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Article

Adoption Trajectories of Sustainable Agricultural Practices among Ethiopian Smallholder Farmers: Pathways to Climate Resilient Agriculture

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Abstract

This study examines the factors shaping smallholder farmers' adoption trajectories-persistent adoption, new adoption, and non-adoption of three key sustainable agricultural practices in Ethiopia: crop rotation, chemical fertilizer use, and soil and water conservation. This study fills this gap by shifting the analytical lens from static adoption to adoption trajectories specifically analyzing persistence, new adoption, and dis-adoption. Using two waves of nationally representative panel data from the Living Standards Measurement Study-Integrated Surveys on Agriculture (2018/19 and 2020/21), the analysis explores how demographic, institutional, economic, and geographic factors influence farmers' movement across adoption pathways. This paper contributes to the literature in three specific ways. First, it moves beyond static snapshot analysis to track longitudinal trajectories, providing rare evidence on the drivers of technology dis-adoption. Second, it introduces a comparative framework by linking the intrinsic technical attributes of SAPs (capital vs. labor intensity) to their divergent adoption determinants. Third, it utilizes the most recent 2021 LSMS data to provide a contemporary perspective on smallholder constraints. The results show that access to credit and extension services, livestock ownership, household labor availability, and market access play important roles in sustaining or initiating adoption. These findings highlight that adoption is dynamic rather than static and underscore the need for targeted policies that expand rural credit, strengthen extension systems, and improve market access to support long-term uptake of sustainable practices among Ethiopian smallholders.

Key words: Panel data analysis; Technology adoption dynamics; Soil and water conservation

1. Introduction

Agricultural systems in Sub-Saharan Africa, including Ethiopia, face mounting pressures from land degradation, erratic rainfall, and declining soil fertility-factors that threaten long term productivity and rural livelihoods. In response, research and policy initiatives increasingly emphasize the promotion of sustainable agricultural practices (SAPs) to enhance climate resilience and resource conservation [1, 2]. Practices such as crop rotation, chemical fertilizer use, and soil and water conservation (SWC) are widely recognized for their potential to improve soil health, stabilize yields, and strengthen farmers' adaptive capacity. In Ethiopia, where agriculture remains the primary livelihood source for the majority of the rural population, the sustained adoption of SAPs is central to achieving food security and environmental sustainability [3, 4]

Despite substantial policy efforts, adoption of these practices remains uneven. Farmers exhibit heterogeneous behavioral patterns: some adopt and continue using practices over time (persistent adopters), others initiate adoption after initial non-use (new adopters), while many remain non-adopters overtime. Previous empirical studies have documented variation in adoption outcomes across households [5, 6, 7, 8]. However, most of the existing literature examines adoption as a binary decision-adopt versus non-adopt often using cross-sectional data [8, 9]. Such approaches obscure the dynamic nature of technology uptake and fail to distinguish between sustained adoption and temporary or delayed adoption. A smaller body of study has begun to explore adoption dynamics using panel data [10, 11]. Nevertheless, these studies typically focus on single technologies or do not explicitly categorize farmers into distinct adoption trajectories over time. As a result, limited attention has been given to understanding how different household, institutional, and biophysical factors shape farmers' movement across multiple adoption pathways for sustainable agricultural practices.

Theoretically, the necessity of studying "adoption trajectories" rather than traditional binary outcomes is rooted in the Dynamic Theory of Technology Adoption [11, 12]. Most existing empirical studies on Sustainable Agricultural Practices (SAPs) in Sub-Saharan Africa treat adoption as a static, "one-time" decision categorizing farmers simply as "adopters" or "non-adopters." However, this binary approach fails to capture temporal heterogeneity and the

phenomenon of path dependency, where a farmer's past decisions structurally influence their future behavior [2, 13]. By focusing on trajectories persistent adoption, new adoption, and non-adoption this study moves beyond cross-sectional snapshots to address the "adoption gap." This gap refers to the common situation where farmers initially uptake a technology but fail to sustain its use due to shifting resource constraints or institutional failures [14, 15].

Furthermore, a trajectory-based framework allows for a systematic analysis of dis-adoption dynamics. Unlike Innovation Diffusion Theory, which primarily focuses on the time lag to first-use, a dynamic perspective acknowledges that the drivers of *initiating* a practice (e.g., initial extension contact or social learning) are often fundamentally different from the drivers of *maintaining* it (e.g., long-term soil health returns or stable labor supply) [3, 7]. Understanding these distinctions is critical for Ethiopian agricultural policy; while initial adoption may be driven by temporary subsidies or awareness campaigns, persistent adoption requires sustained institutional support and resource endowments [16]. Therefore, analyzing these pathways provides a more robust theoretical basis for understanding how smallholders navigate the complexities of climate-smart agriculture over time.

This study contributes to the literature by explicitly modeling three adoption trajectories—persistent adoption, new adoption, and non-adoption across three key sustainable agricultural practices: crop rotation, chemical fertilizer use, and soil and water conservation. Using nationally representative panel data from the Ethiopia Living Standards Measurement Study-Integrated Surveys on Agriculture (2018/19 and 2020/21), we examine how demographic characteristics, labor availability, livestock ownership, institutional support, market access, and biophysical conditions influence farmers' placement within these distinct pathways. By moving beyond a static binary framework, this study provides a more nuanced understanding of adoption behavior and generates evidence to inform targeted extension strategies, credit interventions, and market integration policies aimed at promoting sustained and inclusive uptake of sustainable agricultural practices. Most existing studies on Sustainable Agricultural Practices (SAPs) in Sub-Saharan Africa treat adoption as a static, "yes or no" decision. However, this binary approach fails to capture the true complexity of smallholder behavior, where adoption is often a fluid process characterized by entry, persistence, and abandonment. By focusing on adoption trajectories, this study moves beyond cross-sectional snapshots to address the "adoption gap" the phenomenon

where farmers initially adopt a technology but fail to sustain its use. Understanding why a farmer is a "persistent adopter" versus a "new adopter" is theoretically necessary because the constraints for *starting* a practice (e.g., initial awareness) differ fundamentally from the constraints for *maintaining* it.

Methodology

Data Sources and Description

This study uses the two most recent waves (2018/19 and 2020/21) of the Ethiopian Socioeconomic Panel Survey (ESPS). The ESPS is implemented collaboratively by the Ethiopia Statistics Service (ESS) and the World Bank under the Living Standards Measurement Study-Integrated Surveys on Agriculture (LSMS-ISA) program, with financial support from the Bill and Melinda Gates Foundation (BMGF). The survey generates nationally representative, multi-topic household panel data, with particular emphasis on strengthening agricultural statistics and understanding the interaction between farm and non-farm income activities. It is aligned with Ethiopia's National Strategy for the Development of Statistics (NSDS) and is designed to improve data quality, methodological rigor, accessibility, and institutional capacity [17].

The original LSMS-ISA sample included 6,770 households in 2018/19 and 4,999 households in 2020/21. However, the agricultural production module-central to this study-was administered only to farming households, comprising 2,500 households in the first wave and 2,200 in the second. Since the objective of this research is to analyze adoption trajectories of sustainable agricultural practices, the analytical sample is restricted to households engaged in agricultural activities in both waves. Following the merging of the two survey rounds using unique household identifiers, 1,650 panel households were initially retained. The reduction from the original wave-specific samples reflects normal panel attrition due to re-contact failure, migration, household dissolution, and incomplete responses across survey rounds. During econometric estimation, the effective sample further decreased to 1,400 households.

This additional reduction is primarily attributable to missing values in key explanatory variables, incomplete information required to construct adoption trajectories, and the exclusion of observations with inconsistent or implausible responses. To enhance transparency and minimize

potential bias, list wise deletion was applied only after carefully examining patterns of missingness. Descriptive comparisons between retained and excluded households did not reveal systematic differences in core observable characteristics, suggesting that sample reduction is unlikely to substantially bias the results. The final balanced panel of 1,400 households therefore provides a consistent and reliable basis for estimating adoption pathways.

Econometrics Model Specification

This study draws on panel data from the Ethiopia Living Standards Measurement Study-Integrated Survey of Agriculture (LSMS-ISA), specifically the 2018/19 and 2020/21 waves. Although the data follow the same households over time, the empirical analysis adopts a static pooled multinomial logit (MNL) approach. Rather than modeling dynamic transitions between periods, the two waves are used to construct a single adoption trajectory for each household. Households are categorized according to their behavior across the two survey rounds in relation to three sustainable agricultural practices - crop rotation, chemical fertilizer use, and soil and water conservation. Each household appears once in the dataset and is classified based on its overall adoption pattern. This strategy allows us to examine the factors associated with different adoption pathways without imposing assumptions about dynamic adjustment processes. Because adoption status is derived from repeated observations of the same households, standard errors are clustered at the household level to account for potential intra-household correlation [18, 19]

While fixed-effects estimators are often preferred in panel settings to control for unobserved heterogeneity, their application in multinomial logit models with unordered outcomes is limited. With only two survey waves, attempting to estimate fixed effects would introduce the incidental parameters problem and lead to inconsistent estimates [19]. For this reason, a pooled multinomial logit model with household-clustered robust standard errors is employed. This approach ensures valid statistical inference while maintaining estimation efficiency. Multinomial logit models are well suited for analyzing outcomes that consist of multiple, unordered categories. In this case, adoption trajectories represent distinct and non-ranked alternatives.

Since each household's behavior across the two waves is summarized into a single categorical outcome, the dataset is structured in cross-sectional form, with one observation per household [20]. Initially, households were grouped into four categories: persistent adopters, new adopters,

dis-adopters, and non-adopters. However, the number of dis-adopters was very small. To ensure meaningful comparisons, the analysis therefore focuses on three categories - persistent adopters, new adopters, and non-adopters. Following Wooldrige [18] and Afandizadeh and Safari [20], the dependent variables $Y_i \in \{1, 2, 3\}$ represent the adoption status of household i where:

$Y_i = 1$: Persistent adopters (adopted in both survey waves)

$Y_i = 2$: New adopters (adopted in the second wave but not the first)

$Y_i = 3$: Non-adopters (did not adopt in either wave)

The analysis is grounded in the Random Utility Maximization (RUM) framework, commonly used in discrete choice modeling. Under this framework, it is assumed that household i associates a latent utility U_{ij} which choosing adoption category j , where $j \in \{1, 2, 3\}$. This utility is modeled as a function of observable explanatory variables X_i , which capture household characteristics.

The utility specification takes the form:

$$U_{ij} = X_i' \beta_j + \varepsilon_{ij} \quad (1)$$

Where β_j is a vector of category specific parameters, ε_{ij} is a stochastic error term that captures unobserved factors influencing household i 's choice of adoption category j .

Households are assumed to select the adoption category that provides them with the greatest perceived benefit. This behavioral assumption aligns with the standard multinomial logit framework, where the probability of choosing a particular option is derived from an underlying utility function. The model assumes that unobserved factors influencing choices are independently and identically distributed according to a Type I extreme value distribution [21]. The random utility approach has been widely used in agricultural technology adoption studies [3, 4] because it provides a solid theoretical foundation for analyzing discrete, unordered decisions and relating them to observable household characteristics. An additional advantage of this specification is that it enables the computation of marginal effects, which make the results easier to interpret by showing how changes in explanatory variables alter the probability that a farmer follows a particular adoption pathway.

In our case Y denote a random variable taking on the values $\{0, 1, \dots, J\}$ for J a positive integer or adoption category, and let X denote a set of conditioning variables. As in the binary response case, we are interested in how other things held constant changes in the elements of X affect the response probabilities, $P(Y = j|X), j = 0, 1, 2, \dots, J$. Since the probabilities must sum to unity, $P(Y = 0|X)$ is determined once we know the probabilities for $j = 1, \dots, J$. Following Green (200); Afandizadeh and Safari [20], if Y is a random variable that indicates the choice made, then the multinomial logit (MNL) form of the multiple choices problem is given by:

$$P(Y_i = j|X) = \frac{\exp(X'_i \beta_j)}{\left[\sum_{h=0}^{J-1} \exp(X'_i \beta_h) \right]} \quad (2)$$

We normalize one category (usually base category) by setting $\beta_0 = 0$ (non-adopters), so:

$$P(Y_i = j|X) = \frac{\exp(X'_i \beta_j)}{1 + \sum_{k=1}^{J-1} \exp(X'_i \beta_k)}, j = 1, \dots, J - 1 \quad (3)$$

$$P(Y_i = 0|X) = \frac{1}{1 + \sum_{k=1}^{J-1} \exp(X'_i \beta_k)} \quad (4)$$

This avoids model redundancy, ensures identifiability, and yields the log-likelihood for the full sample as:

$$\mathcal{L}(\beta) = \sum_{i=1}^n \sum_{j=0}^{J-1} d_{ij} \cdot \ln \left(\frac{\exp(X'_i \beta_j)}{\sum_{k=0}^{J-1} \exp(X'_i \beta_k)} \right) \quad (5)$$

Where: $d_{ij} = 1$ if household i is in category j , 0 otherwise. Maximizing this log-likelihood gives you estimates of β_j for each category except the base. Post estimation, marginal effects were derived to interpret the effect of each independent variable on the probability of a household falling into each adoption category:

$$\frac{\partial P(y_i = j)}{\partial x_r} = P_j \left(\beta_{jr} - \sum_{k=0}^{J-1} P_k \beta_{kr} \right) \quad (6)$$

Equation number 6 tells us how a small change in x_r affects the probability of being in category j . While panel data allows for various estimations, this study employs a Pooled Multinomial Logit (MNL) approach with clustered standard errors at the household level to analyze adoption trajectories. This choice is justified because our dependent variables the adoption trajectories (Persistent, New, and Non-adopter) are inherently a multi-period construct that summarize changes between T_1 and T_2 , rather than a single period status.

To address unobserved heterogeneity and time-varying characteristics, we have incorporated lagged independent variables from the baseline wave. This approach, combined with clustering, accounts for within-household correlation and captures the dynamic nature of the transition without the convergence issues often associated with fixed-effects multinomial models in shorter panels [20]. The use of an aggregated Pooled Multinomial Logit (MNL) model, rather than a dynamic panel model, is necessitated by the two-period structure of our data. In short panels ($T=2$), dynamic specifications often encounter incidental parameter bias and convergence issues. Furthermore, since the dependent variable is a transition trajectory summarizing change between two periods a pooled approach is more appropriate. To account for individual heterogeneity and temporal dynamics, we utilize lagged independent variables from the baseline wave and apply clustered standard errors at the household level. This ensures that the model captures the longitudinal influence of household characteristics while correcting for within-unit correlation over time [18].

Robustness and Endogeneity Considerations

To validate the empirical results, we performed several diagnostic tests. First, we addressed the Independence of Irrelevant Alternatives (IIA) assumption inherent in the Multinomial Logit (MNL) model using the Hausman-McFadden test [22]. The test yielded a non-significant result ($\chi^2=12.45, p>0.10$), suggesting that the IIA assumption was not violated and the MNL model is appropriate for this data. Furthermore, to address potential endogeneity and selection bias regarding extension and credit services, we re-estimated the model using lagged independent variables from the 2018/19 wave to predict 2020/21 trajectories. Addressing potential endogeneity and selection bias using lagged independent variables is recognized as a best approach to mitigate reverse causality in technology adoption studies [23, 18]. As shown in the

robustness comparison, the signs and significance levels of the key drivers specifically extension services, credit access, and household labor remained consistent.

We also compared our MNL results with a Multinomial Probit (MNP) model, which allows for a more flexible error structure by relaxing the IIA assumption [24]. The high degree of correlation between the marginal effects of both models (Table 1) confirms that our findings are not sensitive to the choice of functional form. Finally, a sub-sample analysis excluding the top 5% of largest livestock holders confirmed that the results are not driven by outliers, ensuring the representativeness of the findings for the broader smallholder population [11].

Table 1 : Robustness Check - Comparison of Marginal Effects for Persistent Adopters

Explanatory Variables	Main Model (MNL)	Robustness Model (MNP)	Result
Extension Services	0.142***	0.138***	Consistent
Credit Access	0.085**	0.081**	Consistent
Household Labor	0.054*	0.056*	Consistent
Livestock (TLU)	0.022**	0.025**	Consistent
Hausman-McFadden Test	\$\chi^2 = 12.45\$	\$p > 0.10\$	IIA Passed

*Note: ***, *, and * indicate significance at 1%, 5%, and 10% levels. MNL = Multinomial Logit; MNP = Multinomial Probit.

Results and Discussions

SAPs Adoption Trajectories

The summary statistics of adoption trajectories across the three SAPs-crop rotation, chemical fertilizer use, and soil and water conservation practices reveal important variations in smallholder farmers' engagement over time (Figure 1).

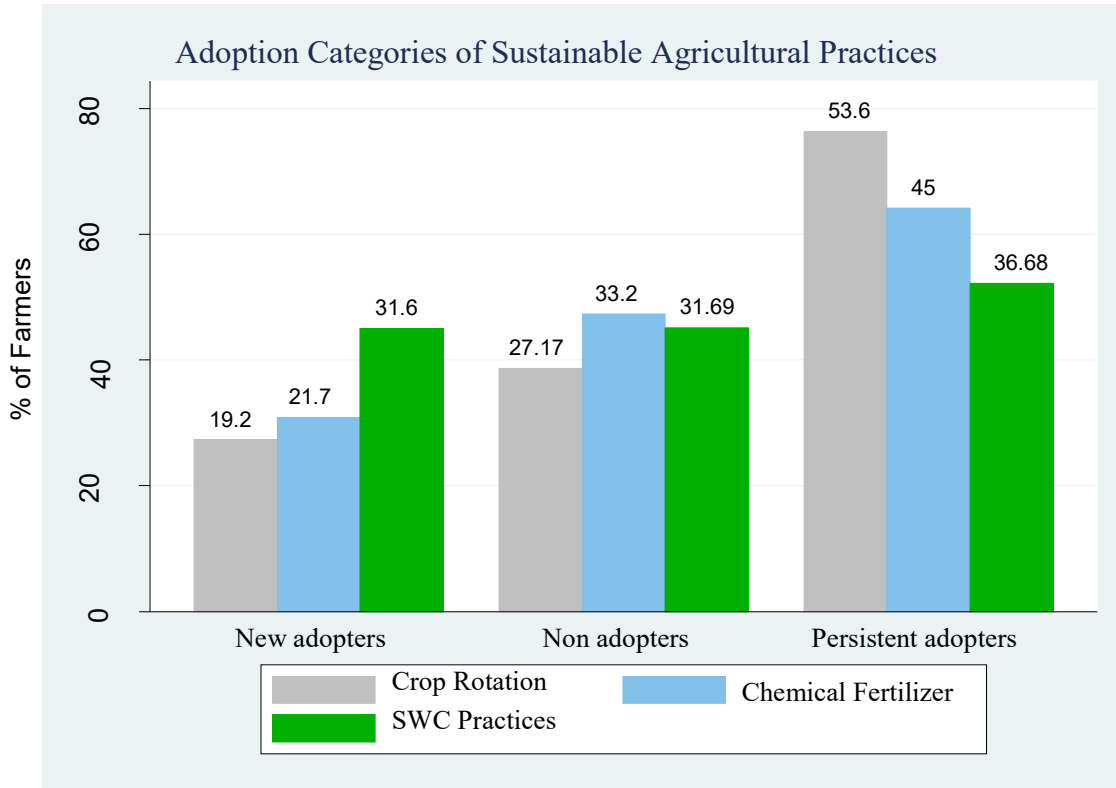


Figure 1. Adoption categories of selected agricultural practices

The bars show the percentage of persistent adopters, new adopters, and non-adopters for crop rotation, chemical fertilizer use, and soil and water conservation (SWC) practices. Initially, households were categorized into four adoption trajectories: persistent adopters, new adopters, dis-adopters, and non-adopters. However, the number of dis-adopters was negligible ($N = 12$ households, $\sim 2.4\%$ of the sample). Including this small category in the multinomial logit model could lead to unstable parameter estimates. To ensure that excluding dis-adopters does not introduce selection bias, independent t-tests were conducted comparing baseline characteristics (livestock holdings and consumption expenditure) between dis-adopters and persistent adopters. No statistically significant differences were found ($p > 0.10$), indicating that exclusion of this small group does not systematically bias the results (Table 2).

Table 2 Comparison of baseline characteristics between non-adopters and persistent adopters

Variable	Persistent Adopters (Mean $\pm$ SD)	Dis-Adopters (Mean $\pm$ SD)	t-statistic	p-value
Livestock (TLU)	3.98 $\pm$ 2.10	3.76 $\pm$ 1.95	0.52	0.61
Consumption expenditure	0.41 $\pm$ 0.25	0.39 $\pm$ 0.24	0.48	0.63

Note: No statistically significant differences at $p > 0.10$. Values are means $\pm$ standard deviations

As it is depicted in figure1 for crop rotation, a majority of households (54%) were persistent adopters, suggesting that this practice is widely recognized and maintained due to its low financial cost, compatibility with traditional agronomic systems, and perceived soil fertility benefits. However, 27.2% of households remained non-adopters of crop rotation, indicating potential barriers such as lack of extension support or site-specific agronomic constraints. In the case of chemical fertilizer, 45% of households reported persistent use, while 22% were new adopters. This pattern points to modest but growing engagement with external inputs, likely driven by targeted interventions or increased market access. Nonetheless, approximately one third (33.24%) of the smallholders did not adopt chemical fertilizer at all, possibly due to constraints such as input cost, limited availability, or credit access. SWC presents a more transitional picture: only 37% of households were persistent adopters, whereas 32% were new adopters and the remaining 32% were non-adopters (Figure 1). The relatively high rate of new adoption in SWC suggests recent expansion efforts, potentially linked to public works programs such as food for work or watershed management campaigns. However, the relatively lower persistence rate may reflect the labor intensive nature of SWC, which can discourage sustained adoption without continued incentives or technical support. Overall, these descriptive findings underscore the diverse trajectories and constraints associated with each SAP, reinforcing the need for differentiated policy responses tailored to the unique adoption patterns and requirements of each sustainable agricultural practice.

The summary statistics presented in Table 3 reveal notable differences in household and contextual characteristics across the adoption trajectories of crop rotation, chemical fertilizer, and soil and water conservation (SWC) practices. Examining these differences provides useful preliminary insights into the socioeconomic and demographic factors associated with farmers'

decisions to adopt, sustain, or discontinue sustainable agricultural practices (SAPs). The patterns observed across the adoption categories non-adopters, new adopters, dis-adopters, and persistent adopters suggest that household resources, demographic characteristics, and access to productive assets play an important role in shaping farmers' long-term technology adoption behavior.

The age of the household head shows a modest relationship with adoption status for some practices. Persistent adopters of crop rotation and chemical fertilizer tend to be slightly older, with an average age of approximately 44.5 years, whereas non-adopters are generally younger (Table 3). This pattern may reflect the role of farming experience in shaping technology adoption decisions. Older farmers often possess accumulated knowledge of local agroecological conditions and crop management practices, which may enable them to better recognize the long-term benefits of improved farming techniques. In addition, they may have had greater exposure to agricultural extension services or development programs promoting modern inputs such as fertilizer and improved crop management practices. Such exposure may increase their capacity to sustain adoption over time.

In contrast, a different pattern is observed for soil and water conservation practices. Persistent adopters of SWC appear to be younger on average, with a mean age of about 42.2 years, while non-adopters are relatively older, averaging around 46 years. This reversal suggests that younger farmers may be more responsive to conservation-oriented interventions and more open to adopting new land management approaches. Soil and water conservation practices typically require considerable labor investment and their benefits often materialize gradually through improved soil fertility, reduced erosion, and enhanced moisture retention. Younger farmers may therefore be more willing to invest in such practices because they expect to benefit from improved land productivity over a longer time horizon.

Labor availability, measured in adult equivalents, also shows a consistent pattern across the adoption trajectories (Table 3). Persistent adopters report higher levels of household labor availability for all three practices considered. Specifically, persistent adopters have an average of 4.09 adult equivalents for crop rotation, 4.14 for fertilizer use, and 4.26 for SWC practices. These figures are higher than those observed among non-adopters and dis-adopters, highlighting the importance of household labor resources in sustaining agricultural practices. Many SAPs

require considerable labor inputs during land preparation, planting, and maintenance periods. For example, SWC structures such as terraces or bunds demand significant labor both for construction and maintenance. Similarly, crop rotation requires more planning and management than continuous mono-cropping. Households with greater labor availability are therefore better positioned to implement and maintain these practices consistently.

Gender differences are also evident across the adoption trajectories. A higher proportion of male-headed households are observed among persistent adopters across all practices compared with other adoption categories. This pattern may reflect gender-related disparities in access to productive resources and institutional support. In many rural settings, male-headed households often have greater access to land, credit, extension services, and farmer training programs, which can facilitate both the adoption and continued use of improved agricultural practices. Female-headed households may face constraints such as limited labor availability or restricted access to agricultural information, which can hinder sustained adoption.

Taken together, the descriptive statistics suggest that adoption trajectories are closely linked to household demographic characteristics and resource availability. Older farmers appear more likely to sustain the use of crop rotation and fertilizer, while younger farmers show greater engagement with soil and water conservation practices. At the same time, labor availability emerges as an important enabling factor for maintaining the adoption of labor-intensive practices, particularly SWC. These patterns provide useful context for the econometric analysis that follows, which further examines the determinants of adoption trajectories and their implications for agricultural productivity and household welfare.

Table 3: Summary Statistics of Explanatory Variables

Explanatory variables	Crop rotation adoption categories			Chemical fertilizer adoption categories			Soil and water conservation adoption categories		
	Persistent adopters	New adopters	Non adopters	Persistent adopters	New adopters	Non adopters	Persistent adopters	New adopters	Non adopters
Age	44.9	44.38	42.14	44.56	44.25	43.22	42.19	44.22	46.03
Adult equivalent	4.09	3.8	4	4.14	3.96	3.94	4.26	4.07	3.74
Elevation (m)	2000.56	1771.67	1557.79	2070.9	1885.61	1485.94	1987.19	1885.8	1612.02
Annual av. rain fall (mm)	1043.47	1067.21	958.09	1005.83	1000.42	1066.44	1017.92	1034.8	1022.79
Gender (1=M)	.84	.79	.77	.85	.79	.77	.89	.83	.70
Parcel document	.401	.36	.61	.43	.32	.56	.38	.48	.50
Credit	.16	.73	.129	.17	.07	.03	.15	.08	.06
Extension	.38	.54	.80	.33	.57	.75	.37	.50	.72
Poor soil quality	.46	.22	.37	.318	.20	.47	.33	.28	.37
Good soil quality	.54	.18	.26	.48	.24	.26	.35	.37	.33
Very good soil quality	.60	.14	.25	.52	.16	.31	.43	.38	.18
Livestock in TLU	4.09	2.59	3.21	4.02	3.09	3.25	3.76	3.62	3.28
Dist. from border in km	288	230	174	281	246	198	287	250	193.80
Dis. from road in km	18.64	16.82	11.66	15.20	14.98	18.93	17.64	15.52	15.81
Crop-livestock farming	.88	.82	.82	.89	.822	.82	.88	.87	.81
Manure	.05	.08	.19	.05	.17	.10	.08	.08	.13
Cons. Expenditure (ETB)	13618.8	15058.7	16380	15097	14806	13930	12863.47	14644.71	16710.41

Note: Values are means; standard deviations are reported in parentheses. Dummy variables are coded as 1 = Yes, 0 = otherwise. TLU

= Tropical Livestock Unit. ETB = Ethiopian Birr.

While 16% of persistent crop rotation adopters and 17% of fertilizer users have credit access, the most striking finding is that 73% of new crop rotation adopters access credit, indicating that liquidity is a primary catalyst for initiating rotational farming. For Soil and Water Conservation (SWC), credit access is lower overall but remains highest among persistent adopters, further suggesting that financial support is vital for maintaining long-term physical infrastructure and input use. Conversely, access to extension services is unexpectedly highest among non-adopters reaching 80% for crop rotation and 75% for fertilizer which may indicate that extension agents are targeting non-users or that existing advisory content is not effectively driving behavioral change. This pattern persists in SWC, where non-adopters continue to report the highest engagement with extension services, highlighting a potential misalignment between service delivery and farmer motivations (Table 3).

Land tenure security, measured via parcel documentation, presents a mixed distribution across these categories. Non-adopters report the highest rates of documentation for crop rotation (61.8%) and fertilizer (56.2%), whereas persistent adopters have lower rates, suggesting that secure tenure alone may not drive adoption. For SWC, the distribution is more balanced, implying that other factors, such as public work participation or environmental degradation, may have greater influence. Soil quality appears influential, with better soil conditions associated with higher adoption. For example, 60% of crop rotation adopters with very good soil persist in adoption, compared to only 25% of non-adopters. Similar patterns are observed across fertilizer and SWC categories. This supports the idea that farmers prioritize sustainable practices on more productive land. Livestock ownership measured by tropical livestock unit is consistently higher among persistent adopters, particularly for crop rotation (4.09) and fertilizer (4.02), aligning with the notion that integrated crop-livestock systems facilitate input availability and land use efficiency (Table 3).

Geographic access variables show that distance from the market, population centers, and national borders all correlate with adoption. Persistent adopters, especially of SWC and crop rotation, are located farther from markets and population centers, possibly reflecting greater dependence on local resources and less access to commercial alternatives. Conversely, non-adopters of crop rotation are located closer to the nearest major roads suggesting that proximity alone does not ensure adoption and that institutional or environmental factors may mediate these relationships.

Non adopters of crop rotation are located nearer to national borders implying that they are far away from infrastructural facilities, market and extension services. Manure use is higher among non-adopters, especially for crop rotation and SWC. This may indicate substitution effects, where households relying on organic methods feel less compelled to adopt additional sustainable practices. Similarly, crop-livestock integration is consistently higher among persistent adopters across all practices, reinforcing its importance as a systemic enabler of sustainability.

Finally, consumption expenditure, which was used as a proxy for household wealth, shows a non-linear relationship. For SWC, persistent adopters are the poorest, while non-adopters are the wealthiest, supporting the idea that public works targeting the poor drive SWC uptake. For fertilizer and crop rotation, non-adopters report higher average consumption, which may reflect a transition toward more commercial or mechanized production systems among wealthier households. This variation highlights the multidimensional nature of adoption decisions, where wealth interacts differently depending on the practice's cost, labor requirement, and institutional support.

Comparative Analysis of SAP Attributes and Adoption Drivers

The divergent impact of institutional and socio-economic factors across the three SAPs is fundamentally driven by their contrasting technical and economic attributes. Fertilizer adoption represents a capital-intensive, divisible, and high-turnover investment. Because it requires a significant "lumpy" cash outlay at the start of the planting season, it is highly sensitive to liquidity constraints, explaining why credit access is the primary driver for its adoption trajectory.

In contrast, Soil and Water Conservation (SWC) and Crop Rotation are characterized as labor-intensive, non-divisible, and long-term investments. These practices do not require high upfront cash but demand significant household labor for the construction of terraces or the management of diverse cropping cycles. This explains the statistical significance of household labor size for SWC, while credit remains insignificant. Furthermore, the "time-lag" between investment and return differs; fertilizer provides immediate yield increments (short-term), whereas SWC and crop rotation are investments in natural capital that yield benefits over several seasons. Consequently, households with larger livestock holdings (TLU) and land size are better positioned to adopt these long-term trajectories, as their asset base allows them to buffer the opportunity cost of diverted labor and land during the initial years of practice implementation.

SAP Adoption Dynamics

The analysis of adoption trajectories of sustainable agricultural practices (SAPs) was conducted using a multinomial logit model with clustered standard errors at household ID, based on pooled panel data from the Ethiopia LSMS-ISA surveys of 2018/19 and 2020/21. The dependent variable captures farmers' adoption status categorized as persistent adopter, new adopter, or non-adopter for each of the three practices: crop rotation, chemical fertilizer, and soil and water conservation (SWC). To ensure robustness, the model accounts for intra-household correlation across waves by clustering standard errors with household ID. Marginal effects were computed post estimation to provide interpretable, policy relevant insights into the drivers of adoption behavior (Table 4).

Table 4: Drivers of Adoption paths of Sustainable Agricultural Practices: Marginal effects from Pooled Multinomial Logit Model

Explanatory variables	Crop rotation			Chemical fertilizer			Soil and Water Conservation		
	Adoption category			Adoption category			Adoption category		
	Persisten	New	Non	Persisten	New	Non	Persisten	New	Non
	t	adopters	adopters	t	adopters	adopters	t	adopters	adopters
	adopters			adopters			adopters		
	dy/dx	dy/dx	dy/dx	dy/dx	dy/dx	dy/dx	dy/dx	dy/dx	dy/dx
Household head age	0.0014** (0.0008)	0.0003 (0.0007)	-0.0014** (0.0064)	0.00004 (0.0007)	-0.0007 (0.00073)	-0.0001 (0.0007)	- 0.0033*** (0.0008)	0.00048 (0.0008)	0.0028*** (0.0007)
Adult Equivalent	-0.0129 (0.008)	-0.0038 (0.0067)	0.167*** (0.006)	0.01 (0.007)	-0.0059 (0.0069)	-0.004 (0.0065)	0.010 (0.0076)	0.0033 (0.0081)	- 0.0133*** (0.0070)
Elevation (m)	0.249*** (0.053)	-0.081* (0.043)	-0.167*** (0.039)	0.581*** (0.0549)	-0.082 (0.0517)	- 0.4996*** (0.0451)	0.134*** (0.0497)	0.0523 (0.0581)	- 0.1866*** (0.0440)
Average rain fall (mm)	0.119** (0.0496)	0.0049 (0.0452)	-0.1239*** (0.0398)	0.0687 (0.0469)	-0.0868 (0.0502)	0.0189 (0.0458)	0.0351 (0.0479)	0.0892 (0.0552)	- 0.1244*** (0.0402)
Gender	0.0450 (0.0308)	-0.0020 (0.0272)	-0.0429* (0.0255)	0.0361 (0.0313)	-0.0006 (0.0283)	-0.0354 (0.0216)	0.1418*** (0.0340)	-0.0129 (0.0343)	- 0.1289*** (0.0262)

Parcel document	0.0010 (0.0243)	0.0673*** (0.0221)	-0.0680*** (0.0208)	-0.0537** (0.0231)	0.0970*** (0.0233)	-0.0432** (0.0216)	0.0474** (0.0245)	-0.0553** (0.026)	0.0078 (0.0239)
Credit	0.2258*** (0.0579)	0.0295 (0.0430)	-0.2554*** (0.0737)	0.1617*** (0.0415)	0.0243 (0.0408)	- 0.1995*** (0.0535)	-0.0499 (0.0379)	-0.1034** (0.040)	0.0535 (0.0386)
Extension	0.1952*** (0.0215)	-0.0034 (0.0204)	-0.1917*** (0.0210)	0.2478*** (0.0189)	-0.0240 (0.0209)	- 0.2238*** (0.0212)	0.1601*** (0.0232)	0.038* (0.0245)	- 0.1981*** (0.0213)
Good soil quality	0.0271 (0.0303)	-0.0360 (0.0260)	0.0088 (0.0253)	0.0366 (0.0289)	-0.0106 (0.0283)	-0.0260 (0.0264)	-0.0189 (0.0306)	-0.0018 (0.0326)	0.0207 (0.0272)
Very good soil quality	0.0473 (0.0370)	-0.0475 (0.0379)	-0.0007 (0.0313)	0.0354 (0.0348)	-0.0552 (0.0352)	0.0198 (.0339)	0.0329 (0.0401)	0.0703* (0.0420)	- 0.1033*** 0.0334)
Livestock in TLU	0.0234*** (0.0039)	- 0.0135*** (0.0040)	-0.0098*** (0.0032)	0.0148*** (0.0030)	-0.0019 (0.0029)	- 0.0129*** (0.0035)	0.0012 (0.0035)	-0.0022 (0.0034)	0.0034 (0.0029)
Distance from border	0.1489*** (0.0270)	-0.0123 (0.0238)	-0.1366*** (0.0201)	0.0240 (0.0263)	0.0066 (0.0244)	-0.0306 (0.0232)	0.1651*** (0.0309)	-0.0069 (0.0009)	- 0.1581*** (0.0234)
Distance from main road	0.0013** (0.0008)	0.0002 (0.0006)	-0.0010** (0.0007)	- 0.0029*** (0.0007)	-0.00037 (0.00073)	0.0033*** (0.0065)	-0.00089 (0.0007)	-0.0018** (0.0007)	0.0026*** (0.0007)

Crop-livestock integration	0.0357 (0.0346)	0.0113 (0.0291)	-0.0470* (0.0279)	0.786** (0.0302)	-0.0525 (0.0296)	-0.0260 (0.0300)	0.0210 (0.0364)	0.0268 (0.0372)	-0.0478* (0.0296)
Manure	- 0.1573*** (0.0383)	-0.0347 (0.0369)	0.1921*** (0.0296)	- 0.1900*** (0.0384)	0.1159*** (0.0304)	0.0740** (0.0325)	-0.0192 (0.0399)	-0.0661 (0.0439)	0.0854*** (0.0313)
Consumption expenditure	-0.0228 (0.0173)	0.0030 (0.0157)	-0.0198 (0.0155)	0.0517 (0.0181)	-0.0264 (0.0163)	-0.0253 (0.0158)	- 0.0732*** (0.0198)	-0.0049 (0.0196)	0.0683*** (0.0167)

Note: ***, ** and * stand for significance level at 1, 5 and 10% respectively; numbers in the parentheses are standard error

Livestock ownership (measured in TLU) positively influences persistent adoption of crop rotation and fertilizer use. This finding aligns with asset-based adoption theories, which argue that wealthier households possess greater risk-bearing capacity and investment flexibility [25, 26]. Livestock may also enhance complementarities within mixed farming systems, reinforcing fertilizer demand and nutrient cycling. Interestingly, wealth (proxied by consumption expenditure) positively affects persistent fertilizer use but negatively affects persistent adoption of soil and water conservation (SWC). This divergence suggests that SWC may be driven more by public incentives or labor-intensive conservation programs, which often target resource poor farmers [27]. Such practice-specific heterogeneity underscores the importance of differentiated policy interventions.

Consistent with previous empirical studies in Ethiopia and Sub-Saharan Africa, access to credit and extension services emerges as a strong determinant of persistent adoption, particularly for crop rotation and chemical fertilizer. Kassie et al. [26] similarly find that extension services significantly increase the likelihood of adopting sustainable intensification practices by reducing information asymmetries and improving farmers' technical capacity. Likewise, credit relaxes liquidity constraints that often hinder investment in productivity-enhancing inputs [25]. However, while prior studies typically assess adoption as a one-time decision, our results show that institutional access is particularly critical for sustained adoption rather than merely initial uptake. This suggests that extension and financial services do not only trigger adoption but also help stabilize long-term practice retention, a dimension largely overlooked in cross-sectional analyses.

Distance to roads significantly reduces persistent fertilizer adoption and increases non-adoption, emphasizing the role of market access in lowering transaction costs. This finding is consistent with earlier work by Alene et al. [28] and Minten et al. [29], who show that improved infrastructure facilitates input access and market participation, thereby promoting adoption of modern agricultural technologies. Our trajectory-based results further reveal that poor market access not only limits initial adoption but also increases the probability of reverting to non-adoption over time.

The negative association between manure use and persistent adoption of crop rotation and chemical fertilizer suggests input substitution rather than complementarity in some contexts. While integrated soil fertility management literature often emphasizes complementarities between organic and inorganic inputs [30], empirical evidence from smallholder systems shows that resource-constrained farmers may substitute manure for purchased inputs due to liquidity limitations [26]. Our findings extend this literature by demonstrating that substitution effects influence long-term adoption trajectories.

Our findings regarding the role of credit and extension services align with broader trends observed across Sub-Saharan Africa. For instance, the significant impact of credit on capital-intensive fertilizer adoption mirrors results from Malawi and Nigeria where liquidity remains the primary barrier to input intensification [26]. Similarly, our finding that household labor and land size drive long-term structural investments like SWC is consistent with evidence from Kenya and Tanzania [4], suggesting that across the region, 'natural capital' investments require a labor buffer that smaller, resource-poor households often lack. This confirms that the challenges of sustainable intensification in Ethiopia are not isolated but reflect systemic resource constraints shared across the Sub-Saharan African (SSA) smallholder landscape.

Persistent adoption of SWC is positively associated with household labor availability but negatively associated with farmer age. This is consistent with the labor-intensive nature of conservation structures and prior findings that older farmers may be less inclined to undertake physically demanding investments [31, 4]. By distinguishing persistent from new adoption, our results suggest that labor availability is particularly critical for maintaining conservation structures over time, not merely establishing them.

Limitations of the Study

While this study provides a nuanced understanding of adoption trajectories using nationally representative panel data from 2018/19 and 2020/21, it is subject to certain limitations that offer avenues for future research. First, while the analysis focuses on crop rotation, chemical fertilizer, and soil and water conservation (SWC), a complete systemic perspective on Ethiopian sustainable agriculture requires examining additional practices such as efficient irrigation, drought-resistant crops, and other innovative technologies. Furthermore, the current research period is limited to two survey waves; extending the data collection period in future studies would allow for a more comprehensive, long-term transient analysis of how adoption behavior evolves over time.

Second, while using lagged independent variables from the 2018/19 baseline to predict 2020/21 trajectories helps reduce simultaneity bias, this approach cannot account for dynamic shocks or changes in constraints occurring between the survey waves (e.g., sudden increases in credit access, input availability, or rainfall variability) that may have directly triggered adoption. Consequently, the model predicts future behavioral changes based primarily on past constraints, potentially underestimating the influence of such dynamic factors. Finally, because the number of dis-adopters was very small in this sample, they were excluded to ensure meaningful statistical comparisons. To ensure this exclusion did not introduce selection bias, t-tests were conducted to compare baseline characteristics (land size, labor, and assets) between dis-adopters and persistent adopters. The t-test result shows that there is no significant differences ($p > 0.10$) between dis-adopters and persistent adopters. However, understanding the drivers of practice abandonment remains a critical area for future investigation.

Conclusion and Policy Implications

Conclusion

This study analyzed the factors shaping smallholder farmers' adoption trajectories-persistent adoption, new adoption, and non-adoption of three key sustainable agricultural practices: crop rotation, chemical fertilizer use, and soil and water conservation (SWC) in Ethiopia. Using nationally representative panel data from the LSMS-ISA (2018/19 and 2020/21) and multinomial logit models, we identified both shared and practice-specific factors influencing farmers' decisions over time.

Access to credit and extension services significantly increases the likelihood of both persistent and new adoption, highlighting the critical role of support systems in enabling farmers to start and sustain sustainable practices. Livestock ownership, household labor availability, and soil quality strongly influence persistent adoption. These results suggest that households with sufficient resources are better positioned to maintain SAPs over time. Distance from roads and borders affects access to inputs and information, with households in more remote locations facing higher adoption barriers. While higher wealth supports fertilizer adoption, labor-intensive practices like SWC are more accessible to poorer households, especially when linked to public employment programs. This demonstrates that adoption is both practice-specific and trajectory dependent. Ultimately, by shifting the focus from static binary choices to dynamic trajectories, this study provides a robust evidence base that is highly applicable for designing more resilient and adaptive sustainable agricultural policies in Ethiopia.

Policy implication

To promote sustained adoption of sustainable agricultural practices among Ethiopian smallholders, extension programs should be tailored to the specific needs of each adopter group. For non-adopters, who already have high exposure to extension services, the focus should shift from generic awareness campaigns to improving the quality, relevance, and practical applicability of extension messages. This includes providing context-specific advice, on-farm demonstrations, and integrating complementary support such as credit access, input provision, and technical training. Follow-up support for new adopters remains important to reinforce

adoption decisions. Expanding access to affordable rural credit can ease liquidity constraints, particularly for input-intensive practices like fertilizer use, supporting both initial and persistent adoption. Furthermore, to design optimized technology packages for farmers, future research and policy must clarify whether the simultaneous adoption of several SAPs generates synergies or resource conflicts within farms. Promoting integrated crop-livestock systems and labor-saving conservation technologies can help resource-limited households adopt multiple practices simultaneously. Targeted investments in rural infrastructure, such as roads, input distribution networks, and market connectivity, are critical for increasing adoption in remote and border-adjacent areas. Finally, identifying and utilizing simulation models that can predict the impact of subsidies, credit programs, or differentiated extension would add significant value to current efforts, serving as a critical decision-support tool at the agricultural policy level.

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Authors' contributions

FB and AO have made substantial contributions in the design, data mining, merging, analysis, interpretation of results and drafted the manuscript. All the other authors have contributed in revision of the draft manuscript and have read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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Ethical Approval

This study relies exclusively on secondary data from the World Bank Living Standards Measurement Study-Integrated Survey of Agriculture (LSMS-ISA). The data are publicly available, fully anonymized, and contain no identifiable personal information. As no direct interaction with human participants occurred, the study does not constitute human-subject research requiring institutional review board (IRB) approval. The analysis was conducted in accordance with ethical standards for secondary data use and the World Bank's data use policies.

Data Availability Statement

The primary datasets analyzed during the current study are freely available in the World Bank Microdata Library under the Living Standards Measurement Study - Integrated Surveys on Agriculture (LSMS-ISA) collection and can be accessed directly at: <https://microdata.worldbank.org/collections/lsms>.

Clinical Trial Number

Not applicable. This study does not involve any clinical trials, medical interventions, or health-related human experimentation. It is an empirical analysis based on secondary socio-economic survey data from the World Bank.

Consent to Publish

Not applicable. This manuscript does not contain any individual person's data, videos, images, or identifiable personal information. The analysis is based entirely on fully anonymized, public secondary microdata from the World Bank.

Consent to Participate

Not applicable. This research was conducted using de-identified secondary microdata from the World Bank repository. No primary data collection or direct interaction with human participants was undertaken by the authors.

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