β_m is the set of parameters that reflect the impact of changes in the vector of the explanatory variables and ε_{im} represents error terms (Eqs. (2) and (3)) following multivariate normal distribution each with a mean of zero and a variance covariance matrix with values of 1 on the leading diagonal and non-zero correlations as off-diagonal elements [69–71]. The off-diagonal components identified the relationship between various types of LMT adoptions while also addressing unobserved characteristics that influence LMT adoptions (Eq. (4)).

$$\text{Covariance matrix } (\varepsilon_i\ , \varepsilon_{ii\ldots\ldots\ldots}\ \varepsilon_n\ ) = \begin{vmatrix} 1 & p_{12} & p_{13} & p_{14} \\ p_{21} & 1 & p_{23} & p_{24} \\ p_{31} & p_{31} & 1 & p_{34} \end{vmatrix} \tag{4}$$

Where ε_i, $\varepsilon_{ii\ \ldots..}$ ε_n, are represents correlation disturbances in MVP model and p (rho) denotes correlation parameter between LMTs in the model (Eq. (4)). Thus, a positive (+) correlation implies complementary associations, whereas a negative (−) correlation between practices implies replacements [39,54]. According to Ref. [15], noted that inability to incorporate unobserved components and relationships between adoption decisions for various practices will result in biased and inefficient results.

2.8.2. Ordered probit model

The MVP modeling approach just merely evaluates the chance of adoption of LMTs without distinction made among households who adopt single technology and those who adopt two or more combined technologies [39]. However, empirical literature reviews have shown that households that have adopted combined LMTs earn more benefit than single LMT adopters [72]. Assessing the intensity (number) of LMTs using the Possession regression model has limitations because the assumption made is that all events have a comparable likelihood of occurrence [39,55]. Therefore, in our cases ordered probit modeling approaches were used to analyze factors that influence the intensity (count variables) of adoptions of LMTs in the study watershed (Eq. (5)). The count variables refer to the number of LMTs adopted in the study watershed. In an ordered probit model, the likelihood of adopting the initial technology may differ from that of adopting the second or third LMTs. Assume that during the second stage, households gained some experience and generated two or more other useful LMTs. We treat the number of LMTs as ordinal variables and hence use an ordered probit model to explore the association between categorical dependent variables and explanatory variables (Table 5). For our objective, we quantified the ordered probit model following the procedures of [73–75] and (Eq. (5) & (6)).

$$Y_i^* = X'ß + ui \tag{5}$$

For the ith households where normalization is that the regressor x not contain an intercept, for the y* > 1 number of LMTs increases, for y* > 2, adoption increase more and more. For m orders following a standard ordered probability model, the probability observing outcome i, resembles:

$$\Pr(outcome\ j = i) = (ki - 1 < 1 < = X'iß + ui < ơi \tag{6}$$

Where ui denotes a normal distribution with standardized normal cumulative distribution function. The coefficient $ß_i$ ….βk joint evaluated with a cut point's $ơ_1, ơ_2$ …... ơk-1; assume k is the number of outcomes (Eq. (6)).

2.9. Variables considered in MVP and ordered probit modeling

2.9.1. Dependent variables

In this study, dependent variables were soil bund plus desho grass, stone bund, fanya-juu, soil bund alone, stone face soil bunds, application of manure, and agroforestry. These LMTs are the dominant technologies adopted in the study watershed and hence selected purposefully during preliminary field work. Their detailed description and benefits are depicted in Table 1.

2.9.2. Independent variables

The selection of independent variables in the present study relied on econometric theory and related empirical literature on the determinants of LMT adoptions [4,5,39,71,76,77]. The independent variables include socioeconomic factors (sex, age, education level, marital status, and family size), physical attributes (land holding size, farm distance, and land rent), institutional-related factors (access to extension, access to credit, training, and households perceptions of soil erosion), economic factors (off-farm activities, livestock size, and crop sharing), social membership (village membership), and technology-related precisions (Tables 6 and 7). The description and hypothesized sign of these variables are presented in Table.

Prior to running MVP and ordered probit models, the model fitness, outliers, and multi-collinearity among independent variables (using variance inflation factors) were checked. According to Ref. [77], if the tolerance value of independent variables is close to one and the variance inflation factor (VIF) is less than 10, there is no significant relationship between independent variables. Thus, in our case study, the tolerance value (1/VIF) and VIF of each independent variable were close to 1 and less than 10, respectively, and the mean value of VIF was 1.28 (Table 3). Therefore, there is no significant correlation between independent variables in this study.

Table 5
Covariance matrixes of joint MVP regression outcome of adopted LMTs.

	P^{SOB}	P^{STB}	P^{STFSOB}	P^{MANURE}	P^{SOBIDG}	$P^{FANYAJU}$	P^{AG}
P^{SOB}	1						
P^{STB}	0.14 (0.11)	1					
P^{STFSOB}	0.15 (0.16)	0.05 (0.03)	1				
P^{MANURE}	0.32** (0.13)	0.21** (0.10)	0.29** (0.14)	1			
P^{SOBIDG}	0.59 ***(0.12)	0.41** (0.14)	0.31**(0.11)	0.60*** (0.10)	1		
$P^{FANYAJU}$	−0.22* (0.12)	0.055 (0.11)	0.27 (0.25)	0.37** (0.18)	0.27** (0.11)	1	
P^{AG}	0.30** (0.11)	0.37*** (0.07)	0.23** (0.10)	−0.19* (0.11)	0.35** (0.16)	0.29* (0.16)	1

Rho Likelihood ratio test: $P^{SOBSTB} = P^{SOBSTFSOB} = P^{SOBMANURE} = P^{SOBSOBIDG} = P^{SOBFANYAJU} = P^{SOBAG} = P^{STBSTFSOB} = P^{STBMANURE} = P^{STBSOBIDG} = P^{STBFANYAJU} = P^{STBAG} = P^{STFSOBMANURE} = P^{STFSOBSOBIDG} = P^{STFSOBFANYAJU} = P^{STFSOBAG} = P^{MANURESOBIDG} = P^{MANUREFANYAJU} = P^{MANUREAG} = P^{SOBIDGFANYAJU} = P^{SOBIDGAG} = P^{FANYAJUAG} = 0$; chi2 (21) = 102.21, Prob > chi2 = 0.00; SOB = soil bund, STB = stone bund; STFSOB = stone-face soil bund; MANURE = manure; SOBIDG = soil bund integrated with desho grasses; FANYAJU = fanya-juu; AG = Agroforestry; In parenthesis are standard error; *,**,and *** are 10 %, 5 % and 1 % level of significance respectively.

Table 6
Determinants of land management technologies with MVP modeling approaches.

Variables	Coefficients Equation						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	SOB	STB	STFSOB	MANURE	SOBIDG	FANYAJU	AG
Sex	0.45 (0.22)**	0.02 (0.23)	0.20 (0.23)	−0.45 (0.24)*	0.40 (0.55)	0.44 (0.22)**	0.76 (0.26)***
Age	−0.21 (0.01)***	−0.10 (0.02)***	−0.01 (0.01)	0.00 (0.01)	0.01 (0.02)	0.00 (0.01)	0.01 (0.01)
Education	−0.05 (0.13)	0.32 (0.13)**	−0.13 (0.12)	0.25 (0.12)**	−0.08 (0.24)	0.12 (0.13)	−0.24 (0.14)*
Family size	−0.02 (0.05)	0.04 (0.05)	−0.01 (0.05)	−0.02 (0.05)	0.22 (0.10)**	0.00 (0.05)	0.02 (0.06)
Land holding size	0.45 (0.14)***	0.12 (0.03)***	0.02 (0.14)	0.004 (0.14)	0.99 (0.28)***	−0.14 (0.13)	0.26 (0.14)*
TLU	0.18 (0.07)**	−0.00 (0.07)	−0.16 (0.07)**	−0.24 (0.07)***	1.29 (0.23)***	0.01 (0.06)	0.13 (0.07)*
Off-farm activity	0.65 (0.17)***	−0.05 (0.17)	−0.16 (0.17)	−0.06 (0.17)	−1.32 (0.37)***	−0.04(0.17)	0.17 (0.19)
Access to extension	0.365 (0.17)**	0.28 (0.12)**	0.04 (0.17)	0.04 (0.17)	1.42 (0.42)***	−0.09 (0.16)	0.27 (0.18)
Access to credit	−0.11 (0.19)	0.40 (0.18)**	0.39 (0.19)**	0.02 (0.19)	0.41 (0.15)**	−0.01 (0.18)	0.04 (0.21)
Training	−0.09 (0.19)	0.02 (0.18)	0.58 (0.19)***	0.11 (0.19)	1.61 (0.35)***	0.26 (0.18)	0.21 (0.20)
Farm distance	−0.04 (0.08)	−0.04 (0.08)	−0.01 (0.09)	0.15 (0.06)**	−0.36 (0.17)**	−0.07 (0.08)	−0.23 (0.09)**
Perception on SE	−0.10 (0.19)	0.09 (0.18)	0.08 (0.19)	−0.41 (0.18)**	1.31 (0.38)***	0.17 (0.08)**	0.29 (0.21)
Village membership	0.28 (0.07)***	−0.11 (0.02)***	−0.25 (0.17)	0.35 (0.17)**	0.24 (0.10)**	0.09 (0.16)	0.02 (0.18)
Perception on BLMTs	−0.32 (0.18)*	0.29 (0.17)*	0.35 (0.18)*	−0.22 (0.17)	−0.22 (0.37)	0.23 (0.17)	0.49 (0.19)**
Land rent	−0.62 (0.18)***	−0.45 (0.18)**	−0.577(0.18)***	0.02 (0.18)	−0.12 (0.37)	0.03 (0.18)	−0.41 (0.19)**
Crop sharing	0.39 (0.20)*	−0.38 (0.18)**	−0.39 (0.19)**	0.74 (0.19)***	0.64 (0.42)	−0.39 (0.18)**	−0.97 (0.21)*
Constant	0.78 (0.36)**	0.29 (0.65)	0.69 (0.68)	−1.28 (0.66)*	−11.60 (2.17)***	0.10 (0.62)	0.63 (0.72)

Likelihood ratio test of rho 21 = rho31 = rho41 = rho51 = rho61 = rho71 = rho32 = rho42 = rho52 = rho62 = rho72 = rho43 = rho53 = rho63 = rho73 = rho5 4 = rho64 = rho74 = rho65 = rho75 = rho76 = 0; chi2 (21) = 83.29, Prob > chi2 = 0.00.
Number of obs, 273, Number of draws = 5, Log likelihood = −976.252, Wald statistic ch2 (112) = 230.26, pro > ch2 = 0.00.
*, **, and *** are significant at 10 %, 5 % and 1 % level of significance, in parenthesis are standard error.

Table 7
Coefficient estimates of ordered probit model.

Variables	Coefficients	Std. Err.	z	P > |z|
Sex	0.25	0.18	1.36	0.17
Age	0.02**	0.01	2.57	0.03
Education	0.27**	0.10	2.64	0.02
Family size	0.24***	0.04	5.52	0.00
Land holding size	−0.24**	0.11	−2.18	0.03
TLU	0.11*	0.05	1.94	0.05
Off-farm activity	−0.28*	0.14	−1.79	0.07
Access to extension	0.35**	0.13	2.53	0.03
Access to credit	−0.05	0.14	−0.34	0.73
Training	0.28**	0.13	2.10	0.04
Farm distance	−0.03	0.06	−0.40	0.68
Perception on SE	0.21	0.151	1.37	0.17
Village membership	0.60***	0.174	3.48	0.00
Perception on BLMTs	−0.26*	0.142	−1.86	0.06
Land rent	−0.04	0.144	−0.28	0.77
Crop sharing	−0.28*	0.150	−1.87	0.06
/cut1	−0.53	0.51		
/cut2	1.07**	0.51		
/cut3	1.72***	0.52		
/cut4	2.09***	0.53		
/cut5	2.53***	0.54		
/cut6	2.90***	0.57		

Model characteristics: number of observation = 273; Likelihood ratio (LR) Chir2 (16) = 32.49, Prob > chi2 = 001; Log likelihood = −346.95, Pseudo R2 = 0.0447.
*, **, and *** are significant at 10 %, 5 % and 1 % level of significance.

2.10. Ethical consideration

Initially, to conduct the research and collect data from respondents, the authors got support letters from Arba Minch University School of Graduate Studies of Doctoral Programs Coordination Office (with identification: DPc/175/15/January 25, 2015) and ethical approval letter from College of Social Science and Humanities (with identification: CSSH/1514/15, protocol CSSHRO/012). Additionally, the ethical committee has approved the verbal consent of the participants with identification: CSSH/1567/15 and protocol CSSHRO/029. Prior to data collection procedures, the authors explained to the participants that data for this study would be used for academic purposes, participant anonymity was safeguarded, they had the ability to request questions, their freedom to revoke consent at any time, there were no penalties, and how data would be collected and stored. Because the participants were over 25 years old and the majority of them were unable to read, write, or sign, the authors requested their agreement to participate in the study in writing or verbally (orally) ways. All subjects provided oral or verbally informed consent. Thus, authors understood and agreed with their verbal agreement to participate in this study, taking into account their privacy concerns, such as age, educational status, and their fears about signing on paper and recording. This helped to develop rapport and trust between the researchers and the participants, thereby increasing the likelihood that they would complete the study.

3. Result and discussions

3.1. Characteristics of households

Demographic, socioeconomic, institutional, and physical characteristics of households were presented in Table 4. The survey result showed that of the total 291 respondents, a large portion (83 %) were male heads, while 17 % were females. Most female household heads in the study area have more responsibility for housing activities. It is true that Ethiopian women primarily engage in homestead activities and face limited access to media, resources, and agricultural credits, despite their primary focus on meals [78]. The respondents are relatively young, with a mean age of 48 years. The respondents have comparatively low educational status, with a mean of 2 years schooling (Table 4). This might be one of the obstacles of households to adopt different LMTs. The survey result revealed that the average family size of respondents was five members, with 2.91 ha of land. Household heads in the study watershed possessed an average of 5 Tropical Livestock Units (TLU). Nearly 47 % of respondents rented their land, while 44 % offered land for crop sharing. The survey also revealed that households walked an average of 1.98 km (km) from their home to their farthest farmlands. Respondents were asked to react concerning on off-farm activities and their perceptions of soil erosion. Nearly 52 % reported engaging in off-farm activities, while 56 % graded the severity of soil erosion in their locality (Table 4).

Around 54 % of the sample respondents received lessons on how to establish, maintain, design, and apply various land management technologies. Nearly 55 % of respondents have obtained agricultural loans from Omo Micro Bank (OMB) and from their relatives in the survey harvesting seasons (Table 4). Respondents were also requested to provide information about their village memberships. Almost 57 % of respondents said they participated in social asset strengthen local institutions (such as *Wonfel*, *Debo*, and *Senbete*). A household survey found that 77 % of respondents believed that adoption of LMTs improved agricultural production, while 23 % disagreed by explaining that most physical LMTs take cultivated lands, produce rats and rodents, and reduce yield production.

3.2. Land management practices in the goyrie watershed

In the Goyrie watershed, farmers have implemented different LMTs to reduce soil erosion, improve soil fertility, ameliorate agricultural productivity, thereby contributing to food security and poverty alleviation. The survey result indicated that soil bunds are widely adopted by (67 %) of the sample respondents. Stone-face soil bunds (65 %), stone bunds (54 %), integrated soil bunds and *desho* grasses (50 %), manure application (47 %), agroforestry (45 %), and fanya-juu (44 %) are commonly adopted by farmers in the

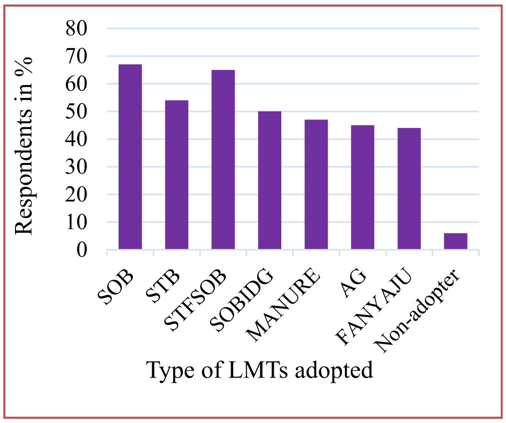

Fig. 4. Type of LMTs adopted in Goyrie watershed.

watershed (Fig. 4). As confirmed by the participants of focus group discussions (FGDs) and key informant interviewee (KII), soil and stone bunds have helped to reduce soil erosion and improve water infiltration, while manure and compost application in the study watershed helped to increase soil organic matter content and nutrient availability. The majority of FGD participants reported that application of soil bunds and desho grass species have contributed to soil fertility improvements by providing shade of grass residues and nutrients to crops. More than half of KII participants also confirmed that currently adoptions of soil bunds plus desho grass by farmers in the Goyrie watershed is a promising sign for the future improvements of agricultural production to alleviate food insecurity in the area.

The FGD participants in the villages of *Selo*, *Gayila-chalibe*, and *Danza* reported that some farmers destroyed and did not properly maintain the adopted technologies. According to the participants, some of the farmers did not implement LMTs on their farmlands because they perceived that the technologies, particularly, the physical practices, require labor, occupied productive lands, were difficult to plough with oxen, and produced rats and termites. Moreover, the KII participants explained that in the watershed, traditional social asset organizations such as *Wenfel*, and *Debo* assisted farmers in effectively implementing the LMTs. According to them *Wenfel* and *Debo* are traditional social asset organization that have been used by local farmers in the watershed to address their common problems, such as soil erosion, flooding control, and labor constraints.

As can be seen in Fig. 5, the intensity of adoption of LMTs in the Goyrie watershed ranged from 0 to 7. From the total respondents, nearly 17.2 % adopted a single LMT, whereas 15.5 % and 5.2 % of the respondents still adopted three and four LMTs on their farmlands, respectively (Fig. 5). The majority of the respondents (50.3 %) adopted at least two technologies. Only (3.6 %), (2 %), and (1.2 %) of the respondents used five, six, and seven practices (Fig. 5).

3.3. Interdependent between adopted land management technologies

Table 5 displays the pairwise correlation of error terms among the different LMTs adopted in the study watershed. The result indicated that adoption of soil bunds is significantly and positively correlated with manure application at the 5 % level of significance. Moreover, soil bunds have a significant positive association with mixed applications of soil bunds and desho grass (0.59) and agroforestry (0.30). Adoptions of stone bunds and manure (0.21), stone bunds and agroforestry (0.37) and stone bunds and mixed soil bunds plus desho grasses (0.41) were significantly and positively correlated with each other (Table 5). We also found that adoptions of mixed technology such as soil bunds plus desho grasses and fanya-juu (0.37) and adoptions of agroforestry and fanya-juu (0.29) were positively and significantly associated with each other (Table 5).This signifies that soil erosion control LMTs such as soil and stone bunds and fanya-juu maintain the soil in its original places while adoptions of desho grasses, agroforestry, and manure application ameliorate the soil fertility status. The highest positive interdependence (60 %) was observed between mixed soil bunds plus desho grasses and manure application, followed by soil bunds plus desho grasses and stone bunds (59 %), and adoptions of agroforestry and mixed soil bunds and desho grasses (35 %). This result is consistent with [5,39,59,60], who reported that adoption of soil erosion control LMTs such as soil and stone bund and fanya-juu encourages the application of soil fertility management technologies such as manure, fodder species, and tree planting. However, fanya-juu and soil bunds (−0.22), agroforestry and manure application has negatively correlated with each other, implies that one substitute by the others.

Generally, our findings demonstrated that almost all implemented physical LMTs are positively correlated with biological and agronomic measures, implying that adoption of combined LMTs could lead to beneficial syntheses.

3.4. Determinants of adoption decision of land management technologies: MVP modeling estimation

The purpose of this study was to evaluate the factors that influence households' decision to adopt land management technologies for conserving, maintaining natural resources, and ameliorating the productive capacity of land in the Goyrie watershed of southern Ethiopia. For this reason, we deployed the MVP modeling approach, and the results are displayed in Table 6. The result of the Wald test ($\chi2$ (112) = 230.26, p > $\chi2$ = 0.00) was statistically significant at the 1 % significance level, indicating that the MVP modeling fit the data plausibly well. This implies that the subset of the model's coefficients was together significant and that the explanatory power of the factor variables presented in the model was satisfactory. Furthermore, the likelihood ratio (LR) test ($\chi2$ (21) = 83.29, p > $\chi2$ =

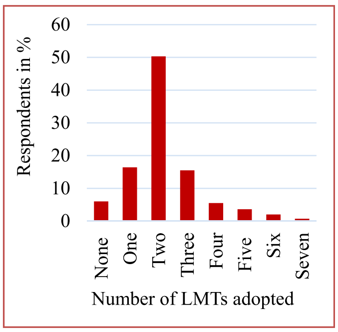

Fig. 5. Intensity of LMTs adopted.

0.00) of the null hypothesis that states independence among the adoptions of LMTs was significant at the 1 % level (Table 6). Therefore, the null hypothesis of all rho values jointly equal to zero (0) is rejected, implying that the MVP modeling approach fit the goodness of model. Thus, MVP modeling is more appropriate to examine factors that determine households' decision to adopt LMTs than separate estimation using univariate probit modeling approaches.

The results of the MVP model revealed that sex of household heads has mixed effects on the adoption decisions of LMTs. The sex of the household head is significantly and positively associated with the application of soil bunds ($p < 0.01$), fanya-juu ($p < 0.05$), and agroforestry ($p < 0.01$). This implies that male household heads are more likely to adopt soil bunds, fanya-juu and agroforestry measures than female household heads. However, application of manure technology is more likely to be adopted by female household heads ($p < 0.1$) than male headed households (Table 6). This is because physical LMTs such as soil and stone bunds, terrace building and check dams require labor force that are more likely to be associated with the participation of male households while preparation of manure is mostly applied around homesteads, which is more associated with females. The result of this finding is coincides with [5,61,79,80], who found that sex of household head had mixed results on the adoption probability of different LMTs. Conversely, studies by Refs. [4,62], reported sex negatively influenced the adoption decisions of land management technologies, while [17], identified it is positively influenced the adoption decisions of management practices. Most FGDs and KII participants were informed that applying manure as land management practices in the Goyrie watershed is a long traditional work that women have adopted around homestead lands and is viewed as more of a women's responsibility than men's.

As shown in Table 6, the age of the household heads significantly and negatively determined the adoption decisions of soil and stone bunds at the 1 % significance level. The result depicted that as the age of the household head increased by one year, the likelihood of adopting soil and stone bunds decreased by a factor of 0.21 % and 0.10 % respectively. This implies that the probability of older household heads adopting soil and stone bunds was lower than that of younger household heads in the Goyrie watershed. This could be due to the fact that older households experience labor shortage, while younger heads may have longer planning horizons, be physically stronger, and able to adopt physical land management technologies. Negative association between age and the decision to adopt soil and stone bunds were observed by Refs. [4,62,63], who explained younger household heads are more likely to be invest in the adoptions of land management practices than older heads. On the contrary [34,60], stated that age is positively associated with the adoption of physical land management practices by explaining older farmers have better experience and more likely to adopt new technologies than younger farmers. However [55], found age did not correlated with the adoption decisions of stone bunds in Bokole and Toni watersheds of Ethiopia.

The study found educational status significantly and positively influenced the decision to adopt stone bunds ($p < 0.05$), agroforestry ($p < 0.1$), and manure applications ($p < 0.05$) (Table 6). This indicated that as the number of years spent in school increased by one year, the probability of adopting stone bunds, agroforestry, and manure application increased by a factor of 0.32 %, 0.24 %, and 0.25 %, respectively. This could be because the educational status of household heads improves their ability to get new information and enhances technology adoption decisions. This finding is consistent with [5,65,81–83], who stated that households that received both formal and informal education were more cognizant of the benefits of the technology as well as effective in farming practices and more likely to adopt soil bunds and manure than those that did not receive either. However, educated household heads might be less likely to invest in LMTs because they might be able to obtain more money from other activities [84]. Regarding landholding size, there is a significant positive association between land size and soil bund, stone bund, and a combination of soil bund and desho grasses at 1 % significance level (Table 6). This signifies that as the household heads land size increase by one hectar, the probability of adopting of soil bunds increases by 45 %, stone bunds by 12 % and combination of soil bunds plus desho by 99 %, holding other variables constant. The positive relationships between land size and adoption of stone and soil bunds was supported by Refs. [10,13,67,68], stated that farmers with larger landholdings are more likely to invest on LMTs than those with smaller farms. On the other hand [84], concluded that land size impacts the adoption of LMTs based on the technologies being driven. This study also found that land size positively influences the application of agroforestry land management practices (Table 6).

Livestock ownership, measured in terms of the topical livestock unit (TLU), was significantly and positively associated with the adoption of soil bunds ($p < 0.05$) and the integration of soil bunds plus *desho* grasses ($p < 0.01$). These positive correlations could be explained by household heads with a comparatively large number of livestock's who needed animal fodder to feed their cattle being more likely to adopt multipurpose fodder species with soil bunds. The current study is similar to the verdicts of [4,59,69], who reported that livestock holding is positively associated with the adoptions of soil and stone bunds and tree planting. Studies by Ref. [84], also found that livestock holding was positively associated with the adoption of physical land management practices and tree planting in the Tigray region. Conversely [55], point out that during the non-crop harvesting season, animals are regularly permitted free grazing on farmland sites, which might undermine the adopted land management technologies, which in turn reduces farmers' willingness to maintain and construct the technologies. However, livestock holding showed a negative correlation with stone-face soil bunds ($p < 0.05$) and manure treatments ($p < 0.01$) (Table 6). This could be because households with a significant number of cattle rely on animal production for income rather than crop production, and so the likelihood of adopting and maintaining land management practices is decreasing. Moreover, as indicated in Table 6, as the household livestock holding decreases by one TLU, the probability of manure application is reduced by 0.24 %. This finding is supported by Refs. [36,64], who stated that household heads with a small number of TLU are less likely to adopt manure because manure application is highly dependent on the number of cattle.

Off-farm activity is one of the main sources of income for most rural households in Ethiopia, including those in the Goyrie watershed. Holding other variables constant, off-farm activities have a positive and negative significant influence on the probability of adopting soil bunds and the integration of soil bunds plus desho grasses at the 1 % level of significance, respectively (Table 6). The positive correlation between off-farm activities and soil bund adoption signifies that households that generate additional income from off-farm activities may be able to overcome monetary constraints and purchase agricultural inputs, which encourages them to invest in

LMTs. Likewise [81], reported that most rural households look off-farm activities as a source of income generating for adopting different land management technologies. They conclude that these households are more likely to invest in land management technologies. On the contrary, the negative correlation between off-farm activities and soil bunds and *desho* grasses revealed that households regularly engaged in off-farm activities as a means of income earning were less likely to adopt soil bunds and desho grasses, with a decrease in probability of adoption by a factor of 1.32 %. This could be attributable to labor rivalry in off-farm activities and the use of soil bunds and desho grasses. Likewise [5,15,16,36], found that off-farm activity had an adverse association with the application of soil and stone bunds because it prohibited the use of labor-intensive practices. Our analysis proved mixed results between off-farm activities and the adoption of land management technologies, implying that the relationship between off-farm activities and adoption decisions varies by technology.

As shown in Table 6, access to extension services (contact with development agents) was positively and significantly associated with the adoption of soil bunds ($p < 0.01$), stone bunds ($p < 0.05$), and a combination of soil bunds and desho grasses ($p < 0.01$). This suggests that households that interact frequently with development agents have received information about the advantages of LMTs, making them more likely to implement soil bunds, stone bunds, and integrated land management practices than those who do not have access to extension workers. Our findings are consistent with the previous studies [9,10,36,61,70], which found that households that regularly interact with extension experts are more likely to receive better information about management practices, maintain them well, and adopt the technologies than households that do not have access to extension agents On the contrary, studies reveal that development agents prioritized loan repayment and political concerns than land management and environmental issues, limiting rural households' interaction with extension agents, which has an adverse effect on land management practices [36]. This study also found that there is a significant positive association between training and adoptions of stone-face soil bunds ($p < 0.01$) and application of soil bunds plus desho grasses ($p < 0.01$) (Table 6). This signifies that households that received training related to LMTs had an increasing probability of adopting stone-face soil bunds by 0.58 % and soil bunds plus desho grasses by 1.61 %. Furthermore, access to training and awareness creation related to land management technology is crucial in improving the adoption of integrated land management technologies. This finding is consistent with those of [5,34,63,71], who suggested that raising awareness about land management practices through training is an essential institutional factor that encourages rural households to adopt various management practices to reduce soil erosion, improve soil nutrients, and maintain the ecological balance of the surrounding environment.

The coefficient of farm distance is significantly and positively correlated with the application of manure at the 5 % level of significance. This implies that as the distance of the household farm decreased by 1 km (km), the probability of adopting manure technologies increased by 0.15 %. It could be true that hauling and preparing manure and compost is easier on homestead lands than on the farthest farmlands. This is consistent with the result of [39], who verified that the application of manure and compost is significantly correlated with plots located near residences. The study found that farm distance is significantly and negatively correlated with agroforestry at the 5 % level of significance. However, it is negatively associated with soil and stone bunds, stone-face soil bunds, and fanya-juu, which is not statistically significant (Table 6). Our observations revealed that households with farmlands located far away from their homes were deterred from using LMTs. This coincides with [81], who stated that farthest plots need energy and time, so farmers are less likely to adopt technologies in their farthest farmlands. Interestingly, access to formal credit was found to be significantly and positively associated with stone bunds, stone-face soil bunds, and the combination of soil bunds and *desho* grasses at 5 % level of significance (Table 6). The study found that household heads that received formal credit services are more likely to utilize stone bunds, stone-face soil bunds, and combined land management technologies (soil bund plus desho grasses). The current study coincides with the notion of [1,72,73] reported that access to formal credit services is one of the main factors encouraging farmers to adopt various land management technologies in their respective studies. On the contrary [10], observed that access to credit had a negative impact on the sustained adoption of LMTs because farm households do not use credit for the proper reasons.

Concurrently, the FGDs and KII participants confirmed that households who contact with development agents were implementing, repairing, and distributing technologies on their farmlands. Moreover, the majority of KII groups responded that households that had regular contact with development agents were able to get crucial information on how to create, execute, and distribute the practices on their farmlands. However, some of them stated that currently development agents are focused on returning loans and political issues rather than achieving their goals, which are to advise, train, monitor, and share relevant information related to land management practices and environmental concerns with farm households. Most FGD participants reported that access to formal credit resolved their financial constraints, enabled to purchase of agricultural inputs, adoption of LMTs, and reduced farmland flooding.

Social asset variables such as village membership are one of the most important determinants that influence households' decisions to adopt LMTs [34]. The findings of this study exhibited that social asset variables (village membership) are significantly and positively correlated with soil bunds ($p < 0.01$), manure, and the combination of soil bunds and desho grasses at the 5 % level of significance (Table 6). This indicated that households involved in village memberships increased the probability of soil bund adoption by.28 %, manure application by.35 %, and combined technologies by.25 %. According to KII participants, *Wenfe*l, *Debo*, and *Senbetie* are known social asset (village organization) memberships that solve farmers' labor constraints to adopt LMTs. Moreover, the majority of FGD participants reported that village membership assisted the farmers in fostering team spirit and solving their common problems like soil erosion, flooding, and adjacent conflicts. Empirical studies elsewhere in Ethiopia indicated that households that involved in village memberships were more likely to adopt LMTs than households that were not involved in village organizations [60,74,75]. However, our result revealed that village membership was significantly but negatively correlated with the adoption of stone bunds.

Households' perceptions of soil erosion are significantly and positively associated with fanya-juu ($p < 0.05$) and combined technologies such as soil bunds and desho grasses ($p < 0.01$). However, it significantly and negatively correlated with manure ($p < 0.05$) (Table 6). The study found that households that perceive the negative impacts of soil erosion on agricultural production are more likely to adopt erosion control practices like fanya-juu and combined technologies. Concurrently, the majority of FGD participants stated that in erosion-prone landscape sites, most households choose to employ stone bund, terraces, and soil bunds integrated with desho grasses, and fanya-juu rather than applying manure. This is comparable to the decisions of [57,71,76,77], who noticed that a higher perception of soil erosion was negatively associated manure application since manure was easily swept away by erosion. Our result in the MVP modeling approach revealed that land rent and crop sharing were significantly and negatively correlated with particularly physical land management technologies (Table 6).

3.5. Factor determining the adoption intensity: ordered probit model

The result of the ordered probit model on the determinants of intensity (the number) of land management technologies adopted in the Goyrie watershed are presented in Table 7.The model's log-likelihood ratio (LR) test ($\chi 2$ (16) = 32.49, $p = 0.00$) was statistically significant at the 1 % level, indicating that the model fit the data well. The result showed that age ($p < 0.05$), education ($p < 0.05$), family size ($p < 0.01$), TLU ($p < 0.1$), access to extension services ($p < 0.05$), training opportunities ($p < 0.05$), and village membership ($p < 0.01$) were found significantly and positively influenced the number of LMTs adopted in the Goyrie watershed. This implies that households with older heads, higher level of education, larger families, more livestock, better access to extension services, more training opportunities, and membership in village organization were more likely to adopt multiple LMTs. When households become members of village institutions such as *Wenfel, Debo*, and *Senbteie*, their chances of adopting more than one or two LMTs increased by 60 %. On the contrary, when households' land holding size reduced by 1 ha, the likelihood of implementing more than one or two LMTs decreased by 24 %. Moreover, if household's perceptions of the benefits of the technology decrease, the likelihood of adopting a number of land management technologies decreases by 26 %. In the study watershed, households that rely on crop sharing were found to decrease the intensity (number) of land management technology adoptions by 28 %, holding other factors constant in the study watershed (Table 7).

4. Conclusion and policy implications

The findings of this study indicated that nearly 17 % of the respondents had adopted a single LMT, while 50 % had adopted only two types of LMTs on their plot of land. The result showed that more than half of respondents applied less than three types of LMTs. The most widely adopted LMTs in the watershed were soil bunds (67 %), stone-face soil bunds (65 %), stone bunds (54 %) and soil bunds plus desho grasses (50 %). The MVP covariance matrixes regression approach revealed that there are both complementary and interchangeable between adopted LMTs. The highest complementary effects were observed in mixed soil bunds plus desho grasses and manure applications (60 %), followed by soil bunds plus desho grasses and stone bunds (59 %) and stone bunds and agroforestry practices (37 %). However, soil bunds and fanya-juu, as well as manure application and agroforestry, were found to be interchangeable for one another. Additionally, the likelihood ratio (LR) was significant at 1 % and assumptions that all rho values were jointly equal to zero was rejected, indicated that households adoption of various LMTs were interrelated.

Our result indicated that sex, education, family size, landholding size, access to development agents, access to credit institutions and training were found to be positively associated and increased the probability for adopting multiple LMTs in the Goyrie watershed. Whereas age, land rent and crop sharing were found negatively and decreased the likelihood of households decision to adopt LMTs. Depending on the type of LMT, livestock ownership, off-farm activities, farm distance, village membership, perception of soil erosion and prescription on the benefits of LMTs have mixed significant roles for the probability of adopting multiple LMTs in the Goyrie watershed of southern Ethiopia. The ordered probit model result showed that village membership, contact with development agent, training, family size and education had substantial and positive influence on the intensity of LMTs, held other variables are constant. We observed social asset variables like village membership play an essential role for enhancing the probability of households adopting and intensity of LMTs in the study area. Being village members, households' labor constraints can easily be solved by adopting the technologies; they shared experience from groups, solved their common problems like flooding, and made team spirits. Therefore, policies and initiatives should support village memberships by providing services, materials, incentives, and awareness to promote sustainable technology adoptions. A farmer training center (FTC) should be established to raise rural households' awareness of the benefits of using multiple LMTs, as well as their complementary and interchangeable natures. Development agents should routinely follow up, monitor, and advise rural communities on LMTs and related difficulties, rather than focusing solely on returning agricultural loans and political concerns.

5. Limitations of the study

The study tried to analyze factors influencing households' decisions to adopt LMTs and the intensity of the adopted technologies. Although the study gives significant insights, it does have certain drawbacks. The findings were based on cross-sectional data gathered from 291 respondents. This study did not conduct a cost-benefit analysis of the adopted technology, taking into account households' opinions of short- and long-term benefits. As a result, households' views of short- and long-term gains, as well as cost-benefit analysis, which influence LMT adoptions, should be examined further using longitudinal data.

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Dessalegne Chanie Haile: Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yechale Kebede Bizuneh:** Writing – review & editing, Validation, Supervision, Data curation, Conceptualization. **Mulugeta Debele Bedhane:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Abren Gelaw Mekonnen:** Writing – review & editing, Validation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the results reported in our work over the last three years.

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Appendix A. Supplementary data

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