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Determinants of tree lucerne adoption and income among smallholder farmers in Ethiopia's highlands

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Abstract

Tree lucerne (Chamaecytisus palmensis) is a multipurpose fodder tree promoted in Ethiopia to address livestock feed shortages while supporting climate-smart and income-diversifying farming systems. However, empirical evidence on the factors influencing its adoption and the income gained from tree lucerne sales remains limited. This study examines the determinants of tree lucerne adoption and income from tree lucerne sales in South Wollo, Ethiopia, using data from 400 randomly selected smallholder households. We used a two-part modeling framework that combines a probit model and a generalized linear model. The results show that adoption is significantly influenced by livestock ownership, household size, landholding size, frequency of extension contact, soil fertility status, gender of the household head, market distance, and membership in local associations. Conditional on adoption, income from tree lucerne sales is primarily driven by livestock ownership and extension contact. The estimated mean conditional income from tree lucerne sales among adopters (12,506 Ethiopian birr [ETB]) is nearly three times the unconditional mean income observed across all households (4,340 ETB). This gap underscores tree lucerne's income potential and supports policy efforts to scale it to a broader set of farmers. As a result, tree lucerne plantations should be promoted as part of the national sustainable land management program and climate-resilient green economy strategy by strengthening extension services and reducing adoption barriers to enhance tree lucerne's contribution to improving farmers' incomes.

Keywords: Adoption, Income, South Wollo, Tree lucerne, Two-part model

Background

Livestock production in Ethiopia, as in much of Sub-Saharan Africa, remains constrained by chronic feed shortages and the poor nutritional quality of available forage. Smallholder farmers rely predominantly on cereal crop residues and communal grazing lands, both of which decline markedly in quantity and quality during the dry season. This seasonal feed scarcity, particularly acute in crude protein and digestibility, leads to reduced milk yield, slower weight gain, and impaired reproductive performance, ultimately undermining household income, food security, and livelihood resilience (Field

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and Kassa 2008; Herrero et al. 2013; Duncan et al. 2016; Bewket et al. 2025). Given the central role of livestock in most African countries, including Ethiopia's mixed crop–livestock systems, addressing feed constraints has long been identified as one of the most critical pathways to enhancing agricultural productivity and reducing rural poverty (FAO 2018; ILRI 2021).

Substantial research and development efforts across Sub-Saharan Africa have focused on improved forage technologies, including improved grasses, herbaceous legumes, and multipurpose fodder trees. These technologies aim not only to increase the quantity and quality of livestock feed but also to improve soil fertility, rehabilitate land, and enhance climate resilience (Thornton and Herrero 2014; Lemaire et al. 2019). Empirical evidence indicates that adopting improved forages can generate multiple livelihood benefits beyond livestock productivity, including enhanced market participation, income diversification, and reduced vulnerability to climate shocks (Kabunga et al. 2012; Shikuku et al. 2017). For example, Ayuko et al. (2024) report that Kenyan farmers adopting Napier grass plantations achieved a 25% increase in annual household income compared with those relying on natural grazing. Income and productivity gains from improved fodder adoption have also been documented in Ethiopia and neighboring countries (Mekonnen et al. 2017; Gebremedhin et al. 2019; Tessema et al. 2020), reinforcing the notion that fodder technologies play a transformative role in smallholder livestock systems. Within this broader category, multipurpose livestock forage trees such as Sesbania sesban and Leucaena leucocephala have received sustained attention in Ethiopia for their multifunctional roles. Farmers value these species not only for high-quality fodder but also for enhancing soil fertility through biological nitrogen fixation, controlling erosion, providing fencing, and supplying fuelwood (Kassa 2008; Franzel et al. 2014). Feeding trials show that incorporating tree legumes into cereal-residue-based diets, often at 25–30% of the ration, significantly improves feed intake, digestibility, weight gain, and reproductive performance in small ruminants and dairy cattle (Kassa 2008; Patra 2009; Melesse et al. 2016). These findings underscore the technical potential of fodder trees to address livestock feed scarcity and land degradation simultaneously.

More recently, tree lucerne (Chamaecytisus palmensis), locally known as "tagasaste", has emerged as a promising yet relatively underexplored fodder option in Ethiopia. Nutritionally, it is highly palatable and rich in crude protein, making it particularly effective as a supplement to low-quality crop residues during the dry season (ILRI 2019; Mekonnen et al. 2023). Agronomically, it is adaptable to a range of agroecological conditions and can be established in homesteads, field boundaries, and outfields. However, successful establishment depends heavily on household management practices such as fencing, watering, mulching, and soil fertility improvement (Mekonnen et al. 2017, 2023). Beyond livestock feeding, tree lucerne contributes to soil conservation, increases biomass availability, and offers opportunities for income diversification through fodder sales and intensified market-oriented livestock production (Franzel et al. 2014; Mekonnen et al. 2017).

Despite documented agronomic and economic benefits of improved forage technologies, adoption among smallholder farmers remains limited, creating an "adoption paradox" (Legesse et al. 2024). Although improved forages are technically superior, structural constraints, including land scarcity, competition with food crops, labor shortages, risk

aversion, and weak extension and market institutions, continue to hinder widespread uptake (Feder et al. 1985; Pannell et al. 2014; Barrett et al. 2019; Gebremedhin et al. 2019; Legesse et al. 2024). Empirical studies consistently show that adoption is more likely among relatively better-off, market-oriented households engaged in dairy production or livestock fattening, whereas poorer, subsistence-focused farmers face higher entry barriers (Field and Kassa 2008; Mekonnen et al. 2019; Shiferaw et al. 2021). Moreover, landholding size, family labor availability, access to extension services, and proximity to markets significantly shape adoption decisions and intensity (Mekonnen 2019; Legesse et al. 2024). Despite growing recognition of tree lucerne as a high-quality feed and income-generating option, evidence on the drivers of adoption and the income derived from tree lucerne sales remains limited. This study contributes by analyzing the determinants of adoption decisions and the income associated with tree lucerne sales, offering insights to promote inclusive and sustainable livestock intensification in Ethiopia and similar settings.

Conceptual and analytical framework

Conceptual framework

This study is guided by Rogers' innovation diffusion theory (IDT), which conceptualizes technology adoption as a process shaped by farmers' awareness, evaluation of benefits, and capacity to implement innovations in their production systems (Rogers 2003). For smallholder farmers, these processes are mediated by household resource endowments, institutional support, market access, and biophysical conditions (Feder et al. 1985; Shiferaw et al. 2021). Drawing on this perspective, the conceptual framework shows how institutional, socioeconomic, and biophysical factors jointly influence farmers' decisions to adopt tree lucerne and the income derived from tree lucerne sales. Tree lucerne is increasingly recognized in Ethiopia as a high-quality livestock feed. Evidence from East Africa shows that integrating fodder trees into crop–livestock systems can substantially improve livestock productivity and household income (Franzel et al. 2014; Place et al. 2009; Mekonnen et al. 2023). Accordingly, adoption reflects the interaction among farmers' demand for reliable feed resources, access to extension and information, and the suitability of local agroecological conditions (Balehegn 2020; ILRI 2019). Consistent with IDT, adoption is more likely when perceived benefits are observable, compatible with existing farming systems, and supported by enabling institutions (Rogers 2003).

Existing studies show that institutional, socioeconomic, and biophysical factors influence farmers' adoption decisions and income outcomes (Feder et al. 1985; Kabunga et al. 2012; Benjamin 1992; Singh et al. 1986; Shiferaw et al. 2021; Melesse et al. 2016; Mekonnen et al. 2023; Legesse et al. 2024). Extension services play a central role in reducing uncertainty and accelerating diffusion by providing technical knowledge and demonstrations, while social networks facilitate peer learning and information exchange (Feder et al. 1985; Kabunga et al. 2012; Legesse et al. 2024). Socioeconomic characteristics, including livestock ownership, family size, education, landholding size, and gender of the household head, shape both the demand for improved feed and the capacity to establish and manage tree lucerne plantations (Benjamin 1992; Singh et al. 1986; Shiferaw et al. 2021). Biophysical conditions are also critical: Soil fertility influences adoption incentives, as tree lucerne enhances soil quality through nitrogen fixation and organic matter

addition, while market proximity affects transaction costs, access to inputs, and opportunities for commercialization (Melesse et al. 2016; Mekonnen et al. 2019, 2023).

In addition to adoption decisions, the framework examines factors that influence income from tree lucerne sales. It distinguishes between conditional income among adopters and unconditional income across all households, thereby highlighting a diffusion gap between participants and non-participants. Based on this framework, the study tests two hypotheses. First, household resource endowments and access to information are expected to increase the likelihood of adopting tree lucerne plantations. Second, livestock ownership and extension contacts are hypothesized to have positive, complementary effects on income from tree lucerne sales. Figure1 summarizes the conceptual framework by linking institutional, socioeconomic, and biophysical factors to farmers' adoption decisions regarding tree lucerne plantations and to the determinants of income from tree lucerne sales.

Analytical model

In our study setting, non-adopters of tree lucerne earn zero income from tree lucerne sales. These zeros are not censored or missing outcomes; instead, they are structural zeros generated directly by the adoption decision. Because non-adopters do not plant tree lucerne, they cannot produce or sell it, and therefore, their income from the tree is necessarily zero. Importantly, these structural zeros do not represent an optimal choice within a continuous decision-making process (as in a corner solution model). Instead, they arise entirely from non-participation in tree lucerne planting, making the zero outcome a structural feature of the production decision rather than an optimal choice. On the other hand, adopters have positive incomes. In such cases, using ordinary least squares (OLS) would yield biased and inconsistent estimates because it ignores the mass of structural zeros in the outcome variable. Likewise, the Heckman selection model assumes a latent continuous outcome that exists for all individuals but is only observed for a selected subsample, relying on joint normality of errors and credible exclusion restrictions for identification. This framework does not fit our context,

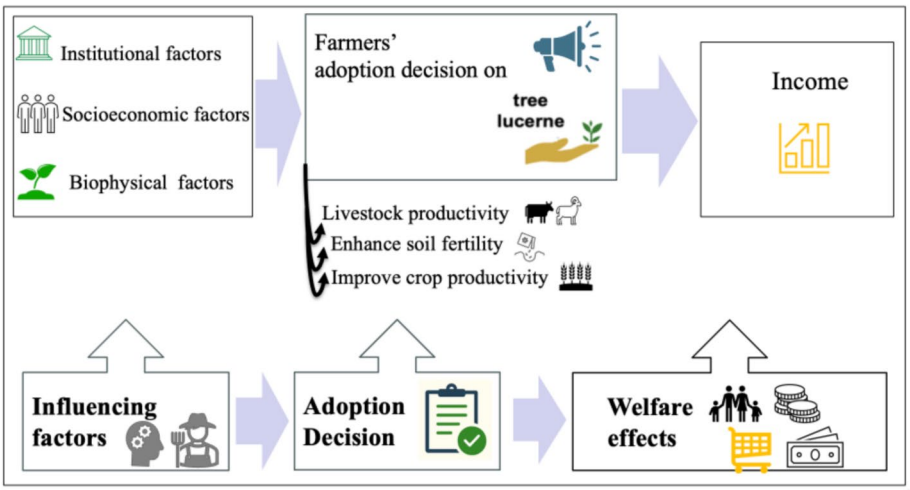


Fig. 1 The conceptual framework of the study

since non-adopters in our study have a structural zero income from tree lucerne due to non-adoption. In contrast, this study examines the determinants of adoption and the income of adopters. Moreover, the Tobit (corner solution) model is not appropriate for estimation because it treats zero outcomes as optimal choices within a continuous decision process. As a result, we use the two-part model, originally introduced by Cragg (1971) and commonly used in agricultural and health economics (e.g., Wooldridge 2010; Marenya & Barrett 2007), to handle structural zero incomes observed in the data. This two-part model clearly separates the factors influencing the decision to adopt (extensive margin) from the income generated among adopters (intensive margin). In the first part, we estimate the likelihood of adopting tree lucerne using a probit model. In the second part, we analyze income among adopters using a generalized linear model (GLM) with a gamma distribution and log link, which is suitable for strictly positive, right-skewed income data.

Part 1: Probit model estimation for adoption decision.

We assume a latent binary variable, which is modeled in Eq. (1).

$$T_i^* = \beta Z_i + \varepsilon_i \varepsilon_i \sim N(0,1)$$

$$T_i = \begin{cases} 1 if T_i^* > 0 (\text{Adopter } t) \\ 0 \, otherwise (Non - adopter \, t) \end{cases} \quad (1)$$

where T_i stands for adoption variable (adopter or non-adopter); Z_i is a vector of covariates; ε_i is an error term $\sim N(0,1)$; and β is the parameters to be estimated.

Thus, the probit model estimates the probability of adoption of tree lucerne plantation as follows:

$$\Pr(T_i = 1 | Z_i) = \Phi(Z_i^T \beta) \quad (2)$$

where T_i is the binary adoption indicator; Z_i are covariates; $\Phi(.)$ is the cumulative distribution function (CDF) of the standard normal distribution; and β is a vector of coefficients to be estimated.

Part 2: Two-part model estimation (GLM estimation).

Let $Yi \geq 0$ represent the annual income from tree lucerne sales and define participation $T_i = 1\{X_i > 0\}$. Then, the conditional on tree lucerne adoption decision (Ti=1), income is modeled as:

$$\mathrm{E}(Y_i | T_i = 1, X_i) = \exp(X_i^T \gamma) \quad (3)$$

where Y_i is annual income from tree lucerne sales; X_i is a vector of covariates (same as Z_i); γ are the GLM coefficients to be estimated. A gamma distribution with a log link[1] function is employed to address the positive skewness in income among adopters.

Finally, the unconditional expected income for each sample farmer (adopters and non-adopters) is computed as a post-estimation of GLM as follows:

[1] In two-part (hurdle) models, conditioning on participation is typically implemented by estimating the second-stage outcome equation on the subsample of participants. As a result, the participation indicator does not appear explicitly in the conditional mean function.

$$E[Y_i] = \widehat{p}_i * \widehat{\mu}_i \tag{4}$$

where $\widehat{p}_i = \Pr(T_i = 1|Z_i)$ is the predicted probability of tree lucerne adoption from the probit model.

$\widehat{\mu}_i = \Pr(Y_i|Y_i > 0 = 1|Z_i)$ is the expected income among adopters from the GLM estimation.

Research methods

Study area and intervention context

The study was conducted in the South Wollo Zone of the Amhara Region, Ethiopia, a highland agroecological area characterized by mixed crop–livestock farming systems. This zone is one of the most densely populated regions in the country, facing severe land degradation, recurrent droughts, and shrinking grazing lands. Farmers heavily depend on livestock for traction, food, and income; however, seasonal fodder shortages remain a constant challenge. To address this, the government and development partners have promoted livestock forage production since 2000. Building on these efforts, the South Wollo Zone Agriculture Office has been implementing community-based initiatives to adapt to climate change. In 2025, it launched the Legambo community-based climate change adaptation project (Washera project) in Legambo Woreda, funded by the Protestant Association Development (PAD) and the Church of Sweden. The project introduced the cultivation of tree lucerne in three kebeles of Legambo to supplement livestock feed with protein-rich forage, especially during the dry season. Tree lucerne is valued not only for its year-round fodder supply but also for its role in improving soil fertility, reducing erosion, and increasingly generating cash income from the sale of seedlings, cuttings, and fresh leaves. This study leverages the Washera intervention, which promotes tree lucerne plantations.

Sampling technique

A three-stage sampling process was used for this study. First, Legambo Woreda in the South Wollo Zone was purposively selected for its potential practitioners (adopters) of tree lucerne plantations, building on the Washera intervention implemented in recent years. Second, three kebeles (Tincha, Chuluke or Delel, and Sehada Qorkora) with a high prevalence of tree lucerne plantations were purposively selected, as these were the initial project sites (Legambo Woreda Agriculture Office 2021). Additionally, four control kebeles (Segno Gebeya, Merkemecha, Gurach or Buqas, and Dereba) were selected based on similar agroecological conditions and potential for livestock production; however, they were not beneficiaries of the Washera project. Finally, about 400 farmers, both adopters and non-adopters, were surveyed, comprising 206 adopters (51.5%) and 194 non-adopters (48.5%) (Fig. 2).

This distribution resulted from proportional random sampling within each kebele and reflects adoption patterns in the selected treatment sites. The three treatment kebeles, which were part of the Washera intervention, have high adoption rates and therefore contributed more adopters to the sample, whereas the four control kebeles, which have no tree lucerne adopters by design. The nearly balanced sample is not an over-representation of adopters but a direct outcome of proportional sampling across kebeles

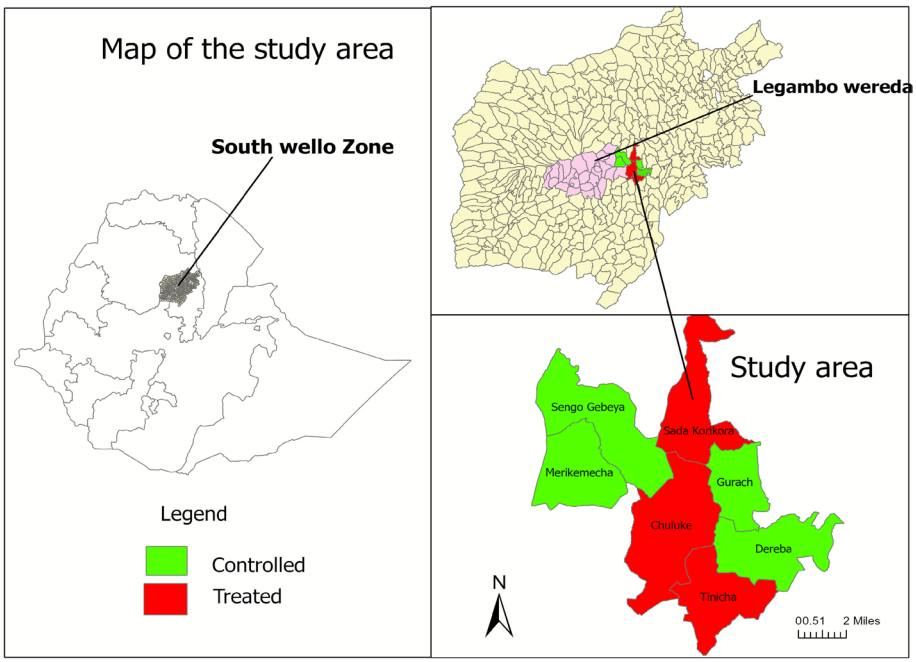


Fig. 2 The study area map

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Sample size determination

In this study, the target populations of selected kebele farmers are already known, and the population of Legambo Woreda is about 192,482 (94,400 males and 98,082 females) (Washera project of Legambo branch, 2016). Since the population is known, Yamane's (1967) sample size determination formula is appropriate. Thus, the sample size was determined by the following formula.

$$\mathbf{n} = \frac{\boldsymbol{N}}{1 + \boldsymbol{N}(\boldsymbol{e})^2} ==> \boldsymbol{n} = \frac{192,482}{1 + 192,482(0.05)^2} \approx 400$$

where n = sample size, N = population size, e = level of precision or the error that the researcher will tolerate. To calculate a representative sample with 95% confidence and a 5% margin of error because the population in the study area is homogeneous in terms of livelihood strategy, cultural, and other socioeconomic and institutional setups (Legambo Woreda Agriculture Office 2021).

Results and discussion

Descriptive statistics

Table 1 presents the summary statistics of farmers' socioeconomic and demographic characteristics for adopters and non-adopters of tree Lucerne plantations. Adopters earned an average of 12,570.25 Ethiopian Birr ETB[2](242.86 USD) from tree lucerne sales. The average livestock holding was 2.38 and 2.08 tropical livestock units (TLU) for adopters and non-adopters, respectively, which is a significant mean difference between the two groups. The majority of both adopters and non-adopters were male-headed. Adopters were slightly older on average (44.37 years) than non-adopters (42.17 years). The level of education was low and did not differ significantly between the groups. However, adopters had significantly larger family sizes, possibly providing more household labor for tree lucerne management. Adopters and non-adopters have 0.88 hectares and 0.79 hectares of farmland, respectively. The proportion of farmers with a mobile phone is generally high in the study area, regardless of phone type (button or smart). Adopters have a higher frequency of extension contact and membership in local associations than non-adopters. Differences in some socioeconomic and demographic variables in the t-test statistics suggest the presence of selection or hidden bias. As a result, we used propensity score matching (PSM) before estimating our two-part model to control for the selection bias. The nearest neighbor matching result is depicted in Appendix 1.

Figure 3 presents a descriptive comparison of farmers' self-reported soil fertility status between tree lucerne adopters and non-adopters. Among adopters, 31.55% classified their land as less fertile, 29.61% as moderately fertile, 20.87% as infertile, and 17.96% as fertile. In contrast, a larger share of non-adopters (35.57%) reported their land as infertile, followed by 23.71% as fertile, 23.20% as less fertile, and 17.53% as moderately fertile. These differences reflect variations in perceived soil fertility between the two groups but do not imply that soil fertility determines adoption behavior. The comparison simply

[2] ETB stands for Ethiopian birr. Calculated at 1 USD ≈51.76 ETB as of the physical year of 2022 at the time of data collection. World Bank: Official Average Exchange Rate in 2022. https://data.worldbank.org/indicator/PA.NUS.FCRF?end=2023&locations=ET

Table 1 Summary statistics

Variables	Full sample (400)	Adopters (206)	Non-adopters (194)	Difference	*t*-test statistics	
Income gained from tree lucerne sales in ETB	6473.68 (7002.83)	12,570.25 (4294.03)	0.00 (0.00)	12,570.25 (308.32)	40.7707	***
Livestock in terms of TLU[1]	2.24(0.83)	2.38 (0.83)	2.08 (0.79)	0.30 (0.08)	3.6916	***
Gender of the household head (1 = male; 0 = female)	0.89(0.31)	0.86(0.34)	0.92(0.26)	−0.06(0.03)	− 1.8949	
Age of the household head (years)	43.30(11.19)	44.37(12.23)	42.17(9.87)	2.19(1.11)	1.9710	**
Level of education of the household head (years of schooling)	2.78(3.49)	2.84(3.56)	2.71(3.41)	0.13(0.35)	0.3825	
Family size in the household (number)	4.52(1.42)	4.79(1.42)	4.22(1.37)	0.57(0.14)	4.0977	***
Land size (hectare)	0.84(0.51)	0.88(0.52)	0.79(0.49)	0.09(0.05)	1.7894	
Distance to primary market (walk in minutes)	33.68(12.65)	31.38(11.07)	36.11(13.75)	− 4.72(1.24)	− 3.7955	***
Mobile ownership (1 = yes; 0 = no)	0.78(0.41)	0.83(0.37)	0.73(0.45)	0.11(0.04)	2.6365	***
Frequency of extension contact in a year (number)	14.07(6.44)	16.29(7.57)	11.71(3.74)	4.59(0.60)	7.6069	***
Membership in rural associations for enhancing their social capital (1 = member; 0 = non-member)	0.52(0.50)	0.59(0.49)	0.45(0.49)	0.14(0.049)	2.9002	***

Statistical significance is indicated by *** for p 0.01, ** for p 0.05, and * for p 0.10

[1] TLU stands for tropical livestock unit. TLU stands for Tropical Livestock Unit. According to Storck et al. (1991) cited by Getachew (2010), the conversion factors for each livestock group are as follows: Calf = 0.34, Heifer = 0.75, Cow and ox = 1.0, Horse = 1.1, Donkey = 0.7, Sheep and Goat = 0.13, and Chicken = 0.013

summarizes how adopters and non-adopters differ in observable characteristics. Any inference regarding the role of soil fertility in influencing adoption decisions is therefore deferred to the multivariate regression analysis, where other confounding factors are explicitly controlled for.

Factors influencing the adoption of tree lucerne plantation

As shown in Table 2, having livestock significantly increases the likelihood of tree lucerne adoption, with a one-unit increase in herd size (TLU) raising the probability

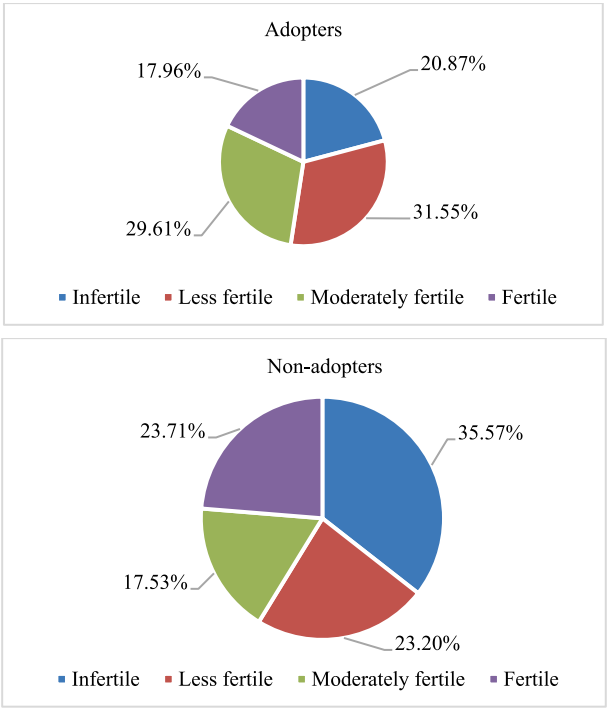


Fig. 3 Farmers' self-response on soil fertility status of the farmland across adopters and non-adopters

Table 2 Factors influencing farmers' adoption decision of tree lucerne plantation

Variables	Coefficients (RSE)		Marginal effects (SE)	
Livestock in terms of TLU	0.264(0.091)	***	0.080(0.027)	***
Gender of the household head	−0.485(0.247)	**	−0.148(0.074)	**
Age of the household head	0.012(0.008)		0.003(0.002)	
Family size of the household	0.174(0.057)	***	0.052(0.016)	***
Distance to the primary market	−0.019(0.006)	***	−0.006(0.002)	***
Mobile ownership	0.272(0.169)		0.083(0.051)	
Frequency of extension contact	0.987(0.016)	***	0.030(0.004)	***
Education level of the household head	0.013(0.024)		0.004(0.007)	
Land size in hectares	0.281(0.142)	**	0.086(0.043)	**
The soil fertility status of the farmland (infertile is the base)				
Less fertile	0.509(0.192)	***	0.161(0.060)	***
Moderately fertile	0.484(0.204)	**	0.153(0.064)	***
Fertile	−0.005(0.206)		−0.001(0.063)	
Membership in local association for social capital (1 = member; 0 = non-member)	0.253(0.144)	*	0.077(0.043)	*
Constant	−2.935(0.575)	***		
Log pseudolikelihood	−210.250			
LR chi2 (13)	117.38	***		
Pseudo R^2	0.2182			
Observation	388			

Statistical significance is indicated by *** for p 0.01, ** for p 0.05, and * for p 0.10

Here RSE represents robust standard error, and SE represents standard error

of tree lucerne adoption by about 8%. This suggests that farmers with larger herds are more motivated to adopt tree lucerne plantation, both to secure a steady supply of protein-rich fodder and to create potential marketable surpluses. Thus, the adoption of tree lucerne plantation underscores a demand-pull effect, where herd size encourages the expansion of forage cultivation. The finding aligns with those of Ayal and Mamo (2024), who found that livestock-rich households are more likely to adopt climate-smart livestock practices, mainly because they face greater feed demand and stand to gain more from sustainable forage sources. Gender of the household head is also a significant factor in tree lucerne adoption. Male-headed households are approximately 14.8% less likely to adopt tree lucerne than female-headed households. This may reflect the small-scale and complementary nature of tree lucerne cultivation, which is often managed on backyard plots or farm boundaries and may align more closely with women's roles in livestock feeding. Household size has a positive and statistically significant effect on adoption, with an average marginal effect of 5.2%. This suggests that greater availability of family labor facilitates the establishment and management of tree lucerne plantations. This finding aligns with the study by Tesfaye and Tessema (2023), who found that family labor availability strongly predicts the adoption of improved animal forages in Ethiopia. Similarly, land size positively affects tree lucerne adoption, with a one-hectare increase in farm size raising the probability of adoption by about 8.6%, indicating that farmers with more land can allocate plots to forage production without crowding out staple crops. The frequency of extension contact has a positive and highly significant effect, with a marginal effect of about 3%, underscoring the role of advisory services in promoting improved forage technologies. In contrast, distance to the primary market negatively affects adoption, reducing the probability by about 0.6%, likely due to higher transaction costs and weaker market incentives for livestock-oriented investments. Soil fertility status significantly shapes adoption decisions on tree lucerne plantation. Relative to infertile plots, farmers cultivating less fertile and moderately fertile land are more likely to adopt tree lucerne, with marginal effects of 16.1 and 15.3%, respectively. In contrast, fertile plots show no statistically significant effect. This suggests that farmers tend to allocate tree lucerne to plots with moderate productive potential, while reserving fertile land for food or cash crops. This result aligns with the study by Tesema et al. (2025), who reported that smallholders in Ethiopia are more likely to invest in agroforestry species such as tree lucerne on moderately degraded soils because they expect greater soil fertility gains and long-term productivity benefits, while they are less willing to invest on severely degraded land due to the high risk of crop failure and low short-term returns. Membership in local associations positively influences the adoption decision on tree lucerne. Farmers who are members of local associations are about 7.7% more likely to adopt tree lucerne than non-members, highlighting the role of social networks and collective learning in facilitating technology uptake, although the effect is marginally significant. This supports evidence that social networks are crucial in promoting agricultural innovation by closing information gaps, building trust, and reducing farmers perceived risks (ILRI 2019).

Income effects: GLM analysis

Table 3 shows the factors influencing farmers' income from tree lucerne sales using GLM estimation. The generalized linear model (GLM) with a gamma distribution and log link demonstrated a good fit for the positively skewed income data from tree lucerne sales. The model achieved a log pseudolikelihood of −696.638, with a low-scale parameter (0.135), indicating limited residual dispersion. Both the deviance (39.4) and Pearson chi-square (24.98) statistics were low, and their values relative to the residual degrees of freedom (0.14 and 0.14, respectively) were well below one, suggesting no evidence of overdispersion and an appropriate model setup. The AIC (7.17) and BIC (−933.6) values further support the model's suitability, as lower values indicate a better fit while penalizing model complexity. The variance function and

Table 3 Factors affecting farmers' income gained from tree lucerne sales using GLM estimation

Variables	Coefficients (RSE)	
Livestock in terms of TLU	0.064(0.030)	**
Gender of the household head	−0.024(0.099)	
Age of the household head	−0.002(0.002)	
Family size in the household	0.001(0.025)	
Distance to the market	0.002(0.002)	
Mobile ownership	−0.002(0.081)	
Frequency of extension contact	0.018(0.004)	***
Education level of the household head	−0.008(0.008)	
Land size in hectares	0.025(0.050)	
Status of the soil fertility of the farmland (infertile is the base)		
Less fertile	0.003(0.072)	
Moderately fertile	−0.062(0.073)	
Fertile	−0.057(0.095)	
Membership in local association for social capital (1 = member; 0 = non-member)	0.013(0.051)	
Constant	2.22(0.269)	***
Log pseudolikelihood	−696.638	
Residual degree of freedom (df)	184	
Scale parameter	0.135	
Deviance	39.40	
Pearson	24.98	
(1/df) Deviance	0.1357	
(1/df) Pearson	0.135	
AIC	7.17	
BIC	−933.633	
Variance function	$v(u) = u^2$	
Link function	g(u) = ln(u)	
Observation	198	
The mean conditional expected tree lucerne income (for adopters only)[1] in thousands	12.506(0.289)	***
The mean unconditional expected income (both adopters and non-adopters) in thousands[2]	4.340(2.588)	***

Here RSE represents robust standard error, and SE represents standard error

[1] For the conditional mean expected income among adopters only, we used the margins command after the generalized linear model (GLM), which directly provides the *p*-value for the mean income of tree lucerne sales conditional on adoption

[2] We used a one-sample *t*-test to assess the unconditional mean expected income from tree lucerne across the entire sample, to test whether the average effect is statistically different from zero. This approach confirms that tree lucerne currently contributes positively to household income at the population level, and it does not involve any group comparison

log link appropriately capture the multiplicative mean–variance relationship typical of income data. Overall, these diagnostics confirm that the gamma–log GLM specification provides a reliable and statistically valid framework for analyzing the determinants of tree lucerne income among adopter households.

Livestock ownership emerges as a key determinant of income from tree lucerne sales. The estimated coefficient implies that a one-unit increase in tropical livestock units (TLU) is associated with approximately a 6.4% increase in expected income from tree lucerne. This positive relationship indicates that households with larger herds tend to generate higher income from tree lucerne sales. Rather than crowding out sales through higher on-farm feed consumption, larger livestock holdings appear to be associated with production at a scale sufficient to generate marketable surpluses. This suggests that livestock ownership complements the commercialization of tree lucerne once adoption occurs, reinforcing its role as both a feed and an income-generating activity. This finding is consistent with Ayal and Mamo (2024), who show that livestock-rich households are more likely to benefit from climate-smart livestock practices due to higher feed demand and more substantial incentives to invest in improved forages. It also aligns with Hailecherkos et al. (2021), who demonstrate that tree lucerne can substitute for costly protein supplements and improve livestock productivity and profitability.

Extension services play a central role in shaping income outcomes among adopters. The frequency of extension contact has a positive and highly significant effect, with each additional contact increasing expected income from tree lucerne sales by about 1.8%. This highlights the knowledge-intensive nature of forage production and utilization, in which appropriate establishment, management, and harvesting practices are critical for achieving higher yields and better-quality fodder. The result supports existing evidence that weak research–extension–farmer linkages constrain the economic potential of improved forages in Ethiopia (Tesfaye and Tessema 2023; Ayal and Mamo 2024). The positive extension effect suggests that, conditional on adoption, improved access to technical advice can substantially enhance the income benefits derived from tree lucerne. In contrast, several household and farm characteristics, including gender, age, education, mobile phone ownership, land size, membership in local associations, distance to market, and soil fertility, do not show statistically significant effects on tree lucerne income among adopters. This suggests that once households have adopted tree lucerne and participate in sales, income differences are driven primarily by livestock endowments and access to extension services rather than by broader socioeconomic or biophysical characteristics. As shown earlier, these factors may be more important in shaping adoption decisions than in determining income levels conditional on adoption.

The estimated mean conditional expected income from tree lucerne sales among adopters is 12,506 ETB (approximately 242 USD), about 188% higher than the unconditional mean of 4,340 ETB (approximately 84 USD) across all households, including non-adopters. This large proportional difference reflects the prevalence of structural zeros among non-adopting households that do not participate in tree lucerne markets. Accordingly, the unconditional mean captures both market participation and earnings (the extensive margin), whereas the conditional mean reflects income

intensity among participating households (the intensive margin), not a causal impact of adoption. The results are consistent with earlier evidence that improved forage technologies offer substantial economic benefits but remain underutilized (Tesfaye and Tessema 2023).

Conclusions and policy implications

Conclusions

Tree lucerne has the potential to play a dual role in Ethiopia's mixed crop–livestock systems by improving livestock feed availability and providing an additional source of farm income. Despite its relevance, empirical evidence on the drivers of its adoption and the income derived from tree lucerne sales has been limited. This study identifies the factors influencing tree lucerne adoption decisions and income earned from tree lucerne sales using a random sample of 400 smallholder farmers in the South Wollo zone and a two-part modeling framework.

The results indicate that household resource endowments and access to information primarily shape the adoption of tree lucerne. Specifically, livestock ownership, household size, landholding size, frequency of extension contacts, soil fertility status, gender of the household head, and membership in local associations significantly influence farmers' decisions to adopt tree lucerne.

Among adopters, income from tree lucerne sales is driven mainly by livestock ownership, indicating that larger herds create a "*demand-pull*" incentive for farmers to adopt tree lucerne. More livestock increases the need for reliable, nutritious, and locally adaptable forage, which pulls farmers toward adopting new forage sources, such as tree lucerne. Moreover, extension support among the adopters enhances farmers' ability to manage tree lucerne efficiently and translate adoption into income gains. The mean conditional expected income from tree lucerne sales among adopters is nearly three times the unconditional mean income observed across all households. This gap underscores tree lucerne's income potential and supports policy efforts to scale it out to a broader set of farmers.

Policy implications and further research

The findings have several important policy implications for promoting the adoption of tree lucerne and maximizing its economic benefits. First, the strong role of livestock ownership in both adoption and income generation suggests that livestock-rich households can serve as effective entry points for scaling-up tree lucerne. Second, the significance of land size and soil fertility in adoption decisions highlights the need to integrate tree lucerne into broader land-use planning and sustainable land management initiatives. Promoting tree lucerne as part of Ethiopia's Sustainable Land Management Program and Climate-Resilient Green Economy strategy could generate multiple co-benefits, including improved livestock forage security, rehabilitation of moderately degraded land, and enhanced farm income. Third, because the frequency of extension contact strongly influences both adoption decisions and tree lucerne income, integrating tree lucerne promotion into Ethiopia's public extension system and farmer training centers could increase adoption and improve income from tree lucerne sales. Emphasis should be placed on practical demonstrations, farmer-to-farmer learning, participatory

training, and agroforestry-based extension approaches that support the effective establishment, management, and utilization of tree lucerne. Finally, the negative effect of market distance on adoption decisions indicates that remote farmers face additional constraints. While continued investment in market infrastructure remains important, policy interventions should also support forage-based self-sufficiency in remote areas to reduce vulnerability to feed shortages and market volatility.

Although this study offers a valuable empirical contribution by linking livestock forage adoption to improvements in farm income, it has some limitations. First, reliance on cross-sectional data limits the ability to observe the long-term effects of factors influencing tree lucerne adoption and income from tree lucerne sales. Second, while the study highlights farmers' self-perceived soil fertility, it does not examine the potential experimental effects of tree lucerne on soil fertility, including carbon sequestration and increases in phosphorus and potassium in farmland, which can boost crop productivity. Future research should use panel datasets to assess these long-term effects on soil fertility, particularly since tree lucerne is promoted as a climate-smart agricultural practice.

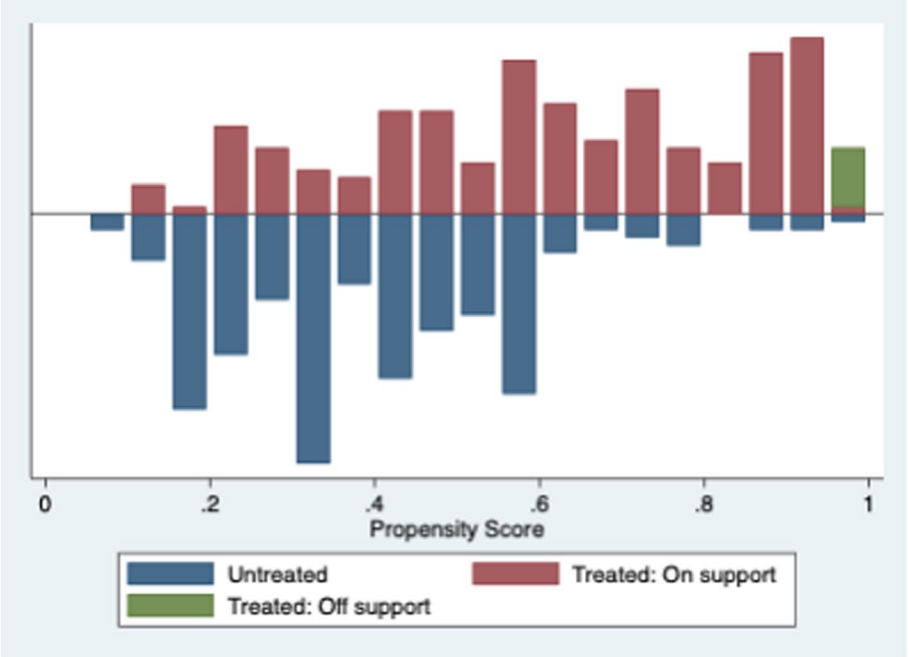
Appendix 1: PSM estimation to control for the selection bias before two-part model estimation

```
. probit treatment livestock age famsize distmarkt freqext

Iteration 0:   log likelihood = -277.07885
Iteration 1:   log likelihood = -226.11717
Iteration 2:   log likelihood = -225.01283
Iteration 3:   log likelihood = -225.01184
Iteration 4:   log likelihood = -225.01184

Probit regression                                 Number of obs =    400
                                                  LR chi2(5)    = 104.13
                                                  Prob > chi2   = 0.0000
Log likelihood = -225.01184                       Pseudo R2     = 0.1879
```

treatment	Coefficient	Std. err.	z	P>|z|	[95% conf.	interval]
livestock	.263847	.0841635	3.13	0.002	.0988895	.4288045
age	.0090465	.0064279	1.41	0.159	-.003552	.021645
famsize	.1735632	.0535956	3.24	0.001	.0685178	.2786086
distmarkt	-.0204072	.0055501	-3.68	0.000	-.0312852	-.0095292
freqext	.0973858	.0149524	6.51	0.000	.0680797	.1266918
_cons	-2.35207	.4497972	-5.23	0.000	-3.233656	-1.470483


0
.2
.4
.6
.8
1
Propensity Score
Untreated
Treated: On support
Treated: Off support

```
. pstest livestock age famsize distmarkt freqext, both
```

Variable	Unmatched / Matched	Mean Treated	Mean Control	%bias	%reduct |bias|	t-test t	t-test p>|t|	V(T)/ V(C)
livestock	U	2.3839	2.0831	37.0		3.69	0.000	1.11
	M	2.3906	2.4205	-3.7	90.1	-0.35	0.725	0.97
age	U	44.369	42.17	19.8		1.97	0.049	1.53*
	M	44.374	44	3.4	83.0	0.34	0.732	1.87*
famsize	U	4.7937	4.2216	41.0		4.10	0.000	1.08
	M	4.75	4.8788	-9.2	77.5	-0.95	0.340	1.01
distmarkt	U	31.383	36.108	-37.9		-3.80	0.000	0.65*
	M	31.313	32.449	-9.1	75.9	-0.93	0.352	0.67*
freqext	U	16.291	11.706	76.8		7.61	0.000	4.10*
	M	15.369	15.343	0.4	99.4	0.04	0.964	1.05

* if variance ratio outside [0.76; 1.32] for U and [0.76; 1.32] for M

Sample	Ps R2	LR chi2	p>chi2	MeanBias	MedBias	B	R	%Var
Unmatched	0.188	104.13	0.000	42.5	37.9	105.6*	2.52*	60
Matched	0.004	2.34	0.801	5.2	3.7	15.3	1.73	40

* if B>25%, R outside [0.5; 2]

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Author contributions
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Data availability
The authors declare that they are willing to submit the data at any time upon the publisher's request. The datasets used and analysed in the current study were made available to the authors upon reasonable request in STATA 17 format.

Declarations

Ethics approval and consent to participate
Not applicable, since our data don't include either a human or an animal experiment.

Competing interests
The authors declare no competing interests.

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