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Factors influencing adoption of climate-smart livestock practices in eastern Africa: insights from Uganda

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Introduction: Climate-smart livestock (CSL) practices have the potential to boost food production while improving the resilience and environmental sustainability of agricultural systems in sub-Saharan Africa. However, their adoption rates in the region remain low. Focusing on Uganda as a case study, multivariate Probit and Tobit regression models were applied to determine the factors influencing the adoption of CSL practices by dairy farmers.

Methods: Data were collected from 626 cattle-keeping households located in southwestern, central and eastern Uganda. The Adoption and Diffusion Outcome Prediction Tool (ADOPT) was used to predict the peak adoption levels and the number of years to reach these for CSL practices. The CSL practices identified and considered were forage cultivation, artificial insemination, routine vaccination and planting trees.

Results and Discussion: The results showed that 37%, 14%, 45% and 19% of cattle-keeping households grew forage, used artificial insemination, carried out routine vaccination and planted trees respectively. Forage cultivation, artificial insemination use and planting trees were positively and significantly influenced by access to credit and keeping farm records. Use of artificial insemination was associated with higher milk revenues. The household head's education level significantly influenced both the area allocated to forage cultivation and the number of trees planted. Households that allocated a large portion of their land to grazing cattle were less likely to grow forage and use artificial insemination. The number of trees planted was positively and significantly influenced by the age of the household head, household size, keeping farm records, access to credit and total adult equivalent (total number of working hours among adults per household). Forage cultivation and use of artificial insemination were practiced interdependently, pointing to the existence of complementarities and synergies between these two practices. The complementarities and synergies between both practices should be explored for increased adoption.

Conclusion: CSL practices should be introduced as a package of practices rather than as stand-alone practices, as their complementarities can enhance adoption. Development programs and policies should focus on improving access to credit, while investing in capacity building for record keeping, to increase the likelihood for adoption and intensification of CSL in the region.

KEYWORDS

adoption levels, climate-smart agriculture, dairy cattle, probit and tobit regression modeling, resilient livestock systems, sub-Saharan Africa

1 Introduction

Agriculture accounts for 23% of the gross domestic product (GDP) on average in sub-Saharan Africa (SSA), with its contribution varying between 20 and 50% among individual countries (Giller, 2020). The sector employs about 60% of the population, with over 75% of farms owned and managed by smallholder farmers (Langhans et al., 2022). Despite its importance, agriculture is constrained by low productivity, limited access to suitable technologies and high vulnerability to climate change impacts that threaten food security and rural livelihoods (Akinsemolu et al., 2024). The livestock sub-sector is particularly crucial for agriculture, contributing 5–15% of the regional GDP and nearly 60% of the agricultural GDP. Beyond income generation, the livestock sub-sector supports food and nutrition security by providing milk and meat; these are rich in protein, vitamin B12, iron, and calcium and thus provide nutrients essential for human growth and development (Murphy and Allen, 2003).

Livestock will remain central for SSA as the demand for animal-sourced food continues to rise, driven by urbanization, higher incomes and population growth (Bateki et al., 2019). With the region's population projected to surpass 2 billion by 2050, food production must increase accordingly. While this could enhance food security, stimulate economic growth and reduce poverty, it may also further strain limited resources like forests, arable land and fresh water. Moreover, food systems in SSA are on one hand increasingly affected by climate change impacts, including rising temperatures and declining rainfall (Akinsemolu et al., 2024). On the other hand, they also contribute significantly to driving climate change, accounting for 40 to 60% of the annual greenhouse gas (GHG) emissions (Omotoso and Omotayo, 2024). Thus, there is a need for climate-smart agriculture (CSA) approaches that can increase livestock productivity while simultaneously reducing environmental impacts.

CSA aims to sustainably boost productivity and food security while addressing climate change. Applying CSA offers a triple-win strategy of higher productivity, reduced GHG emissions, and climate change adaptation (Steenwerth et al., 2014). CSA initiatives have been implemented with benefits across SSA, including Eastern (Yihdego et al., 2015), Southern (Mutenje et al., 2019) and West (Antwi-Agyei et al., 2023) Africa. Applying CSA principles to livestock farming has resulted in climate-smart livestock (CSL) practices that enhance productivity, especially in resource-limited systems. A CSL practice is any intervention in livestock farming that reduces GHG emissions or emission intensity while increasing animal productivity and enhancing the system's resilience to climate change impacts, or improving resource use efficiency (Giro and Kumar, 2022). Evidence from SSA demonstrates the potential of CSL practices: for instance, the use of improved forage in Tanzania increased milk productivity (Mwendia et al., 2022), while improved grazing management in Kenya led to an increase in milk productivity, reduction of GHG emissions and adaptation to climate change (Bryan et al., 2011). Other examples are shown in Table 1 which summarizes the range of CSL practices that have been implemented across SSA and their documented benefits in terms of productivity, emission reduction and climate change adaptation. Despite these demonstrated benefits of CSL practices across SSA, their sustained adoption by smallholder farmers remains low, highlighting the need to better understand how these practices can be effectively promoted and integrated on-farm. Consequently, understanding what factors determine farmers' adoption decisions is

essential, particularly in dairy systems where CSL practices have been extensively promoted.

According to the Food and Agriculture Organization (FAO (Food and Agriculture Organization), 2025), East Africa accounts for over 63% of the milk produced from cattle in SSA, with more than 120 million head of cattle producing about 11 million tonnes of milk annually. The region is also the largest contributor to agricultural GHG emissions in SSA, accounting for over 34% of the total emissions, with emissions from enteric fermentation being the dominant source and showing a rising trend (Tongwane and Moeletsi, 2018; World Bank, 2025). To address this challenge, several CSL practices have been promoted in East Africa among dairy farmers, including use of improved forage such as *Brachiaria* grass, production and use of silage and manure management (Galla et al., 2020; Maleko et al., 2018; Mwendia et al., 2022). However, despite the promotion of these practices, adoption rates remain low across the region, and the factors influencing farmers' decisions to adopt CSL practices are not well understood.

Uganda is a country in East Africa with significant dairy production potential. Milk production has grown at 5% annually since 2005 (Ariong and Van Campenhout, 2024), outpacing the SSA average of 3.6% (FAO and GDP (Global Dairy Platform), 2018). Milk production in Uganda remains below its potential due to low animal productivity, driven by poor feeding, inadequate animal health management and limited adoption of improved husbandry practices (Ariong and Van Campenhout, 2024). To address these constraints, Uganda participated in the East Africa Dairy Development (EADD¹) project (2014–2018), which sought to increase milk yields and raise household incomes from dairy farming (Omondi et al., 2017). However, several years after the EADD project ended in the country, the adoption of CSL practices remains low. The absence of empirical evidence on the determinants of farmers' adoption decisions hampers the effectiveness of policy and extension strategies in the country. Elucidating these determinants is crucial because of Uganda's high dairy potential, as well as the ongoing adoption challenges, which are similar to those faced across SSA. Therefore, the present study examined the factors influencing both the adoption rate and the intensity of adoption of CSL practices among dairy cattle-keeping households in Uganda, using the EADD end-of-project data.

2 Methodology

2.1 Research context and study area

The EADD project promoted four main CSL practices in Uganda: (i) forage cultivation, (ii) use of artificial insemination, (iii) routine vaccination of cattle and (iv) tree planting (growing trees). Forages promoted for cattle included: *Pennisetum purpureum*, *Desmodium intortum*, *Calliandra calothyrsus*, *Leucaena leucocephala*, *Sesbania sesban*, *Medicago sativa*, *Vicia sativa*, *Lablab purpureus*, *Centrosema pubescens*, *Chloris gayana*, *Mucuna pruriens* and *Brachiaria* spp. Artificial insemination involved use of semen from exotic breeds such as Friesian, Jersey, Ayrshire and Guernsey. Routine vaccinations

¹ The project was implemented by Heifer International, the World Agroforestry Centre, the International Livestock Research Institute, and the African Breeders Services.

TABLE 1 Climate-smart livestock practices carried out in sub-Saharan Africa.

Climate-smart livestock practice	Animal species	Climate-smart benefit	Country			References
			Increased milk productivity	Greenhouse gas mitigation	Climate change adaptation	
Improved forage	Cattle	x			Kenya, Rwanda	Mwendia et al. (2022)
Grass hay	Cattle	x			Ethiopia, Uganda, Tanzania	Mekuriaw et al. (2020), Ntakyo et al. (2020), Mwendia et al. (2022)
Silage	Cattle	x			Uganda, Ethiopia	Galla et al. (2020), Tsegaye et al. (2024), Yadessa et al. (2024)
Forage quality improvement ^a	Cattle	x			Ethiopia	Tirusew et al. (2023)
Concentrate feed	Cattle	x	x		Tanzania, South Africa, Cameroon	Maleko et al. (2018), Van Wyngaard et al. (2018), Mama et al. (2024)
Fodder shrubs	Cattle	x		x	Democratic Republic of Congo	Barwani et al. (2023)
Silvo-pastoral system ^b	Cattle			x	Benin	Assani Seidou et al. (2023)
Grazing intensity management ^c	Goat, sheep	x	x	x	Kenya	Lalampaa et al. (2016)
Grazing management ^d	Cattle	x	x	x	Kenya	Bryan et al. (2011)
Improved breeds ^e	Cattle	x			Ethiopia Cameroon	Gizaw et al. (2017), Mama et al. (2024)
Manure management	Cattle	x	x	x	Kenya	Wambugu et al. (2014), Maindi et al. (2020)

^aUrea-molasse treatment, ^bIntegration of tree growing with the rearing of cattle, ^cIntensity (duration) of grazing, ^dDestocking and rotational grazing, ^eUse of high milk producing cross breeds.

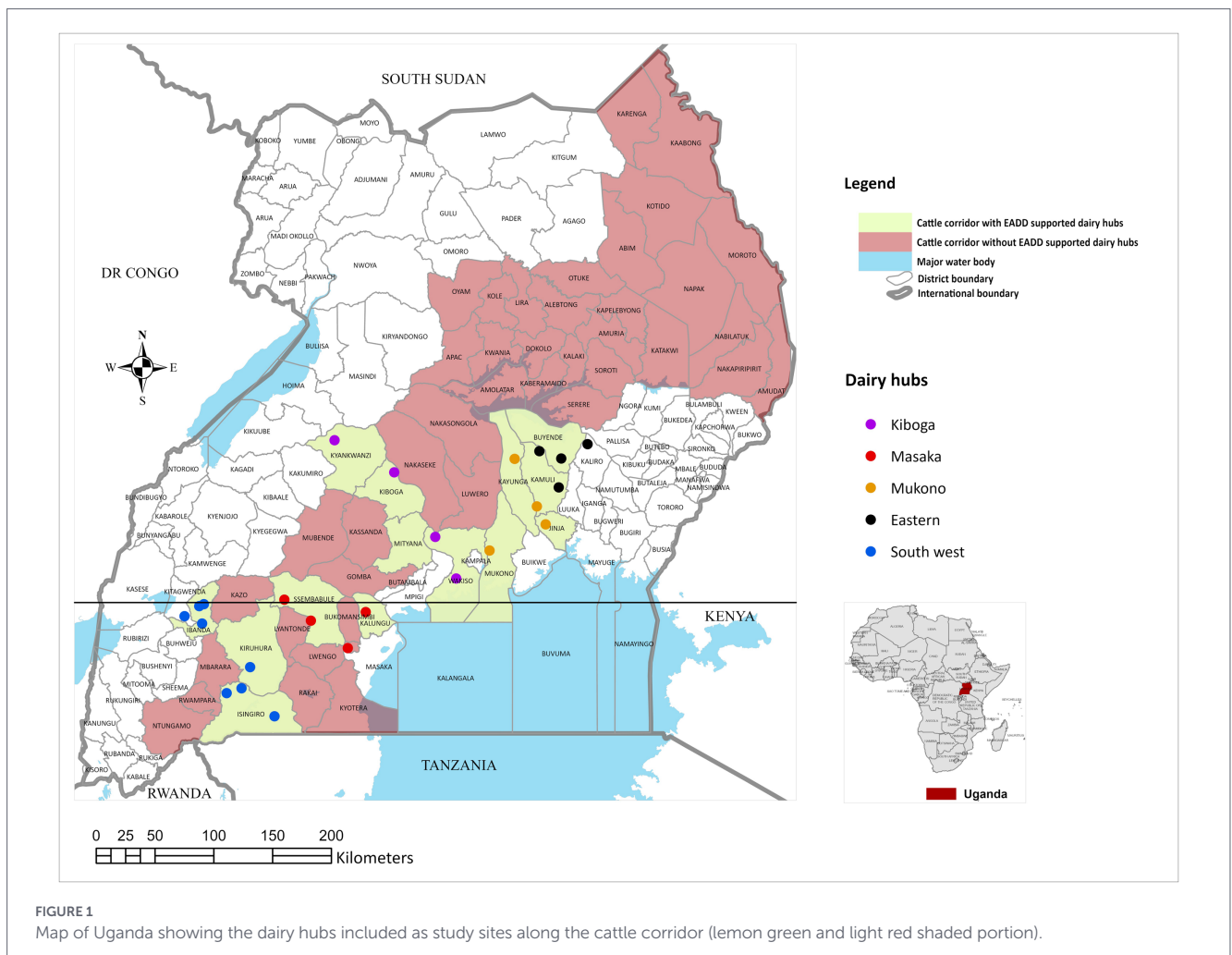
consisted of regular or scheduled vaccination carried out by farmers to improve animal health. These included vaccinations against lumpy skin disease, East Coast fever, brucellosis, contagious bovine pleuropneumonia and parasites. Tree planting consisted of agroforestry practices aimed at, among other goals, land, soil, and water conservation, as well as feeding cattle. Some of the tree species promoted included *Calliandra calothyrsus*, *Leucaena leucocephala* and *Grevillea robusta*. The CSL practices were promoted via a dairy hub approach designed to enhance the integration of cattle keepers into formal markets. These dairy hubs were farmer-managed producer organizations that bulked and marketed milk, linked farmers to agribusiness partners, and provided dairy cattle-related inputs (e.g., veterinary medicines) and services (Omondi et al., 2017). The present study was conducted in dairy hubs selected along Uganda's cattle corridor which stretches from the southwestern to northeastern part of the country (Figure 1).

The study area has a bi-modal rainfall pattern, with a long rainy season between March and May and a shorter one from September and November. The southwestern end of the cattle corridor, covering western Uganda, lies at an average altitude of 1800 m above sea level,

receives about 1,200 mm of rainfall annually, and experiences temperatures between 17 and 30 °C (Twongyirwe et al., 2019; Nampanzira et al., 2025). The middle section of the cattle corridor (Figure 1) encompasses central and eastern Uganda, standing at 1090–1115 m a.s.l., with temperatures ranging from 15 to 33 °C and an annual rainfall of 1,000–1,600 mm (Midamba et al., 2024). In terms of Uganda's total milk output, the Western region contributes the largest share (32.5%), followed by the Central (30.3%) and Eastern (17.6%) regions (Government of Uganda [GOU], 2024).

2.2 Sampling strategy and data collection

The project beneficiary households were stratified into three groups based on the intensity of the dairy management system (i.e., extensive, semi-intensive and intensive). Stratification ensured the representation of cattle-keeping households from the three dairy management systems. Out of 33 dairy hubs supported by EADD, 24 hubs that had a good representation of the intensity of the dairy management systems were selected. A geo-spatial random sampling technique was then used to select cattle-keeping households in each stratum



(Omondi et al., 2017). In total, 626 dairy cattle keeping households were sampled from the 24 hubs. In southwestern Uganda, data were collected from eight dairy hubs located in Kiruhura, Isingiro, and Ibanda districts. In central Uganda, 12 dairy hubs were selected from Mukono (covering Mukono, Wakiso and Kayunga districts), Masaka (covering Sembabule and Kalungu districts), and Kiboga (covering Kiboga, Kyenkwanzhi, and Mityana districts). Four dairy hubs were selected in the eastern region (Kamuli, Buyende, and Kagulu districts).

2.3 Data collection and handling

Data from the selected households were collected by 30 enumerators and entered electronically into a structured questionnaire designed in the CSPRO Census and Survey Processing system (US Census Bureau, 2010). The collected data were exported from CSPRO to Stata version 16.0 (Stata Corp, College Station, Texas, USA) and cleaned by running several commands (e.g., describe, summarize and browse). Missing data (e.g., monthly milk production and sources of income) were addressed by re-collecting data from the surveyed households where possible. Furthermore, additional data were collected from 20 stakeholders to estimate the peak adoption level and the number of years to peak adoption of the CSL practices using key informant interviews. The key stakeholders who were aware of the CSL practices and the population they represented were randomly selected. The stakeholders included three dairy farmers and three

district local government officers (one each from southwestern, central and eastern Uganda), two staff from the Netherlands Development Organization, eight committee members of dairy hubs (three each from southwestern, central and eastern Uganda) and four EADD project staff from Heifer International, World Agroforestry Centre, International Livestock Research Institute and African Breeders' Services involved in scaling CSL practices at the study sites. The key stakeholders responded to questions for a specific population of farmers and not for individual farmers.

2.3.1 Independent variables

The independent variables for the present study were grouped into three categories: household, farm and institutional variables. Household variables included age of household head (years), household size², education level of the household head (years spent in school), annual milk revenue (USD), land rented (acres), and total adult equivalent (TAE) as a measure of household labour. The TAE is a standardized measure of household labour availability, which adjusts household size by age and gender to reflect differences in labour

² Household size consisted of the number of people that lived together in the same household and shared meals and resources, regardless of whether they were biologically related or not.

capacity, and provides a more reliable proxy for effective household labour supply (Assenga and Kayunze, 2016). Farm related variables included the proportion of owned land allocated to grazing, time to water source (minutes) and tropical livestock units (TLU; animal equivalent of 250 kg body weight³) as a measure of herd size. Additional farm-level dummy variables included crop sales, stall feeding, group membership, keeping farm records, keeping indigenous cattle, water harvesting, geographical location of the related dairy hub, and training in business enterprises. Institutional variables included dummy variables for access to credit and livestock extension services.

2.4 Modeling framework

A multivariate Probit model (MVP) was employed to identify the factors affecting the adoption rate of CSL practices, while a Tobit model examined determinants of adoption intensity. Both models were computed in Stata (Version 16.0, StataCorp LLC, College Station, TX, USA). In addition, the Adoption and Diffusion Outcome Prediction Tool (ADOPT) was used to predict the peak adoption levels and time (in years) required to reach peak adoption for the CSL practices.

2.4.1 Multivariate Probit model

Given that the decision to adopt one CSL practice may depend on the adoption of others, simultaneous modeling is required (Greene, 2003). As such, a MVP model was employed to capture farmers' decision-making regarding the adoption of four CSL practices: (i) forage cultivation, (ii) use of artificial insemination, (iii) routine vaccination of cattle, and (iv) tree planting. These CSL practices formed the dependent variables in this model. The MVP model simultaneously estimates the effect of independent variables on each CSL practice, while allowing the error terms (i.e., unobserved and unmeasured factors) to be freely correlated (Greene, 2003). Positive correlations indicate complementarities and negative correlations suggest substitutability between CSL practices. The MVP model is particularly important since univariate Probit or Logit models tend to ignore the potential correlation in the error term and the relationships between the various practices under study. Because of this, biased estimates can be obtained as a result of failure to correct for the error terms (Lin et al., 2005). Following Lin et al. (2005), a MVP model with four dependent variables ($m = 1, 2, 3, 4$) was formulated as shown in Equations 1 and 2 below:

$$CSL_{km}^* = X_{km}\beta_m + \varepsilon_{km}, \quad m = 1, 2, 3, 4 \tag{1}$$

$$CSL_{km}^* = 1 \text{ if } CSL_{km}^* > 0, 0 \text{ otherwise,} \\ \varepsilon_{km} = (\varepsilon_{k1}, \dots, \varepsilon_{k4})' \sim N(0, \Sigma) \tag{2}$$

Where CSL_{km}^* is a latent variable that explains unobserved preferences or demand associated with the m th choice of CSL practice; X_{km} is a combination of observed characteristics that affect the adoption of the m th CSL practice, β_m the corresponding vector of parameters to be estimated for each CSL practice. CSL_{km}^* is assumed to be a linear combination of observed characteristics (X_{km}) that influence the

adoption of the m th CSL practice as well as unobserved characteristics captured by the stochastic error term ε_{km} . As a result of the latent nature of CSL_{km}^* , the estimations in this study are based on the observable binary discrete variable CSL_{km} , that shows whether a dairy farmer adopted a CSL practice or not. The ε_{km} is the error term that follows a multivariate normal distribution each with zero conditional mean and variance normalized to unity, i.e., $\mu F, \mu A, \mu V, \mu T \approx MVN(0, \Omega)$, where F, A, V and T denote forage cultivation, use of artificial insemination, routine vaccination and tree planting, respectively.

The covariance matrix of the error terms is specified in Equation 3:

$$\Omega = \begin{bmatrix} 1 & \rho_{FA} & \rho_{FV} & \rho_{FT} \\ \rho_{AF} & 1 & \rho_{AV} & \rho_{AT} \\ \rho_{VF} & \rho_{VA} & 1 & \rho_{VT} \\ \rho_{TF} & \rho_{TA} & \rho_{TV} & 1 \end{bmatrix} \tag{3}$$

Where ρ denotes the pairwise correlation coefficient of the error terms corresponding to any two CSL practices.

2.4.2 Tobit regression model

The Tobit model was used to examine factors influencing the intensity of adoption of CSL practices, given that it is appropriate when the dependent variables are censored at zero. Following Splett et al. (1994), the model was specified as shown in Equation 4:

$$y_{(t)} = X_t + \beta + u_{(t)} \quad \text{if } X_t\beta + u_{(t)} > 0 \\ = 0, \quad \text{if } X_t\beta + u_{(t)} \leq 0 \\ t = 1, 2, \dots, N \tag{4}$$

Where $y_{(t)}$ are the dependent variables, X is the vector for the independent variables, N is the number of observations, $u_{(t)}$ is an independently distributed error term that is assumed to be normally distributed with a zero mean and constant variance.

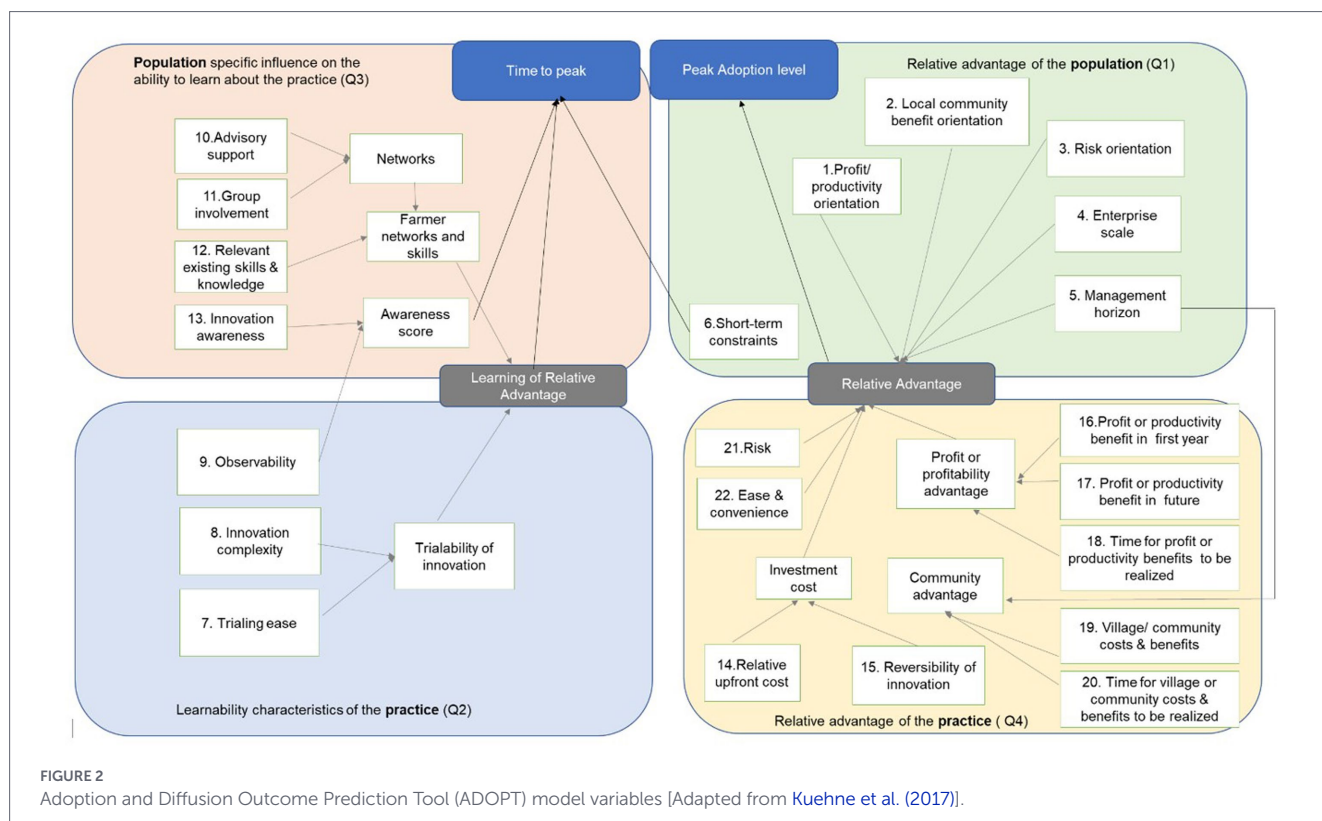
The dependent variables used in this model were area allocated to forage cultivation and number of trees planted. As the independent variables such as household size, TAE and distance to water source were positively skewed, their log-transformed data was used for the modeling. Consequently, the Tobit models were specified with the log-transformed area allocated to forage cultivation and the log-transformed number of trees planted as dependent variables.

2.4.3 The ADOPT evaluation

ADOPT is a web-based tool⁴ that utilizes the adoption theory framework to evaluate and predict the likely adoption level and diffusion of specific agricultural innovations within a target population (Kuehne et al., 2017). In ADOPT, variables are grouped into two categories: (i) those related to the target population and (ii) those related to the characteristics of practice under study. When combined with (a) the relative advantage of the practice and (b) the relative advantage of the population, these categories form four sets of issues which determine the rate and peak level of adoption (Figure 2). From these, 22 parameters were developed and included in the ADOPT

³ One TLU = 250 Kg.

⁴ <https://adopt.csiro.au/>



questionnaire to predict both peak adoption and time required to reach it for the CSL practices in our study. After obtaining the peak adoption and time to peak adoption, a sensitivity analysis was conducted using a “one-factor-at-a-time” approach by step-up and step-down changes to each parameter while holding all others constant, to assess their influence on adoption outcomes. In the present study, the ADOPT focused only on forage cultivation, use of artificial insemination and tree planting, which were considered innovations of the EADD project.

3 Results

3.1 Household and farm characteristics

On average, household heads were 53 years old with 7.3 years in school (Table 2). Households comprised an average of seven members, farmed 46.6 acres of land and owned 17 TLU. About 50% of the land owned by households was allocated to grazing cattle.

3.2 Adoption of climate-smart livestock practices and determinant factors among dairy farming households

The rates of adoption for forage cultivation, use of artificial insemination, routine vaccination, and tree planting were 32, 14, 45, and 19%, respectively. Households which adopted forage cultivation used about 0.31 acres for forage cultivation while those who planted trees owned 15 trees on average.

The Wald Chi-Square statistic ($\chi^2 = 469.11, p < 0.0001$) was significant at the 1% level (Table 3), rejecting the null hypothesis that all

TABLE 2 Summary statistics of household and farm characteristics of the 626 sampled dairy cattle keepers.

Variable	Mean	Standard deviation
Age of household (years)	52.80	13.291
Household size	7.15	3.074
Total adult equivalent (hours)	28.30	34.262
Education level of household head (years)	7.29	4.736
Share of own land used for grazing cattle	0.50	0.325
Total herd size (TLU)	17.22	30.558
Milk revenue (USD)	1,382	1949.061
Land owned (acres)	46.60	91.700
Time to water source for cattle (mins)	10.38	21.126

regression coefficients are jointly zero. The likelihood ratio test ($\chi^2(6) = 38.18, p < 0.0001$) further confirmed the joint significance of the error correlations, validating the use of the MVP model over a univariate Probit model. The MVP model revealed that household, farm and institutional factors significantly influenced the adoption of CSL practices (Table 3).

Households that sold crops, practiced stall feeding, kept farm records, and accessed credit were more likely to grow forage, while a larger share of own land allocated to cattle grazing cattle reduced this likelihood. Similarly, keeping indigenous cattle lowered the probability of forage cultivation or use of artificial insemination. Adoption of

TABLE 3 Multivariate Probit model for the determinants of adoption of CSL practices.

Variable	Forage cultivation (G)		Use artificial insemination (A)		Tree planting (T)		Vaccinate cattle (V)	
	Coefficient	SE	Coefficient	SE	Coefficient	SE	Coefficient	SE
Constant	0.180	0.561	-0.937	0.708	-1.959***	0.611	-0.396	0.509
Milk revenue (USD)	0.00004	0.000	0.0001***	0.000	0.00001	0.000	-0.0085	0.004
Time to water source for cattle (min)	0.001	0.003	-0.007	0.006	-0.001	0.003	-0.005	0.003
Household size (n)	-0.033	0.022	-0.021	0.027	0.048**	0.021	0.017	0.018
Total adult equivalent (h)	0.003	0.002	0.004*	0.002	0.005***	0.002	-0.004**	0.002
Age of household head (years)	0.004	0.004	0.003	0.006	0.008	0.005	-0.001	0.004
Education of household head (years)	0.022	0.014	0.0455**	0.018	0.025	0.015	-0.021	0.013
Proportion of land for grazing cattle	-1.760***	0.284	-1.387***	0.359	-0.012	0.296	0.150	0.239
Total livestock units (n)	0.002	0.003	-0.003	0.004	-0.001	0.003	0.003	0.003
Sells crops (yes = 1)	0.550***	0.133	0.088	0.166	0.298**	0.141	0.362***	0.122
Location: Masaka as reference								
Southwest	-0.378*	0.314	-0.141	0.255	0.193	0.216	-0.184	0.180
Eastern	0.125	0.265	0.401	0.304	0.173	0.280	-0.911***	0.245
Mukono	0.152	0.249	-0.883***	0.305	0.087	0.258	-0.752***	0.219
Kiboga	-0.199	0.258	-0.119	0.278	-0.086	0.259	-0.967***	0.214
Group membership (yes = 1)	0.108	0.145	0.186	0.187	0.216	0.156	0.2148*	0.129
Stall feeding (yes = 1)	0.661***	0.236	0.786***	0.239	-0.092	0.246	0.197	0.210
Training in business and animal husbandry (yes = 1)	-0.196	0.154	-0.205	0.182	-0.351**	0.159	0.107	0.139
Practice water harvesting technologies (yes = 1)	0.185	0.129	0.163	0.161	0.5749***	0.136	0.6806***	0.119
Keep indigenous cattle (yes = 1)	-0.567***	0.149	-0.479**	0.204	0.144	0.151	-0.172	0.133
Access to livestock extension (yes = 1)	0.068	0.209	-0.079	0.283	-0.391*	0.227	0.176	0.188
Keep farm records (yes = 1)	0.641***	0.171	0.586***	0.181	0.2875*	0.163	-0.112	0.154
Access to credit (yes = 1)	0.380*	0.199	0.4595**	0.227	0.443**	0.189	-0.282	0.190
N = 625	*, **, *** denote significance at 10, 5, and 1%, respectively							
Wald chi ² (84)	469.11***							
Log pseudo-likelihood	-1,059.817							
rhoAG ^{0.444***} rhoTG ^{0.149*} rhoVG ^{0.146**} rhoTA ^{-0.082} rhoVA ^{0.026} rhoVT ^{-0.125}								

artificial insemination was positively and significantly associated with the household head's education level and revenue from milk sales. In addition, households that practiced stall feeding, kept farm records, and accessed credit were more likely to use artificial insemination. Tree planting was positively and significantly influenced by household size and TAE, as well as crop sales, water harvesting, record keeping and access to credit (Table 3). In contrast, training in business and animal husbandry, and access to extension services negatively influenced the growing of trees. Also, routine vaccination was more likely among households that sold crops, practiced water harvesting, and were members of professional groups. The estimated correlation coefficients (see the bottom of the Table 3) indicated that some CSL practices were

adopted in combination with other practices, while others (artificial insemination, vaccination, and tree planting) were adopted independent of each other.

3.3 Factors influencing area under forage cultivation and number of trees planted

The likelihood ratio Chi-square statistics for area under forage cultivation ($\chi^2 = 4.77, p < 0.01$) and number of trees planted ($\chi^2 = 5.54, p < 0.01$) revealed that both models were statistically significant and appropriate for explaining the variation observed in adoption intensity at household level (Table 4). The education level of the household

TABLE 4 Tobit model results for the intensity of forage cultivation and number of trees planted on smallholder dairy cattle farms in Uganda.

Variable	LN_forage cultivation		LN_trees planted	
	Coefficient	Robust SE	Coefficient	Robust SE
Constant	-0.751	0.464	-2.294	2.606
Age of household head (years)	0.003	0.003	0.038**	0.016
LN_household size	0.004	0.053	-0.470	0.274
LN_distance to water points	0.059	0.047	0.361	0.225
LN_total adult equivalent	-0.003	0.017	0.345***	0.093
Education of household head (years)	0.030***	0.010	0.092**	0.046
Share of own land used for grazing cattle	-0.972***	0.223	0.609	0.762
Group membership (1 = yes)	0.047	0.104	0.574	0.554
Business and other training (1 = yes)	-0.228	0.116	-1.025**	0.518
Access livestock extension (1 = yes)	-0.082	0.135	-1.119	0.753
Location: Eastern as reference				
Mukono	0.126	0.117	-0.707	0.683
Southwest	0.196	0.145	0.309	0.732
Kiboga	-0.110	0.139	-1.756**	0.717
Masaka	0.259	0.162	-0.951	0.846
Stall feeding (1 = yes)	0.641***	0.120	0.597	0.508
Keep farm records (1 = yes)	0.443***	0.125	1.462***	0.514
Access to credit (1 = yes)	0.065	0.123	1.860***	0.564
N	625		625	
R squared	0.211		0.067	
Likelihood Ratio (LR) Chi-Square	4.77***		5.54***	
Log pseudo likelihood	-417.3		-492.9	
Left censored observations	396		504	

, * denote significance at 5% and at 1%, respectively.
LN indicates natural log transformation of a variable.

head, practicing stall feeding and keeping farm records were positively and significantly associated with the area allocated to forage cultivation. In contrast, the proportion of own land allocated to grazing cattle was negatively associated with the area allocated to cultivating forage. The number of trees planted were positively and significantly influenced by the age and education level of the household head, household size, TAE, keeping of farm records and access to credit. However, training in business and animal husbandry and residing in Kiboga were negatively associated with the number of trees planted.

3.4 Predicted estimates for adoption rates and time to peak adoption of climate-smart livestock practices

The ADOPT's predicted adoption rates after the fifth year of adoption were 22, 8 and 16% for forage cultivation, use of artificial insemination and tree planting, respectively (Table 5). The tool predicted that

it would take 11 years to reach a peak adoption level of 42% for forage cultivation and 31% for tree planting, while 15 years would be needed to reach a peak adoption level of 25% for using artificial insemination.

The sensitivity analysis revealed that peak adoption levels for forage cultivation (Figure 3), use of artificial insemination (Figure 4) and tree planting (Figure 5) were most influenced by factors related to the relative advantage of the practice (questions 14–19, 21 and 22; quadrant 4, Figure 2), followed by those linked to the relative advantage of the population (questions 1–4; quadrant 1, Figure 2). Relative advantage of practice-related factors included upfront costs, profit and productivity benefits (first year and in future), risk, environmental benefits, and ease of the practice. The step-up modifications indicated that the largest increase in peak adoption of forage cultivation (24%), use of artificial insemination (23%) and tree planting (24%) would result from higher profit and productivity benefit in the first year, followed by higher expected profit and productivity benefits in future. The sensitivity curves (Figures 6A,B,C) illustrate how the peak

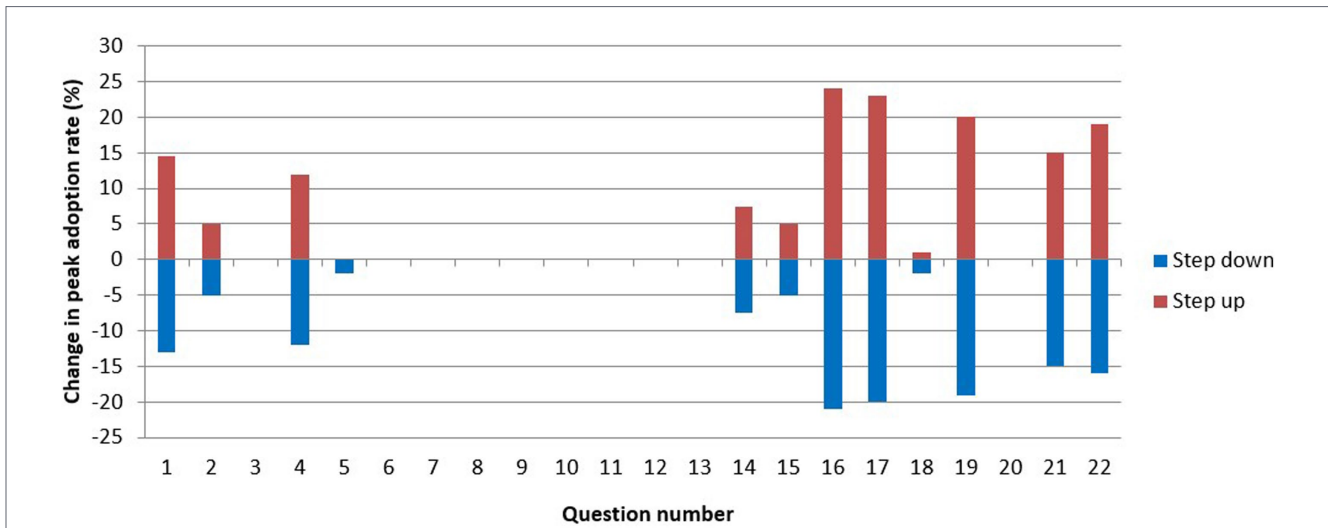


FIGURE 3 Sensitivity of predicted peak adoption rates for forage cultivation among smallholder dairy farmers in Uganda to favorable and unfavorable changes in parameters of the Adoption and Diffusion Outcome Prediction Tool (ADOPT) (The red bar shows the estimated increase (%) in the peak adoption rate, resulting from a single step (favorable increase) in any of the questions, whereas blue bars indicate the decrease (%) in peak adoption rate resulting from a one-step unfavorable change).

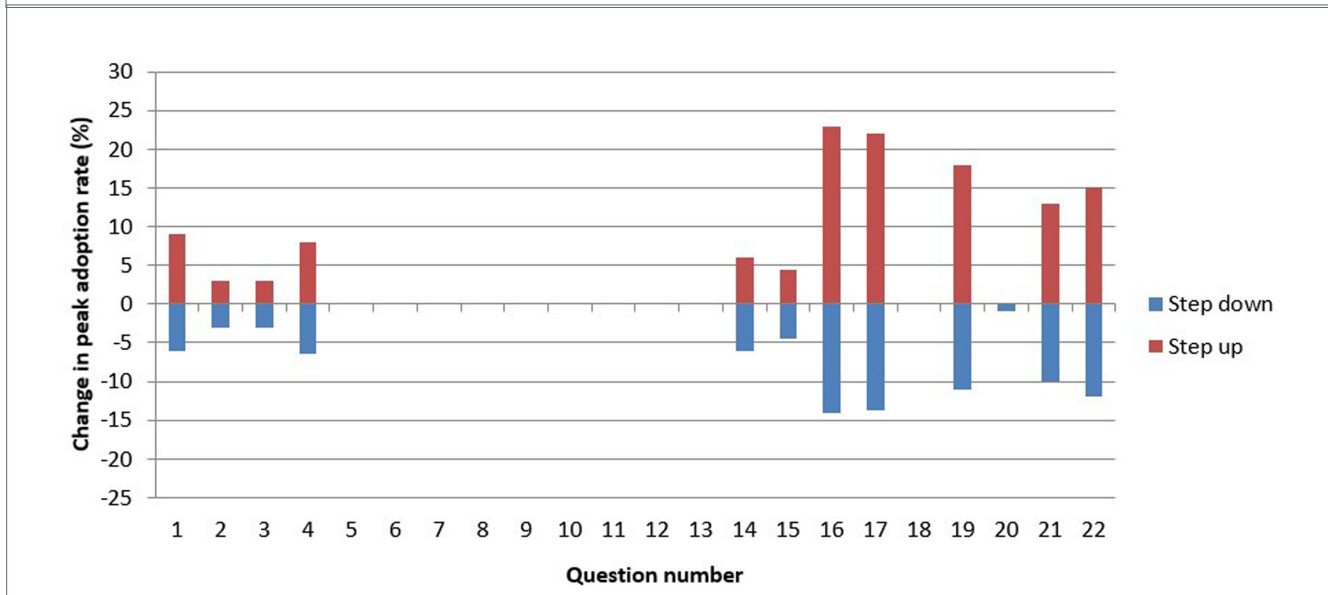


FIGURE 4 Sensitivity of predicted peak adoption rates for artificial insemination use among smallholder dairy farmers in Uganda to favorable and unfavorable changes in parameters of the Adoption and Diffusion Outcome Prediction Tool (ADOPT) (The red bar shows the estimated increase (%) in the peak adoption rate, resulting from a single step (favorable increase) in any of the questions, whereas blue bars indicate the decrease (%) in peak adoption rate resulting from a one-step unfavorable change).

adoption rates are expected to change as a result of a single step change to the most sensitive question for each CSL practice.

4 Discussion

4.1 Factors influencing the adoption rates of climate-smart livestock practices

Selling crop products positively influenced the adoption of forage cultivation and tree planting among dairy cattle households. Diversification of farm enterprises is often used by farmers as a risk

management strategy and as a means to stabilize income of farmers (Grilli et al., 2024). The extra cash earned is then used to support both the household but also to fund further investments in dairy production. This highlights the importance of integrating crop-livestock systems as a resilience strategy for livestock keepers. Stall feeding was positively associated with both forage cultivation and use of artificial insemination (Table 3). Farmers practicing stall feeding often have a small herd size and limited land but aim to achieve high milk outputs from their herd. As such, they rely on high-yielding forages like Napier grass to maximize productivity. Such improved forages support higher milk yields than natural pastures, especially in cross-bred cattle predominantly obtained via artificial insemination, which is more resource efficient than maintaining a bull (Mwangi et al., 2019; Bateki

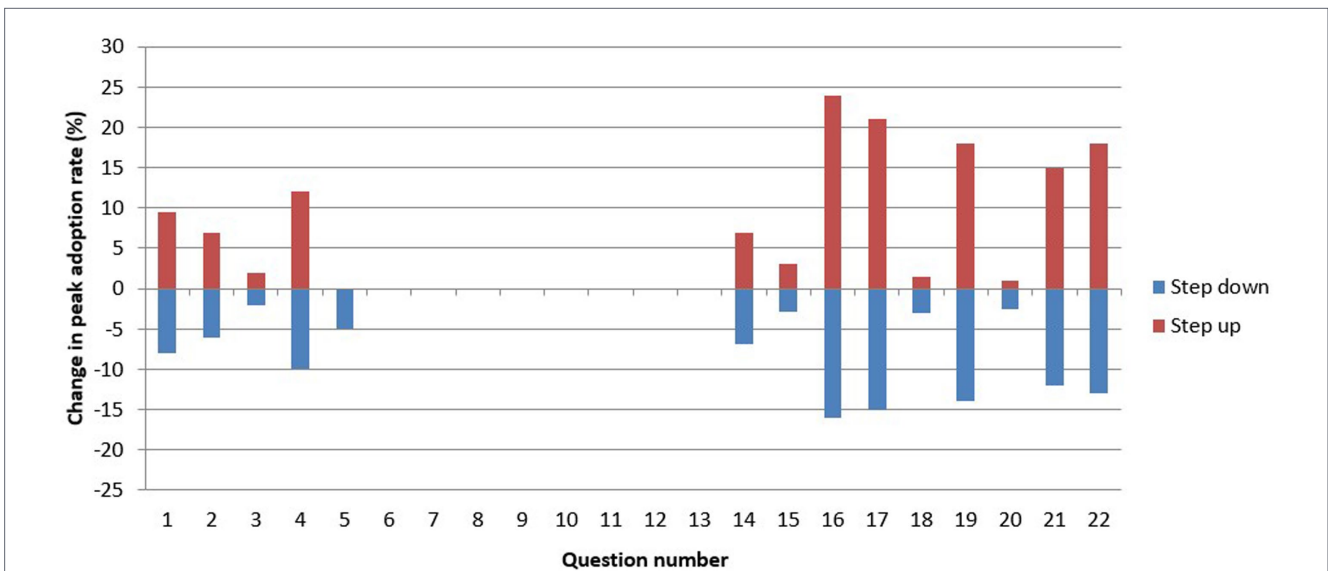


FIGURE 5 Sensitivity of predicted peak adoption rates for tree planting among smallholder dairy farmers in Uganda to favorable and unfavorable changes in parameters of the Adoption and Diffusion Outcome Prediction Tool (ADOPT) (The red bar shows the estimated increase (%) in the peak adoption rate, resulting from a single step (favorable increase) in any of the questions, whereas green bars indicate the decrease (%) in peak adoption rate resulting from a one-step unfavorable change).

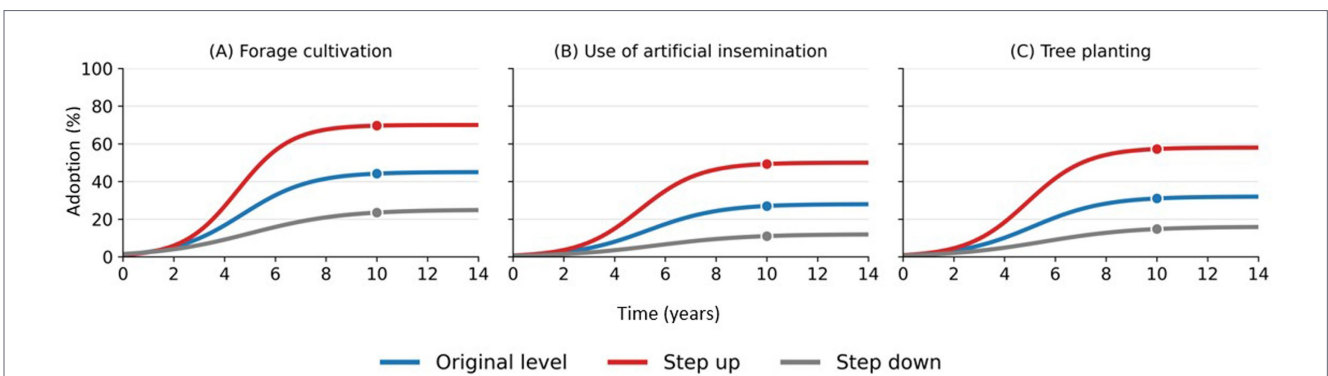


FIGURE 6 Sensitivity curves for changes in peak adoption levels when a single step change was made to the most sensitive question in the Adoption and Diffusion Outcome Prediction Tool (ADOPT) for selected climate-smart livestock practices among smallholder dairy farmers in Uganda under original, favorable (step-up), and unfavorable (step-down) parameter.

et al., 2020). Thus, identifying the existence of intensification strategies like stall feeding among livestock-keeping households could provide a proxy for the promotion and adoption of productivity enhancing CSL practices across the region.

Keeping indigenous cattle significantly reduced the likelihood of forage cultivation and using artificial insemination. Indigenous cattle breeds such as the Ankole long-horned cattle produce less than two litres per cow per day, even under improved feeding conditions (Manzi et al., 2020). This makes use of improved forage for feeding economically unattractive among indigenous cattle keeping households. Indigenous cattle keeping households also prefer to maintain the local breeds because they are more adaptable to the local environmental conditions and are more tolerant to tropical diseases and parasites (Okwasiimire et al., 2026), as opposed to cross breeds that are obtained from artificial insemination. Households that allocated a larger proportion of own land to cattle grazing were less likely to use artificial insemination. Such households typically practice an extensive system of cattle grazing and keep large herds. Under such systems, cows are spread out, making heat detection, estrus monitoring and

actual artificial insemination difficult, resulting in low conception rates and an added cost to the farmer. This makes natural mating a cheaper option than the use of artificial insemination (Mbuma and Msalya, 2026). Similar patterns have also been reported in other parts of the Eastern Africa region (Mushonga et al., 2017; Ingabire et al., 2018). These findings highlight the structural challenge of shifting from extensive to more managed market-oriented and high output dairy systems across SSA.

Labour availability measured as TAE emerged as an important determinant of the adoption of tree planting. Tree growing requires initial labour for land preparation, digging holes, transporting seedlings, planting, fencing, watering and gap filling. Households with fewer TAE (such as less than 3 TAE), are not able to meet the upfront demands for such initial activities, a finding consistent with evidence from South Sudan, where households with limited TAE showed lower adoption of agroforestry practice (Mayindo and Takeshi, 2025). Similarly, greater labour availability has been shown to facilitate adoption of complex agroforestry systems, such as the Tef–*Acacia decurrens*–charcoal system in northwestern Ethiopia (Beshir et al., 2022).

TABLE 5 Actual adoption rates and predicted estimates for peak adoption of climate-smart livestock practices by smallholder dairy cattle farmers in Uganda.

Climate-smart livestock practice	Observed adoption level after 5 years (%)	Predicted adoption level after 5 years (%)	Predicted peak adoption level (%)	Predicted time to peak adoption level (years)
Forage cultivation	37	22	42	11
Artificial insemination	14	8	25	15
Tree planting	19	16	31	11

Together, these findings suggest that labour constraints remain a key barrier to tree planting across Eastern Africa. Furthermore, differences emerged with respect to the geographical location of the farm. The probability of adopting artificial insemination was higher in Masaka than in Mukono (Table 3), likely due to the presence of NGOs (e.g., the Masaka Diocesan Development Organization and Caritas International) in Masaka. These NGOs were actively promoting livestock production as well as providing artificial insemination, which may explain this finding. Additionally, routine vaccination of cattle was relatively lower in Mukono and in the Eastern hubs than in the Masaka hubs. This may have been due to smaller average herd sizes, as well as careful herd isolation and confinement practices in Mukono and the Eastern hubs, which reduced the risk of disease transmission and consequently the need for routine vaccination. Sailevu et al. (2025) found that dairy farmers in Kinondoni district (Dar es Salaam region), in Tanzania, were more likely to adopt artificial insemination than those in Bagamoyo district (coast region) due to better access to advanced breeding methods and extension services. These findings highlight that effective local institutional support and service delivery are crucial for the adoption of CSL practices across SSA, while regional disparities in adoption likely signal institutional weaknesses that must be addressed to achieve widespread and equitable uptake of these practices.

The positive association between water harvesting and both tree planting and routine vaccination indicates that households in climate-stressed areas adopted complementary strategies. Households that harvested water were often located in drought-prone areas with limited water resources, where cattle needed to trek long distances to watering points, thereby increasing the exposure to diseases and the need for routine vaccination (Ndlovu et al., 2020). These results suggest that climate adaptation practices tend to be jointly adopted, so that the uptake of one CSL practice could facilitate broader adoption of other strategies. Access to credit was highly associated with forage cultivation, use of artificial insemination and planting trees (Table 3). Ingabire et al. (2018) found that cattle keepers who accessed credit in Rwanda were more likely to adopt artificial insemination technology than their counterparts. As such, financial inclusion is a crucial enabler that must be considered for promoting sustainable livestock practices among smallholder farmers across the region.

The MVP model revealed interdependencies between some CSL practices. For example, forage cultivation and the use of artificial insemination were adopted together. This is because the benefits of feeding improved forage can best be realized with improved (i.e., cross-bred) cattle (Mwendia et al., 2022). Such interdependencies between improved feeding of cattle and the use of artificial insemination have also been documented in Ethiopia (Gebre et al., 2022), suggesting that the presence of one of the two CSL practices will enhance the adoptability of the other. Routine vaccination was also carried out together with the cultivation of forage. Routine vaccination is a vital aspect for promoting cattle health, thereby enabling maximum

productivity (Ndlovu et al., 2020). Such complementarities suggest that promoting CSL practices in packages rather than as stand-alone practices could generate greater productivity and resilience gains in SSA.

4.2 Factors influencing forage production area and number of trees planted

The education level of the household head positively influenced the area allocated for forage production and the number of trees planted (Table 4). Education enables farmers to quickly understand and analyze emerging information and knowledge, helping them to access more information on a given practice than their counterparts. Moreover, such farmers may have better analytical skills in assessing the potential benefits of a practice and in making informed decisions regarding the adoption of a practice (O'Donoghue and Heanue, 2018). Evidence from Malawi supports this finding as the number of trees and shrubs farmers planted for feed and for enhancing soil fertility significantly increased as farmers' education level increased (Musa et al., 2018). Furthermore, record keeping was another significant factor that positively affected the intensity of adoption (Table 4). The plausible reason is that production, costs and income records help to keep track of the performance and beneficial effects of the adopted practice. These findings together suggest that promoting education for farmers and building capacity for record keeping must be a major focus of present and future interventions aiming at sustainably improving livestock production in the region.

The proportion of owned land allocated to cattle grazing, negatively and significantly affected the area allocated to forage cultivation. Land is one of the most limiting resources among smallholder farmers in SSA (Giller, 2020). As such, allocating more land to grazing will inadvertently reduce the land available for forage cultivation. Farmers may do this either when they are satisfied with the performance of the animals on natural pasture or when the labour required for forage production and use outweigh the potential benefits (Ahikiriza et al., 2021). This implies that cultivated forages are more likely to be taken up by livestock keepers with small holdings and with a higher likelihood of experiencing qualitative and or quantitative shortage of feed.

The TAE was a significant factor that affected the number of trees planted. Households with a higher TAE can carry out labour-intensive tree planting activities such as transporting seedling and general maintenance. Households with a lower TAE such as those with more female household members or with a more younger household members can carry out activities that are not labour-intensive such as planting and weeding, but are likely to be excluded from adopting tree planting if they cannot carry out other tree planting activities. To overcome this, gender-based division of labour at community level could increase the adoption of tree planting.

In terms of geographical location, fewer trees were planted in Kiboga than in the Eastern area. Location-specific factors, such as

topography and climatic conditions may also influence the intensity of tree planting. In eastern Uganda, tree planting is mainly driven by the need for soil erosion control, wind protection and shade provision (Graham et al., 2022), reflecting the region's proximity to erosion and land slide prone slopes of the mount Elgon area. The age of the household head also influenced the number of trees planted, with older cattle keepers being more likely to plant more trees than their younger counterparts. A similar pattern was observed by Beshir et al. (2022) in Ethiopia. According to Knoke et al. (2025), tree planting is a long-term investment which requires patience to achieve the benefits, an attribute highly expected among older farmers. Lower cash flows during the waiting period are likely to occur compared to alternative land uses. The anticipated benefit may also fail to be realized as a result of environmental factors. This uncertainty limits the adoption of tree planting especially among the younger farmers and clarifying the uncertainty factors, could facilitate the adoption of CSL practices.

4.3 Predicted adoption rates of climate-smart livestock practices

The predicted peak adoption level for CSL practices was most sensitive to variables related to the perceived relative advantages of a practice (Figures 3–5, quadrant 4 of Figure 2). The red bars in Figures 3–5 show the estimated increase (%) in the peak adoption rate for each CSL practice, resulting from a single step favorable change in any of the 22 questions (e.g., increase in profit and profitability benefit in the first year), whereas the blue bars indicate the estimated decrease (%) in peak adoption rate resulting from a single step unfavorable change (e.g., a decrease in profit and profitability benefit in the first year). A longer red bar means that improving any of the 22 questions by a single step would substantially increase the predicted adoption level, while a longer blue bar means that worsening any of the 22 questions, would substantially reduce the peak adoption level.

Profitability and productivity benefits in first year and in future were key factors likely to bring about the biggest increase in adoption rate for the CSL practices. Economic assessment of CSL practices is important since farmers use profitability and productivity benefits in deciding whether to adopt a practice or not (Watkiss and Cimato, 2016). Farmers are more likely to adopt a CSL practice if the expected profits are more than the profits from current practices. Milk processing plants in Uganda such as Pearl Dairies and Brookside Limited are exporting milk to Nigeria, Democratic Republic of Congo, Burundi, Rwanda, and South Sudan to ensure that farmers make profits even in period of high supply (Van Campenhout et al., 2021). These strategies highlight the importance of ensuring that farmers understand and are aware of the profit associated with adoption of a CSL practice for increased adoption. Upfront costs are also critical for adoption of CSL practices among dairy farmers in Uganda. These costs are needed for labour, as well as for purchasing fertilizers and chemicals to control pests and diseases. Where possible, farmers should be encouraged to use own labour or use readily available organic manure and locally made insecticides to minimize costs and maximize profits. Figure 6 focused on the most sensitive question for each CSL practice and was derived from Figure 3 (for forage cultivation), Figure 4 (for use of artificial insemination) and Figure 5 (for tree growing). The blue curves show the predicted peak adoption rate for the three CSL practices. The red and grey curves show the expected peak adoption rate as a result of a single step increase and single step decrease respectively, to the

most sensitive question (i.e., profit and productivity benefit in first year of use for both forage cultivation and tree growing and community costs and benefits for use of artificial insemination). ADOPT predicted that after 10 years, the adoption rate for forage cultivation would be 40% (blue curve of Figure 6A). If the profit and productivity benefit in first year of use changed favorably by one step increase, then the predicted peak adoption would increase by approximately 24% (see question 16 of Figure 3) to make 64% (red curve of Figure 6A). However, if it decreased by one step, then the predicted peak adoption rate would decrease by 20% (grey curve of Figure 6A).

When considering artificial insemination as a CSL practice, it is important to note that it is not without risk. Heat detection and timing of insemination are important for achieving a successful insemination. Failure to do so can lead to multiple insemination which is risky for the farmers because more time and money will be spent. Low success of insemination due to inadequate services or wrong timing leads to conception failure, which discourages many farmers from adopting it (Mathewos et al., 2023). Use of oestrus synchronization and establishing artificial insemination centres with qualified staff are potential solutions that can enhance the adopting of artificial insemination.

5 Conclusion

The present study revealed strong complementarities and synergies among CSL practices, highlighting their potential to be more effective when adopted jointly rather than in isolation. Forage cultivation was positively associated with the use of artificial insemination, routine vaccination and tree planting, suggesting that it may function as an enabling practice that enhances the adoptability of other CSL interventions. These interdependencies indicate that promoting CSL practices as integrated packages, rather than as stand-alone practices, is likely to yield greater productivity and resilience gains in smallholder dairy cattle households across SSA. Further exploration of these synergies could also accelerate adoption, thereby increasing dairy farm-level benefits. Results from the ADOPT further revealed that CSL practices have varying peak adoption level, with some CSL practices such as artificial insemination having a particularly low peak adoption level. Addressing some of the factors that are likely to increase adoption, such as profitability and productivity benefits in the first year of implementation is therefore critical. Increasing farmer awareness of the economic and productivity benefits the CSL practices will be essential to improve uptake among smallholder dairy farmers.

The adoption of CSL practices was constrained by several structural and institutional challenges: the limited availability of household labour (as reflected by low TAE) reduces farmer's capacity to take up labour-intensive practices such as tree planting. Limited access to credit restricts farmers' ability to cover upfront investment costs, while poor record-keeping practices undermine informed decision-making regarding the adoption of CSL practices. To overcome these challenges, development efforts should prioritize labour-saving technologies such as improved tools and or flexible implementation options that reduce the initial labour demands, and community level approaches (e.g., gender-based division of labour) to support practices like tree planting. More so, policies should focus on improving access to credits while future programs invest in

capacity building for record keeping, thereby creating an enabling environment for increased adoption and intensification of CSL practices across the region.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: the data can be made available upon request. Requests to access these datasets should be directed to rolandmugumya@gmail.com.

Author contributions

RM: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. IO: Conceptualization, Data curation, Methodology, Software, Writing – review & editing. IB: Conceptualization, Data curation, Funding acquisition, Methodology, Writing – review & editing. ST: Conceptualization, Methodology, Writing – review & editing. AN: Conceptualization, Writing – review & editing. WM: Conceptualization, Data curation, Funding acquisition, Validation, Writing – review & editing. ES: Resources, Supervision, Visualization, Writing – review & editing. CB: Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was used in the creation of this manuscript. During the final preparation of this work, the corresponding author used ChatGPT 5 to obtain suggestions for more concise and clear text for some parts of this manuscript. Selected suggestions were taken and applied to the manuscript wherever considered acceptable. As such full responsibility remains with the corresponding author.

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