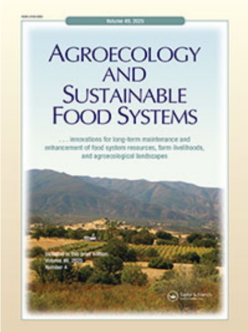


Agroecology and Sustainable Food Systems

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/wjsa21

Understanding farmers' choices in climate-smart agriculture: adoption of agroecology principles and impacts on rural livelihoods in semi-arid Tanzania

Mahlet Degefu Awoke, Katharina Löhr, Anthony A. Kimaro, Custodio Efraim Matavel, Marcos A. Lana, Johannes Michael Hafner & Stefan Sieber

To cite this article: Mahlet Degefu Awoke, Katharina Löhr, Anthony A. Kimaro, Custodio Efraim Matavel, Marcos A. Lana, Johannes Michael Hafner & Stefan Sieber (25 Feb 2025): Understanding farmers' choices in climate-smart agriculture: adoption of agroecology principles and impacts on rural livelihoods in semi-arid Tanzania, Agroecology and Sustainable Food Systems, DOI: 10.1080/21683565.2025.2466439

To link to this article: https://doi.org/10.1080/21683565.2025.2466439

AGROECOLOGY AND SUSTAINABLE FOOD SYSTEMS
https://doi.org/10.1080/21683565.2025.2466439

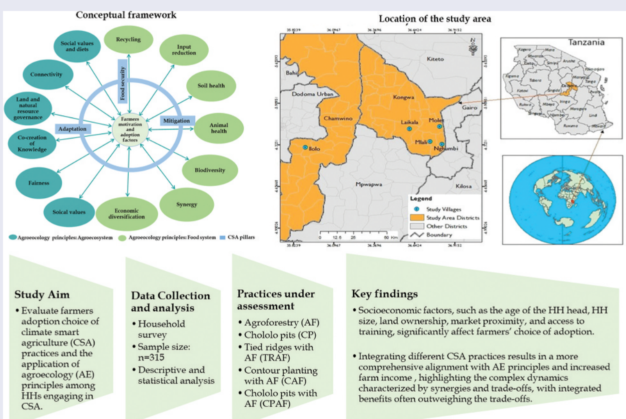
Understanding farmers' choices in climate-smart agriculture: adoption of agroecology principles and impacts on rural livelihoods in semi-arid Tanzania

Mahlet Degefu Awoke[a,b], Katharina Löhr[a,c], Anthony A. Kimaro[d], Custodio Efraim Matavel[e], Marcos A. Lana[f], Johannes Michael Hafner[a,d], and Stefan Sieber[a,b]

[a]Sustainable Land Use in Developing Countries(SusLAND), Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany; [b]Faculty of Life Science, Thaer-Institute of Agriculture and Horticultural Sciences, Department of Agricultural Economics, Humboldt-Universität zu Berlin, Berlin, Germany; [c]Faculty of Life Science,Thaer-Institute of Agriculture and Horticultural Sciences, Department of Urban Plant Ecophysiology, Humboldt-Universität zu Berlin, Berlin, Germany; [d]Center for International Forestry Research-World Agroforestry Center (CIFOR-ICRAF), Tanzania program, Dar es Salaam, Tanzania; [e]Leibniz Institute for Agricultural Engineering and Bio economy (ATB), Potsdam, Germany; [f]Crop Production Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden

ABSTRACT

This study explores climate-smart agriculture (CSA) adoption and the application of agroecology (AE) principles among Tanzanian smallholders, using a survey of 315 households (HHs). Findings reveal that most CSA adopters integrate several AE principles, though application varies by CSA practices. Socioeconomic factors, like HH head, HH size, land ownership, training access, CSA interventions, and local initiatives, influence and shape adoption patterns. Integrating different CSA practices improves alignment with AE principles, increasing farm income and creating ecological-economic synergies. Highlighting CSA's and AE's potential to enhance smallholder livelihoods and mitigate climate change, the study stresses horizontal knowledge sharing in promoting integrated approaches.



KEYWORDS

Adoption; agroecology principles; climate-smart agriculture; farm income; tree intercropping

SUSTAINABLE DEVELOPMENT GOALS

SDG 1: No poverty; SDG 2: Zero hunger; SDG 3: Good health and well-being; SDG 13: Climate action

CONTACT Mahlet Degefu Awoke Mahlet-Degefu.Awoke@zalf.de Leibniz Centre for Agricultural Landscape Research (ZALF), Sustainable Land Use in Developing Countries(susLAND), Müncheberg 15374, Germany

Supplemental data for this article can be accessed online at https://doi.org/10.1080/21683565.2025.2466439.

Introduction

Smallholder agricultural production in Africa is affected by numerous challenges, including scarce arable land, declining soil fertility, persistent droughts, and the detrimental impacts of climate change. The latter is contributing to a rise in food insecurity and poverty across Africa (Nyasimi et al. 2017). Specifically, the agricultural sector in arid regions faces severe consequences from rising temperatures, unpredictable precipitation patterns, and severe weather events, including droughts and floods. These conditions jeopardize the reliability of food production systems (Bongole, Kitundu, and Hella 2020; Jones et al. 2023). Such challenges are anticipated to exacerbate poverty and food insecurity for millions of people due to the unpredictability of agricultural productivity, loss of biodiversity, and socioeconomic instability (Shilomboleni et al. 2020). These are expected to pose considerable barriers, especially for small-scale farmers. Although African agricultural output increased throughout the 21st century, it did not keep pace with the growing population's food demand, leading to persistent food shortages among rural households. Therefore, it is imperative to enhance agricultural productivity and address underlying poverty in the face of climate change. The need for concerted efforts to tackle global food security has never been more critical (Bongole, Kitundu, and Hella 2020; Fanzo et al. 2013).

Tanzania faces significant climate change vulnerability due to its agricultural economy, which employs 78% of the population and is largely dependent on rain-fed and subsistence farming (Rioux, Lava, and Karttunen 2017). Projected temperature rises could drastically reduce crop yields, particularly for small-scale farmers in arid regions. For instance, in 2025, shifting temperature and rainfall patterns are expected to minimize maize and sorghum yields, staple crops of Tanzania, thus increasing the direct impact of climate change on food security (Rowhani et al. 2011; Yusuph et al. 2023). Enhancing the adaptability of small-scale farmers, particularly in arid regions, is crucial to sustain the desired level of food security and income to cope with the growing population's needs. The Government of Tanzania (GoT) is taking multiple steps to mitigate adverse climate change impacts, including the commitment to transition the agricultural sector to be climate-smart by 2030 (Jones et al. 2023; Rioux, Lava, and Karttunen 2017) and promote agroecology practices (Yusuph et al. 2023), such as agroforestry technologies (Kimaro et al. 2016).

Climate-smart agriculture (CSA) and agroecology (AE) are complementary strategies, both aiming to transform smallholder food systems at global and regional levels (Gliessman and Tittonell 2015; Lipper et al. 2014; Shilomboleni et al. 2020; Were, Gelaw, and Singh 2016). CSA focuses on integrating new technologies to ensure food security and improve rural livelihoods, mainly targeting the vulnerable. FAO (2010) defines CSA as an approach that sustainably increases productivity and resilience, while reducing greenhouse gases (GHGs), thus facilitating the achievement of national food security and development goals. It encompasses a range of actions, both on and off the farm, which include the adoption of technologies, engagement with institutions, implementation of policies, and allocation of investments (Pimbert 2015; Scherr, Shames, and Friedman 2012). The primary goal of CSA is to enhance productivity and resilience, while mitigating the effects of climate change. CSA achieves these goals by improving input efficiency, soil quality, and the cost-benefit returns to farmers, thereby addressing the anticipated adverse impacts of climate change (Schaller et al. 2017).

AE, the second strategy, focuses on diversified and context-specific agricultural activities designed to stabilize food supply in the face of climate change, taking into account social and human dimensions (Wezel et al. 2020). This approach applies ecological and social concepts to agriculture, with the aim of sustaining agricultural production through reduced reliance on external inputs, enhancing natural processes, and integrating indigenous knowledge (HLPE 2019; Van Zutphen et al. 2022). Interestingly, CSA proponents are now incorporating specific agroecological techniques with mainstream technologies, underscoring AE's vital role within CSA (Andrieu and Kebede 2020).

Both CSA and AE offer valuable insights, and their complementary aspects can be integrated to facilitate the transformation of the smallholder farmer food system into a more sustainable and resilient system in the face of climate change. However, their adoption in Tanzania remains limited (Jones et al. 2023; Shilomboleni et al. 2020; Yusuph et al. 2023). Despite numerous related projects and programs, widespread adoption across various regions remains challenging (Mugabe 2020). Some critics argue that African agriculture is already agroecological in nature, thus further promotion may not necessarily enhance productivity (Mazibuko et al. 2023). Additionally, there are some concerns about the yield potential of agroecological practices, with Wassie and Pauline (2018) noting that farmers often favor approaches that provide immediate benefits, offering high crop productivity in the short term.

The alignment of CSA and AE remains a subject of ongoing debate. While many agroecological practices are categorized as CSA due to their contribution to adaptation and mitigation, not all CSA practices align with AE principles (Hrabanski and Fallot 2017; Sinclair et al. 2019; Tittonell 2015). Kaczan, Arslan, and Lipper (2013) also highlight that AE practices are considered climate-smart due to their ability to enhance diversity and promote positive interactions with nature by fostering resilience while minimizing dependence on external inputs.

A gap in understanding how the adoption of CSA aligns with AE principles is evident, particularly among smallholder farmers. For instance, the role of agroforestry (AF), often categorized as CSA, is not yet extensively evaluated in terms of its contribution to input reduction (Suresh Ramanan and Arunachalam 2021) – a fundamental AE principle. AF is a leading practice in various CSA and AE programs, exemplifying socio-ecological systems where social and environmental systems interact (Antoh et al. 2021; Fischer et al. 2017). While existing literature investigates CSA and AE separately, the interaction between these two concepts and the determinants of farmers' adoption choices remains underexplored.

The overall objective of the study was to address the knowledge gap in understanding how CSA adoption aligns with AE principles. The specific objectives were: i) to identify the factors influencing smallholder farmer's choice of adoption of CSA practices; ii) to assess the extent to which smallholder farmers practicing CSA align with AE principles; and iii) to understand and compare outcomes of different CSA practices using farm income. The study explores specific CSA and application of AE principles within the context of small-scale farming in Tanzania. Tanzania is chosen as the country of study because its government has committed to implementing CSA and promoting AE, as indicated in the Tanzania CSA guideline (Tanzania and Fisheries 2017). The findings of this research can inform policymakers and practitioners for future sustainable and climate-resilient agricultural interventions.

Conceptual framework

Our study's conceptual framework draws on insights from Dumont, Wartenberg, and Baret (2021), Rosenstock et al. (2016), HLPE (2019), and Van Zutphen et al. (2022). These foundational studies provide diverse perspectives on the relationship between CSA and AE. As emphasized by Pimbert (2015), CSA and AE, while distinct, are interconnected concepts, each possessing unique characteristics. Although some practices are common to both due to their contributions to climate adaptation and mitigation, not all CSA practices align with AE principles. For instance, employing no-till farming with herbicides for weed control may be considered climate-smart, but it contradicts AE principles that favor minimal chemical inputs, as noted by Sinclair et al. (2019). These examples highlight the necessity for a nuanced understanding of both concepts.

CSA primarily aims to enhance food production, resilience, and climate change adaptation, encompassing dimensions such as food security, stability of food access, and measurable income increases (Rosenstock et al. 2016). In contrast, AE, which incorporates social and cultural elements of food systems, is guided by 13 principles outlined by the High-Level Panel of Experts (HLPE). These principles cover various agricultural, ecological, socioeconomic, and political aspects, further categorized by Nicolétis et al. (2019) and Van Zutphen et al. (2022) into agroecosystems (farm level) and food systems (community level), focusing on environmental sustainability and socioeconomic aspects, respectively.

The conceptual framework systematically examines the interplay between AE principles in smallholder farming, evaluating how CSA practices influence the application of these principles. At the core of the framework (Figure 1) lies the farmer's motivation and adoption factors, representing the central decision-making process of smallholder farmers while choosing specific CSA practices. Surrounding this core are the three CSA pillars, encircled by the AE principles, subdivided into agroecosystem and food system principles as per Nicolétis et al. (2019). The agroecosystem principles focus on ecological aspects, such as soil health, synergy, and biodiversity, contributing to environmental sustainability at the farm level. Meanwhile, food system principles encompass co-creating knowledge, fairness, and social values at the community level (Nicolétis et al. 2019; Van Zutphen et al. 2022). For instance, co-creating knowledge is essential for integrating local knowledge with broader agricultural innovations, ensuring that practices are both socially relevant and technologically reliable.

The study postulates that the adoption of specific CSA practices can influence outcomes that, in turn, impact adherence to AE principles and vice versa. This suggests an iterative process of improvement and refinement of practices, illustrated by the bidirectional arrows indicating the dynamic relationship between AE principles and practices, facilitating continuous learning and adaptation. Using the conceptual framework, the study extends its exploration through empirical testing, focusing on smallholder farmers in Tanzania as a case study. This approach enables an evaluation of the practical application of CSA, which encompasses representatives of CSA approaches and AE principles. The study specifically examines the factors influencing farmer's adoption choices. Understanding farmer's motivations and factors that shape farmers' decisions to engage with specific practices is critical for developing ecologically, socially, and economically viable interventions.

Methodology

Case study area

This study sites, situated in the Kongwa and Chamwino districts of central Tanzania's Dodoma region, are located in a semi-arid zone at altitudes ranging from 1000 to 1500 meters. With annual rainfall between 400 and 800 mm and a dry period lasting 7 to 8 months, the area is characterized by flat plains, rocky hills, and low soil fertility (Mkonda 2021). Rain-fed agriculture, sometimes supplemented by livestock keeping, is the primary livelihood activity in the region, with maize, sorghum, sunflower, and pigeon peas as the main crops (Mayaya, Opata, and Kipkorir 2015). The study region is one of the most drought-affected areas of Tanzania, with numerous challenges, including livelihood insecurity, deteriorating socioeconomic conditions, land

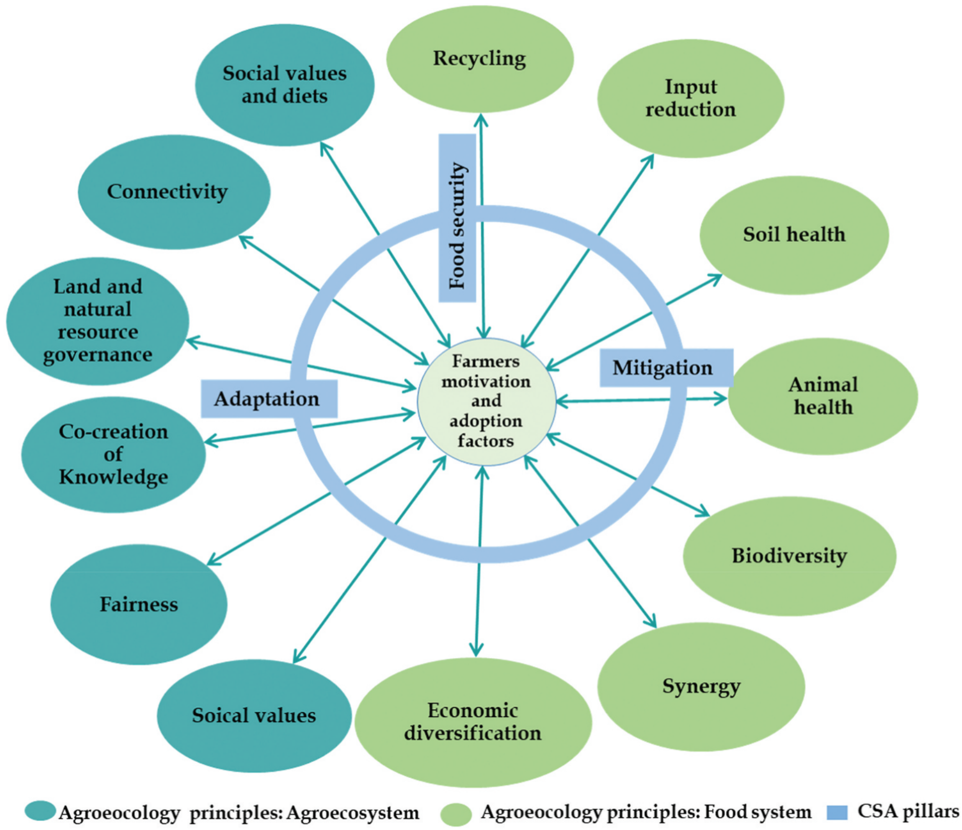


Figure 1. Conceptual framework illustrating the interplay between agroecology (AE) principles (Nicolétis et al. 2019), Climate-smart agriculture (CSA) (Jat et al. 2020), and adoption factors.

degradation, and vulnerability to drought (Awoke et al. 2025; Brüssow, Faße, and Grote 2017).

For this study, four villages from the Kongwa district and one village from the Chamwino district were selected, based on each village's biophysical characteristics, vulnerability to climate change and drought, erratic rainfall patterns, and the local farmers' engagement with CSA and agroecology practices (Awoke et al. 2023; Gamba, Kimaro, and Mtei 2020; Yusuph et al. 2023). Study villages were part of various initiatives that introduced CSA intervention packages aimed at enhancing climate resilience and productivity among subsistence farmers. Specifically, Ilolo village participated in the Trans-SEC project, which promoted practices such as agroforestry and tied ridges (Uckert et al. 2018). Molet, Mlali, and Laikala were part of the Africa RISING initiative, where CSA practices such as agroforestry, contour farming, tied ridges, and chololo pits were introduced individually or in packages. Additionally, Molet, Mlali, and Nghumbi were involved in the CSA Capacity Building for Resilient Food Security project, with Nghumbi also serving as an Africa RISING scaling village (Kizito et al. 2022; Swamila et al. 2020). The inclusion of these five villages, all exposed to CSA practices, ensured the study effectively captured the dynamics of adoption and adaptation. Moreover, the shared climatic conditions and agricultural challenges across neighboring villages in the Dodoma region enhance the generalizability of the findings, providing insights applicable to other semi-arid regions facing similar risks

Sampling design and data collection method

From June to August 2022, a household (HH) survey was employed through one-on-one interviews using a questionnaire facilitated by Kobo Toolbox. The questionnaire was designed to capture a wide range of data, comprising binary, multi-choice, and open-ended questions. This format addresses the diverse aspects of the study comprehensively. All interviews were conducted in *Kiswahili*, the national language. Enumerators, all fluent in both Swahili (as their mother tongue) and English, were carefully selected. They held at least a Bachelor's degree and had experience Marin similar surveys. Prior to the commencement of the survey, the survey instrument was pre-tested with individuals who were not part of the sample to ensure that the enumerators were familiarized with the questionnaire and the concepts, and that respondents provided meaningful responses. Modifications were made based on the feedback from the pretest.

HHs implementing at least one CSA practice were included in the survey. The selection of five major practices in the study area was guided by previous research (Awoke et al. 2023; Gamba, Kimaro, and Mtei 2020; Liingilie 2019). A list of 598 CSA practitioners was provided by lead farmers from the study villages and World Agroforestry (ICRAF). Initially, a sample size of 218 respondents was calculated using the method described in Bukhari (2020) with a 95% confidence interval. However, to account for potential variations arising from unregistered CSA farmers, we used a 99% confidence interval. Additionally, we employed gender-based random stratified sampling, resulting in the inclusion of 315 HHs comprising 167 female and 148 male respondents. This approach ensures that our study provides a more comprehensive and accurate representation of CSA adoption in the area, enhancing the reliability and validity of the findings.

The survey instrument gathered detailed information on various aspects, encompassing demographics, socio-economics, and institutional background of the sampled HHs, as well as plot-specific characteristics and types of practices implemented by each HH. The practices evaluated here include tree intercropping (TI), tied ridges + TI, contour farming + TI, chololo pits (CP), and chololo pits + TI. The majority of HHs reported practicing tree intercropping alone, closely followed by contour farming with tree intercropping. Detailed descriptions of the practices, their categorization, the percentage of HHs' adoption of each practice, and the contribution of CSA practices to the selected AE principles based on previous research are provided in appendix 1. The practical applicability of these principles is further assessed in this study. The most dominant tree species observed in the case study villages include *Gliricidia sepium* and other indigenous trees, such as *Acacia tortilis* and *Adansonia digitata*.

Selected agroecology principles for further assessment

Subsequent evaluations determined the extent of adherence to AE principles by HHs implementing CSA practices. Recognizing the comprehensive scope of AE, which encompasses 13 AE principles, this study selectively focused on those most applicable to smallholder farmers at the farm level. These include recycling, input reduction, soil health, synergy, and economic diversification. Additionally, we examined one principle at the community level: co-creation of knowledge. This principle plays a central role when implementing an agroecological approach, ensuring the local applicability of the practices and their successful dissemination among farmers, which is crucial since farmers are more receptive to knowledge from peers than experts and researchers (Sinclair et al. 2019). In total, six principles were chosen to thoroughly assess HH adherence to AE principles -five agroecosystems at the farm level and one food system from the community level (Van Zutphen et al. 2022). A detailed explanation of each selected AE principle and indicators used for the assessment is presented in appendix 2. To assess the extent of AE adherence of HHs implementing CSA, we ensured mutual exclusivity. This involved including farmers who practiced only one specific CSA practice, which resulted in a reduced sample size of 291 HHs.

Data analysis

Descriptive statistics of demographic and socioeconomic data

Descriptive statistics summarize the data from the household survey, examining demographic, physical, and socioeconomic characteristics, alongside motivations for adopting or discontinuing CSA practices and adherence to agroecology principles. Insights from open-ended questionnaire responses further enriched the quantitative data.

Table 1 summarizes key categorical and continuous variables. The majority of households were male-headed (79%) and married (76%), with 94% having over 5 years of farming experience. While 86% owned land – important for CSA adoption – only 8% reported non-farm income, with Mlali village having the highest proportion (13%) and Ilolo and Laikala villages reporting none. The average age of household heads was 48 years, with variation across villages: Laikala had the oldest (55 years), while Nghumbi had the youngest (46 years). Households had an average of 4 years of CSA experience, with Ilolo village having the highest average CSA experience of 5.5 years, while Nghumbi had the lowest at 3 years. Households allocated 0.8 hectares to CSA out of a total average farm size of 1.62 hectares. The mean market distance was 24.5 km, which may limit access to inputs and markets. On average, households cultivated three crops, indicating modest crop diversification.

Multivariate probit model

A multivariate probit model (MVP) was applied to identify the determinants influencing the choice of CSA practices among smallholder farmers. Our empirical analysis focuses on the choice of CSA practices from the set of five practices previously selected for the analysis. The MVP model examined potential correlations among unobserved factors influencing the adoption of each practice. Here, a binary dependent variable is assigned a value of one when the farmer adopts the practice; zero otherwise. The different choices of practices by smallholder farmers were identified during the HH survey. It is important to note that smallholder farmers often adopt multiple CSA practices

Table 1. Descriptive statistics of selected categorical and continuous variables.

Village names	All Villages	Ilolo (n=65)	Laikala (n=26)	Mlali (n=82)	Molet (n=73)	Nghumbi (n=69)
Categorical variables	%	%	%	%	%	%
Household (HH) head gender (Male)	79	66	76	73	88	74
Marital status (Married)	76	72	72	61	81	70
Education Level						
No formal education	16	17	36	10	25	7
Primary education	76	74	64	80	73	81
Secondary education	4	3	0	4	0	10
Higher education	4	6	0	6	3	1
Farm experience						
2–3 Years	3	3.08	4	4.88	0	5.8
4–5 Years	3	0	0	6	3	1
>5 Years	94	97	96	89	97	93
HHs with non-farm income	8	0	0	13	7	12
HHs with owned land	86	100	100	88	89	90
HHs with leased land	14	5	16	12	19	17
Training access	95	95	100	93	93	100
Training is given by						
Fellow farmers	68	92	100	46	60	68
NGOs	79	78	100	74	78	80
Extension officers	21	15	48	9	25	28
Continuous variables	**Mean (Std. Dev.)**	**Mean (Std. Dev.)**	**Mean (Std. Dev.)**	**Mean (Std. Dev.)**	**Mean (Std. Dev.)**	**Mean (Std. Dev.)**
HH head age (years)	48 (12.7)	51 (15.26)	55 (12.44)	48 (11.42)	47(11.62)	46 (11.75)
HH size (numbers)	6 (2.6)	6 (1.98)	7 (2.75)	6 (2.77)	7 (2.59)	6 (2.74)
Farm holding size (ha)	1.66 (1.65)	1.72 (2.58)	2.05 (1.25)	1.53 (1.41)	1.84 (1.37)	1.44 (1.10)
CSA allocated size (ha)	0.7 (0.49)	0.53 (0.42)	0.83 (0.60)	0.58 (0.46)	0.60 (0.53)	0.69 (0.49)
CSA experience (years)	4 (2.3)	5.69 (2.33)	3.64 (2.90)	4.77 (2.38)	4.07 (1.97)	3.14 (1.51)
Family labor (numbers)	3 (1.3)	2.68 (1.32)	3.08 (1.12)	2.20 (1.33)	3.18 (1.37)	2.75 (1.21)
Number of crops cultivated	3 (0.9)	3.03 (1.00)	2.72 (0.79)	2.89 (0.90)	2.73 (0.89)	2.80 (0.81)
Farm input cost/ha (USD)	42.21 (45.8)	45.89 (60.78)	70.18 (132.53)	114.93 (102.59)	114.25 (174.44)	80.60 (141.02)
Total farm income/ha (USD)	285.07 (258.5)	344.58 (416.96)	394.28 (624.19)	783.63 (1087.70)	770.29 (690.75)	575.29 (555.50)
Nearest local market distance (km)	24.5 (14.5)	1.50 (0.00)	12.00 (0.00)	35.00 (0.00)	23.00 (0.00)	40.00 (0.00)

on a single farm plot and that these measures can be interdependent (Amare and Darr 2020; Sileshi et al. 2019).

Following Sileshi et al. (2019), the MVP econometric method formulated for this study involves a set of binary dependent variables P_{pj}, defined by the relationship:

$$P^*{}_{pj} = x_{pj}\beta_j + u_{pj}, j = 1, 2, \ldots, m \tag{1}$$

$$Where\ P_{pj} = 1\ if\ P_{pj} > 0\ or\ (indicating\ the\ adoption\ of\ CSA) \tag{2}$$

0, otherwise.

The subject j denotes the different practices under consideration; *p* indicates the number that represents the different exploratory variables, x_{pj} - is a vector of explanatory variables (Table 1); β_j represents the parameter to be estimated; u_{hj} is the random error terms.

The latent variable $P^*{}_{pj,}$ reflects the unobserved preferences or tendencies associated with the j^{th} practice choice. This variable is assumed to be a linear function of both observed HH characteristics affecting the adoption of CSA practices and unobserved characteristics captured by the error term. Our estimate relies on the observed variable P_{PJ}, which indicates whether a HH has adopted a specific practice. Considering that the HH may adopt several techniques, the error terms in equation (1) are presumed to have a multivariate normal distribution with a conditional mean of zero and variance normalized to one. The off-diagonal elements in the covariance matrix denote the unobserved correlation between the error components of the j^{th} and m^{th} types of adaptation strategies.

This assumption means that equation two gives an MVP model that simultaneously represents decisions related to adopting specific CSA practices. This specification with non-zero off-diagonal elements allows for correlation across the error terms in multiple latent equations describing unobserved characteristics. The Wald chi-squared result affirmed that the model fitted the data well, and the null hypothesis of no effect of the variables can be rejected (Wald chi^2 = 217.15, p_{value} = 0.000).

Analysis of variance (ANOVA) and Tukey's HSD test (Post-hoc analysis)

A one-way ANOVA was used to assess variation in mean farm income across different CSA practices. Farm income was calculated based on crop farm income, including both sold and consumed crops. To minimize recall bias, farmers reported the total quantities harvested in the last season, the amounts sold, and sale prices. For crops consumed and stored, their value was estimated using prevailing market prices from local markets at the time of the survey (Spicka et al. 2019). Fuelwood revenue was excluded from the calculation for two reasons. First, many of the trees reported were still immature, with harvesting expected in one or two years. Second, farmers practicing chololo pits did not integrate tree planting into their farming systems, meaning their income was derived solely from crop production. To ensure consistency and comparability, only crop production income was included in the analysis. A post-hoc Tukey's HSD test was performed to identify specific pairwise differences in mean income between CSA practices and villages.

Results

Factors influencing smallholder farmers' decision to choose specific CSA practices

Farmer's motivation for CSA adoption

Figure 2 highlights the percentage of households adopting various CSA practices across villages, showing clear preference variations. Ilolo village primarily focuses on tree intercropping (TI), while Mlali and Molet exhibit a more balanced adoption of multiple practices, particularly chololo pits and chololo pits + TI. In contrast, Nghumbi demonstrates notable adoption of contour farming + TI and tied ridges + TI. Meanwhile, Laikala village adopted more contour farming + TI, followed by TI alone. Overall, there is a significant difference in the distribution of CSA practices across villages, as confirmed by the Chi-square test results ($p < 0.05$), indicating that the adoption of CSA practices is not uniform and varies considerably between villages.

Farmers were asked to provide their motivations for abandoning conventional agriculture and deciding to apply CSA practices on their farms. The primary motivation for adopting CSA was to improve productivity, followed by reducing land degradation and soil erosion. The study shows that motivations varied depending on the specific CSA practice, especially in addressing soil erosion and land degradation. Specifically, those combining tree intercropping with soil and water conservation techniques showed a greater focus on both enhancing productivity and addressing land degradation, unlike those solely engaged in water harvesting practices, like chololo pits (Figure 4).

Other reasons to adopt CSA that were not included in the questionnaire include: primarily focusing on income improvement, securing farm boundaries, and, specifically, those with trees on the farm, a source of shade. The motivation for the adoption of each practice varied. For instance, 97% of farmers practicing contour farming + TI, 92% of those practicing chololo pits + TI, 86% of those practicing tied ridges + TI, 72% of only TI farmers, and 54% of Chololo pits farmers stated their motivation for adopting CSA is to reduce soil erosion and land degradation (Figure 4).

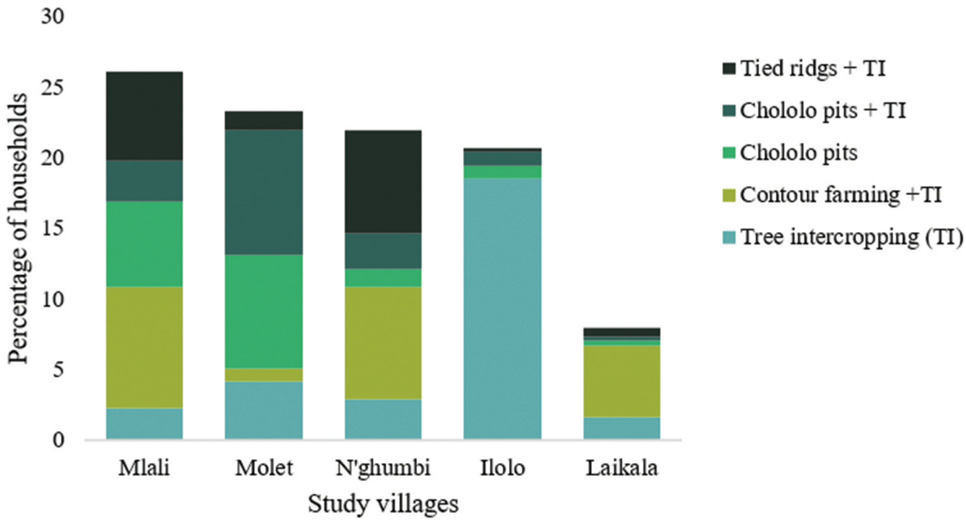


Figure 2. Percentage of households categorized by CSA level of adoption, classified by village and CSA practices.

Adoption and dis-adoption patterns of CSA practices.

The study revealed that the majority of respondents continued implementation of CSA. Several reasons were stated, including its positive impact on crop productivity and soil fertility, while reducing soil erosion. Out of the 315 respondents interviewed, 15% discontinued adopting a particular CSA practice. However, it is important to note that they shifted from one CSA practice to another, ensuring they continued engaging with at least one CSA approach. A range of factors influenced this choice. The primary stated reason was the labor-intensive nature of specific practices, mainly related to soil and water conservation techniques (Figure 5). Furthermore, farmers stated that low productivity was a key reason for changing their practices, particularly tree intercropping. In response, these farmers integrated TI with other CSA techniques (chololo pits, and tied ridges) to enhance agricultural productivity.

The reasons for dis-adoption and changes in practices varied, ranging from labor intensiveness to technological failure. For example, some farmers switched to chololo pits due to their better water-holding capacity compared to tree intercropping. Others switched to combined TI and chololo pits from implementing them separately for improved productivity, as the combined effect was more effective. For instance, 3% of tree intercropping farmers transitioned to adopting or integrating chololo pits with tree intercropping. On the other hand, 3% of chololo pit farmers shifted away from this practice due to its labor-intensive nature and high capital costs, opting instead for tree intercropping or integrating it with tree intercropping to achieve better productivity.

Additionally, respondents indicated other reasons, such as soil and crop types, for abandoning specific CSA practices. Some cited the unsuitability of chololo pits and tied ridges for certain soil types and crops. For instance, chololo pits and tied ridges were ineffective in sandy soils because they collapsed easily. Some interesting insights were also noted from the relationship between crop types and dis-adoption patterns. The majority of farmers who exclusively adopt pure tree intercropping tend to cultivate crops such as sorghum (51%), groundnuts (36%), sunflower (35%), maize (30%), and pigeon pea (13%). In contrast, farmers who combine chololo pits and tied ridges with tree intercropping predominantly focus on maize (above 40%).

Determinants of HH choice of CSA: results from multivariate probit model

The MVP examined the factors influencing the selection of CSA practices among smallholder farmers (Table 2). As the Chi-square test confirmed that the decisions regarding the adoption of the five CSA practices are not mutually exclusive, indicating that farmers may adopt multiple CSA practices simultaneously, understanding the factors influencing these choices is essential.

The analysis revealed several significant associations, with significant factors presented in Table 2. For instance, a significant positive association between HH head age and the adoption of TI was observed. Conversely, the adoption of chololo pits + TI decreased with the age of the HH head. More married HH adopted TI than non-married HH, indicating the effect of marital status on technology adoption. The adoption of chololo pits increased with family size, highlighting the role of household size as a determinant of CSA practice adoption. Conversely, the size of HH was negatively associated with TI adoption.

Landownership is another factor negatively correlated with the adoption of chololo pits preference while positively associated with the adoption of tied ridges + TI. Furthermore, training exposure shows a negative and significant association with the adoption of Chololo pits. In contrast, training exposure is correlated positively with the other practices, although it was not significant. The study further explored the sources of training or information access to determine if farmers received specific training from particular stakeholders or acquired the practices independently. Only 3% of farmers indicated they had adopted the CSA practices without formal training. Further analysis showed that the majority of adopters (above 80%) who received training integrated tree intercropping with other CSA practices. On the other hand, those who did not receive formal training typically adopted chololo pits and tree intercropping alone, while nobody combined tree intercropping with another CSA practice.

Lastly, market distance shows a positive significant correlation with tree intercropping, combined tree intercropping, tied ridges with tree intercropping, and combined tied ridges with tree intercropping, while no significant

Table 2. Determinants of household choice of climate-smart practices in Chamwino and Kongwa Districts, Dodoma, Tanzania ($n = 315$).

Explanatory Variables	Tree intercropping (TI) Coeff. (SE)	Chololo pits Coeff. (SE)	Chololo pits + TI Coeff. (SE)	Contour farming + TI Coeff. (SE)	Tied ridges + TI Coeff. (SE)
HH head age	0.018* (0.008*)	−0.009 (0.010)	−0.022* (0.009*)	0.005 (0.008)	−0.001 (0.011)
Marital status	1.117* (0.501*)	−0.490 (0.362)	−0.027 (0.375)	−0.297 (0.332)	−0.099 (0.425)
HH size	−0.076* (0.039*)	0.088* (0.040*)	0.022 (0.040)	−0.043 (0.035)	−0.052 (0.043)
Additional water source	−1.033′ (0.542′)	1.529** (0.496**)	0.362 (0.481)	−0.437 (0.507)	−5.201 (421.152)
Land owned	0.531 (0.572)	−1.154* (0.504*)	0.255 (0.530)	0.730 (0.464)	1.223* (0.623*)
Farm distance	−0.003 (0.003)	0.005* (0.003*)	−0.003 (0.003)	0.000 (0.003)	0.000 (0.003)
Training exposure	0.361 (0.623)	−1.233* (0.604*)	2.688 (18.261)	−0.430 (0.575)	5.340 (175.763)
Market distance	0.051*** (0.008***)	0.009 (0.009)	0.020* (0.008*)	0.033*** (0.008)	0.053*** (0.012***)
_cons	−0.595 (1.113)	0.877 (1.059)	−4.058 (18.272)	−2.024 (0.985)	−8.166 (175.767)

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1'' 1.
Number of obss=315.
Log likelihood = −487.54212
Wald chi2 (112) =217.15.
Prob > chi2=0.000.
Likelihood ratio test of rho21 = rho31 = rho41 = rho32 = rho42 = rho43 = 0.
chi2 (6) = 44.5746 Prob > chi2 = 0.0000.

association was observed with the adoption of chololo pits. Farm distance positively correlates with the adoption of chololo pits.

Adherence to agroecological principles and relationship with CSA

Figure 6 illustrates the percentage of smallholder farmers adhering to AE principles while implementing CSA practices. The findings reveal that over 80% of HHs applied economic diversification through crop diversification on their farms, cultivating at least two non-tree crops for either marketing or subsistence purposes, thereby enhancing economic resilience. Following crop diversification, knowledge co-creation showed the second-highest adherence, with 73% of HHs participating in horizontal or farmer-to-farmer knowledge exchange on CSA practices. In terms of soil health, 32% of HHs applied farmyard manure to improve soil fertility, demonstrating partial alignment with AE principles. All CSA practitioners, except chololo pits implementers, engaged in tree intercropping, aligning with the AE principles of synergy. Therefore, we exclude the synergy aspect from further analysis.

The following indicators measure the principles: 1) recycling: use of farm-saved seeds; 2) input reduction: avoiding the use of pesticides; 3) soil fertility: use of farmyard manure; 4) income diversification: crop diversification; and 5) knowledge sharing: farmer-to-farmer training.

The application of manure and using farm-saved seeds align with multiple AE principles, including recycling, input reduction, and soil health. For instance, these indicators support AE principles of recycling and input reduction by encouraging the reduction of input such as pesticide use and relying entirely or mostly on local inputs such as manure and farm-saved seeds.

Upon examining overall adherence to agroecology principles, HHs were categorized based on their adoption of CSA (Figure 7). Those practicing tied ridges + TI led in crop diversification, followed by chololo pits + TI. Despite some variation among the practices, this result implies the majority of HHs practicing CSA incorporated crop diversification on their farm.

In examining input reduction, tree intercropping farmers reported the highest minimization of external inputs, with 84% avoiding pesticide use, aligning strongly with AE principles. Similarly, chololo pits + TI demonstrated notable input reductions, with 80% of farmers avoiding pesticide use. In contrast, tied ridges + TI farmers reported the least input reduction, as 52% used pesticides. In terms of soil health, tied ridges + TI farmers reported the highest application of farmyard manure to enhance soil fertility, while tree intercropping farmers reported the lowest use of this practice. However, TI farmers exhibited the highest reliance on farm-saved seeds, contributing to the AE principle of recycling and resource efficiency.

The study also revealed slight variations in knowledge co-creation across CSA practices. TI farmers, followed by chololo pits farmers, exhibited the highest levels of engagement in horizontal knowledge sharing, reflecting strong farmer-to-farmer collaboration. In contrast, tied ridges + TI farmers reported the lowest levels of horizontal knowledge sharing.

Perceived benefits of CSA and economic outcomes

The transition of farmers from conventional agriculture to CSA practices and the application of AE principles positively influenced their overall livelihood (Figure 8). The highest perceived benefits are the enhancement in soil fertility, food access, and food diversity improvement. A substantial number of HH reported improvement in fuel collection time. Another benefit is enhancing economic stability, with respondents suggesting that CSA has positively influenced income and financial security. Moreover, over half of the HH reported improved school access for their children. While these perceived benefits are valuable in understanding the broader impact of CSA on farmers' lives, they are based on farmers' subjective assessments and cannot be quantified precisely.

To further quantify the economic outcomes of CSA adoption, we evaluated the income generated from crop production. This aligns with the primary motivation for CSA adoption – improving crop productivity (Figure 3). The quantification of farm income provides a more objective measure of the economic benefits of CSA, supporting the notion that CSA adoption contributes to improved livelihoods and economic stability.

The analysis of average farm income across CSA practices revealed notable differences. Among the practices, chololo pits reported the highest mean farm income of 381.55 USD, followed by tied ridges + TI, with a mean income of 355.94 USD. In contrast, contour farming + TI and chololo pits + TI showed comparable mean incomes of 229.79 USD and 230.29 USD, respectively. Tree intercropping had the lowest mean income of 181.52 USD. The ANOVA results, followed by post-hoc analysis, revealed significant differences ($p < 0.05$) in farm income. Chololo pits demonstrated significantly higher farm income compared to TI, with a mean difference of 200.04 USD. Similarly, tied ridges + TI generated significantly higher income than TI alone, with a mean difference of 174.42 USD. While TI did not exhibit a statistically significant difference from contour farming + TI, the integration of contour farming with TI generated a higher income, with a mean difference of 113.37 USD. No significant differences in farm income were observed across villages, indicating that the performance of these CSA practices is consistent across different locations. Detailed results from the post-hoc Tukey's analysis of farm income across practices and villages are presented in the Appendix.

Discussion

Factors influencing farmers' decision to adopt CSA

Farmer's motivations for adopting CSA practices are predominantly driven by the need to enhance crop productivity (Figure 3). This reflects a broader inclination in which economic reasons are seen as a primary motivator for

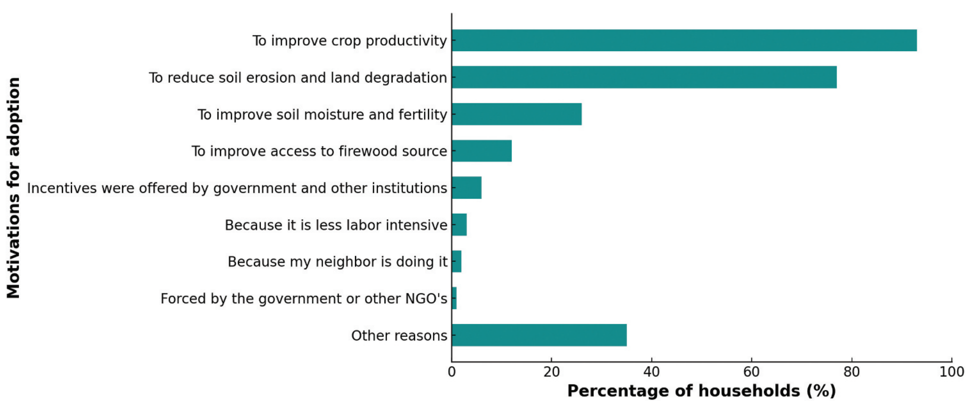


Figure 3. Motivations of farmers for transitioning from conventional to CSA practices (*n*=315).

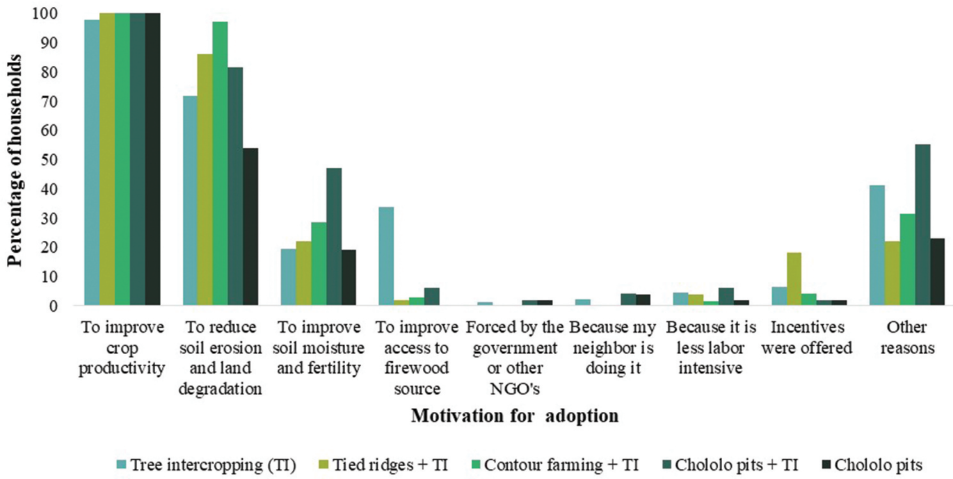


Figure 4. Motivations of farmers for transitioning from conventional to CSA practices categorized according to their adoption of each CSA practice. The colors distinguish between types of CSA practices (*n*=291—each HH adopting one specific CSA practice).

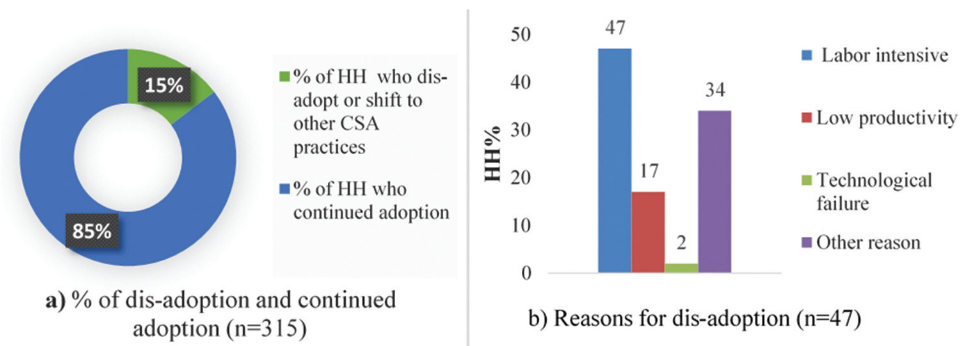


Figure 5. Adoption and dis-adoption patterns (a) and reason for dis-adoption of CSA practices (b).

engaging with CSA practices that promise improved yields and resilience against climate change (Lipper et al. 2014; Thorlakson and Neufeldt 2012). The differentiated motivation across the various CSA practices (Figure 3) suggests complex decision-making, where farmers consider various aspects. For instance, the combined effect of tree intercropping with other CSA practices seems more attractive to farmers motivated by addressing land degradation and enhancing productivity, simultaneously underlining the synergy between different CSA practices and how they complement each other (Lasco et al. 2014).

Notable variations observed in CSA adoption across the villages can be attributed to the nature of CSA interventions introduced in each location. For

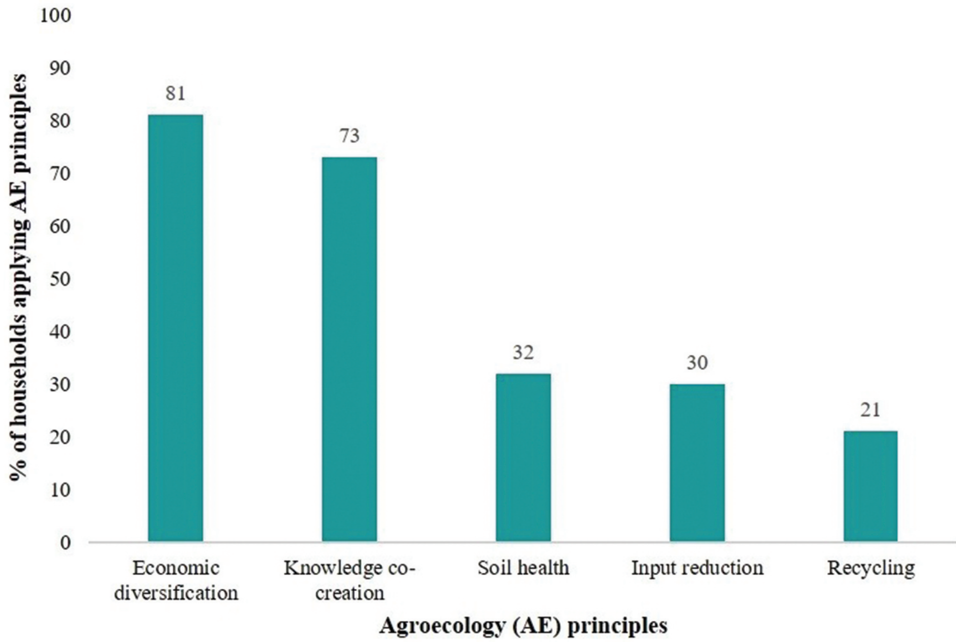


Figure 6. Percentage of households adhering to agroecological principles in Chamwino and Kongwa Districts, Dodoma, Tanzania (*n*=315). The figure illustrates the proportion of households implementing agroecological principles.

instance, Ilolo village's focus on tree intercropping aligns with its involvement in the Trans-SEC project, which promoted agroforestry practices (Uckert et al. 2018). Similarly, the Africa RISING initiative in Molet and Mlali villages promoted a range of practices (Kizito et al. 2022), fostering integrated adoption approaches that may explain the observed patterns of combining multiple practices. These examples illustrate how targeted interventions shape CSA adoption patterns within specific contexts, emphasizing the importance of tailoring interventions to local needs and conditions.

The primary barriers to continued CSA adoption, such as labor intensive and high capital cost (Figure 5), reflect long-standing challenges faced by smallholder farmers in developing countries. These findings (Figure 5) align with the broader literature on the barriers to adopting sustainable agricultural practices, emphasizing the need for measures that minimize the entry barriers for smallholder farmers (Knowler and Bradshaw 2007). This underlines the necessity for interventions that reduce these constraints, such as improving access to credit facilities, which could highly influence the uptake of CSA practices.

These findings highlight the diversity of adoption among farmers. Age plays a vital role, with the adoption of TI increasing with HH head age, while the

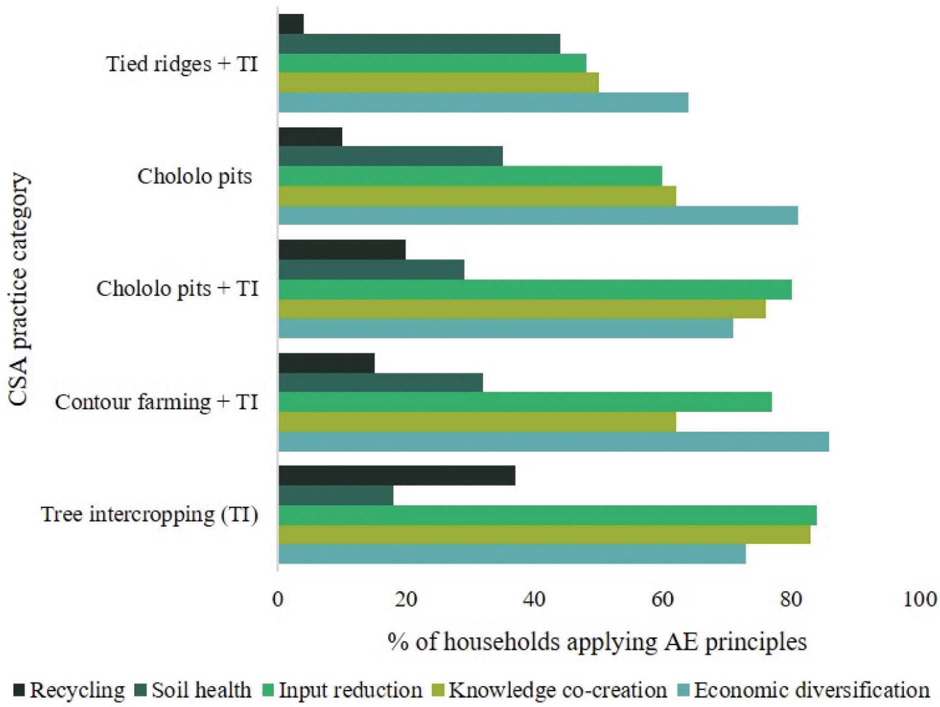


Figure 7. Extent of smallholder farmer's adherence to AE principles while practicing climate-smart agriculture categorized according to their adoption of each CSA practice. The colors distinguish between types of CSA practices (*n*=291—each HH adopting one specific CSA practice).

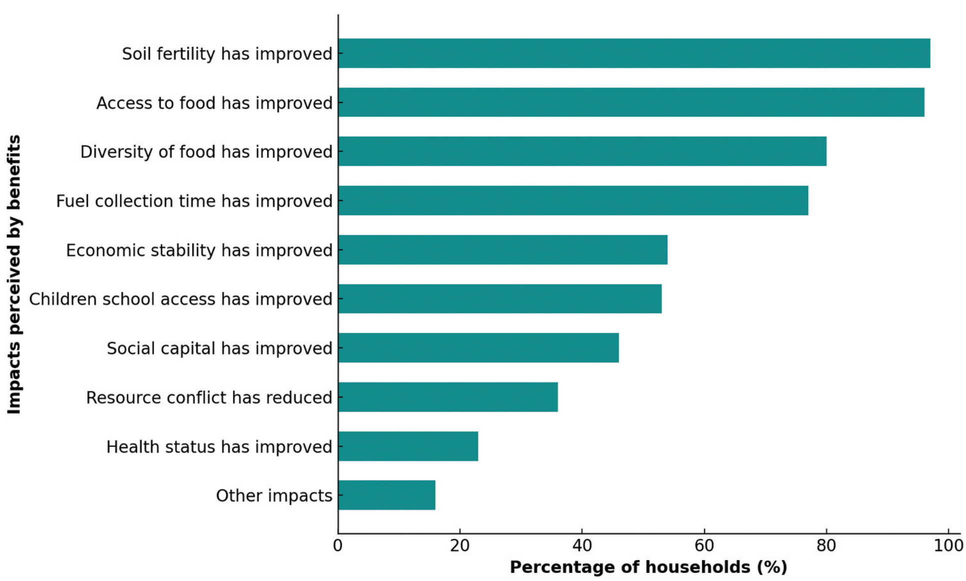


Figure 8. CSA and AE practice impact on household well-being and livelihood perceived by farmers (*n*=315).

adoption of chololo pits + TI decreases with the age of HH (Table 2). This might be because young- and middle-aged farmers are more motivated to adopt new technologies and take risk than old farmers. This is consistent with Kelemewerk Mekuria et al. (2020), who found that older household heads were less likely to adopt soil and water harvesting practices due to risk aversion, reliance on tradition, and the labor-intensive nature of the practices, whereas younger heads, with greater exposure to information, were more open to adoption. Similarly, larger family sizes correlate with chololo pits adoption, likely due to labor availability (Addisu, Husen, and Demeku 2015; Darkwah et al. 2019). In contrast, TI was negatively correlated with adoption among larger families, possibly due to its long-term benefits, which may be less appealing when immediate returns are needed to meet household needs. Fané et al. (2024) and Pello et al. (2021) reported similar findings that larger household sizes hindered agroforestry adoption in West Africa and the semi-arid regions of Kenya.

Land ownership emerges as a significant determinant, with landowners more inclined to TI (Table 2), suggesting that landowners may have a greater tendency toward adopting TI, likely due to the long-term benefits of integrating trees into their farming system. This result is consistent with Kurgat et al. (2020), who stated that agroforestry adoption positively correlates with land ownership, potentially limiting the accessibility of the practices to smallholder farmers. Market proximity is also a factor, with those further from markets more likely to adopt tree intercropping. A similar finding was observed in other studies (Mahmood and Zubair 2020; Zerihun, Muchie, and Worku 2014), pointing to the resilience of agroforestry in marginal areas. Smallholder farmers adapt their strategies based on the knowledge and skills acquired from various sources. It is evident that the training source influences the choices to adopt CSA practices. For instance, as stated above, farmers trained by fellow farmers tend to focus on tree intercropping, and the MVP result revealed that farmers with access to training are not inclined to adopt CP alone (Table 2). The majority of farmers trained by NGOs and have access to extension services seem to favor an integrated approach, combining TI with other CSA practices. This might be because visits to extension service centers increase farmers' knowledge through demonstration plots on farm fields, enhancing their understanding of the technology and improving adoption rates (Pello et al. 2021). This diversity in practice adoption is crucial as it demonstrates that there is not a one-size-fits-all approach to CSA implementation. Failing to recognize and account for the diversity within small-scale farming may hinder the promotion of CSA practices, and assuming a uniform practice during the promotion and scaling up of CSA could impede long-term adoption (Abegunde, Sibanda, and Obi 2019).

Interplay of CSA practices with agroecology principles: an economic outcome

The study highlights the complex relationship between CSA practices, agroecology principles, and economic outcomes. While CSA adopters typically apply multiple AE principles (Figure 6), the extent of their application varies across households, reflecting differences in farming systems, resource access, and farmers' motivations, as noted by Tittonell (2015) and Altieri, Nicholls, and Montalba (2017). Tittonell (2015) distinguishes CSA and AE as distinct concepts, noting that CSA focuses on food insecurity, climate resilience, and reduced GHGs, while AE centers on ecological principles like diversity, resource efficiency, and natural regulation to design sustainable food systems. Dumont, Wartenberg, and Baret (2021) further emphasize that the application of AE principles can differ even among farmers with shared geographic and socioeconomic contexts.

While AE principles promote minimizing synthetic inputs, economic pressures often lead farmers to prioritize yields. For example, farmers practicing tied ridges + TI and chololo pits reported the highest pesticide usage but also achieved the highest farm incomes. This finding aligns with Dumont, Wartenberg, and Baret (2021), who noted the challenges of fully adhering to AE principles while ensuring economic viability. These trade-offs highlight the tension between ecological sustainability and economic imperatives. Significant synergies also exist between CSA practices and AE principles. Tree intercropping serves as a sustainable alternative or complement to inorganic fertilizers, offering yield benefits at low cost, as noted by Kaczan, Arslan, and Lipper (2013). However, tree intercropping's lower average income reflects a trade-off between ecological benefits and economic returns. Integrating TI with water harvesting techniques and manure application could yield better outcomes, particularly in arid regions like Dodoma. This aligns with Suresh Ramanan and Arunachalam (2021), who emphasized the need for complementary practices to maximize benefits.

The evaluation of average farm incomes under different CSA practices and AE principle applications reveals notable variations. Practices like chololo pits and tied ridges + TI, integrated with farmyard manure, are associated with higher incomes, potentially due to their efficient water harvesting techniques and soil fertility improvement potential (Jones et al. 2023). Additionally, the type of crops grown under each CSA practice might affect income variations. Aluku et al. (2021), observed that the profitability of soil and water conservation practices depends on the crops cultivated.

Interestingly, most farmers practicing tied ridges + TI and chololo pits reported the highest farmyard manure usage (Figure 7) and the highest income, further explaining the observed income variation. This aligns with Jensen et al. (2003), who stated that manure application improves soil fertility and reduces transaction costs, thereby enhancing farm income. While the majority of TI farmers align closely with AE principles, its lower income reflects a potential trade-off between ecological sustainability and economic gain. This observation is consistent with Mazibuko et al. (2023), who discuss the economic challenges of practices prioritizing ecological benefits. Notably, this study's income data excludes revenue from firewood, which could significantly enhance the economic appeal of TI, as highlighted by Hafner et al. (2021).

The slight increase in farm income observed when chololo pit is combined with TI demonstrates the potential benefit of integrating multiple approaches. As noted by Antoh et al. (2021) and Fischer et al. (2017), agroforestry, such as tree intercropping; is a leading practice across CSA and agroecology programs. Combining it with other CSA practices not only improves farm income but also adheres to at least three components of agroecology: soil health, input reduction, and synergy. This is consistent with Hrabanski and Fallot (2017), who emphasize the effectiveness of combining practices to mitigate land degradation and enhance economic viability. Farmer-to-farmer knowledge exchange, a core AE principle, also plays a critical role. A majority of CSA adopters engage in horizontal knowledge sharing (Figure 6), which Sinclair et al. (2019) affirmed as a significant influence on CSA practice choices.

Conclusion

This study investigates CSA practices among smallholder farmers in Tanzania, focusing on factors influencing adoption, alignment with agroecology (AE) principles, and implications for livelihoods. The findings reveal that farmers primarily adopt CSA to enhance crop productivity and resilience to climate change. However, motivations vary across practices, reflecting the complexity of decision-making processes among smallholder farmers.

Socioeconomic, demographic, and institutional factors, such as household head age, family size, land ownership, and access to training, influence adoption patterns. Barriers like labor demands and financial constraints emphasize the need for interventions to improve access to credit and align CSA practices with local contexts. Knowledge dissemination, primarily through horizontal sharing, agricultural extension services, and local NGOs, plays a pivotal role in promoting CSA adoption. Strengthening farmer networks and platforms for sharing knowledge and experiences can enhance peer-to-peer learning and support the scaling up of successful CSA practices.

The study explores the relationship between CSA practices and AE principles, emphasizing the benefits of integrated approaches. Households adopting CSA practices implement AE principles to varying degrees, with those integrating multiple practices – such as agroforestry, water harvesting techniques, farmyard manure, and crop diversification – achieving better socioeconomic and ecological outcomes. In semi-arid regions, like Dodoma, such integration addresses both ecological and economic challenges, improving yields, enhancing economic resilience, and promoting sustainability.

The findings have significant policy implications. To enhance CSA adoption, policymakers should prioritize improving access to various resources, like credit, and strengthening agricultural extension services, thus equipping farmers with essential resources, knowledge, and technical support. Tailored interventions must address diverse socioeconomic and institutional factors to meet the specific needs of different farmer groups. Observed differences in adoption across villages underscore the importance of CSA interventions and training programs in influencing adoption patterns. Policies should encourage the integration of CSA practices, promote horizontal knowledge sharing, and engage local NGOs in training and outreach. Emphasizing CSA practices aligned with AE principles can maximize environmental sustainability and farm productivity.

While the study focuses on farm-level agroecology, future research should explore CSA and AE interactions at both farm and community levels to assess the broader ecological, social, and economic impacts. Such research will deepen our understanding of how CSA and AE can address climate resilience, food security, and livelihoods. By adopting a farmer-centered, context-specific approach, policymakers can improve food security, enhance livelihoods, and build climate resilience, offering a model for other regions facing similar challenges.

Acknowledgement

The authors thank those who participated in the household survey and shared their perspectives. A special thanks to the Leibniz Centre for Agricultural Landscape Research (ZALF) in Müncheberg, Germany, and the staff of the Center for International Forestry Research-World Agroforestry Center (CIFOR-ICRAF) in Dar es Salaam, Tanzania, for their technical and logistical assistance.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was funded by the Academy for International Agricultural Research (ACINAR). ACINAR, commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ), is implemented by ATSAF e.V. on behalf of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. Open access for this article was provided by the Leibniz Centre for Agricultural Landscape Research (ZALF) through an open access agreement.

ORCID

Mahlet Degefu Awoke http://orcid.org/0009-0008-0105-375X
Katharina Löhr http://orcid.org/0000-0003-2691-9712
Anthony A. Kimaro http://orcid.org/0000-0002-4703-1539
Custodio Efraim Matavel http://orcid.org/0000-0002-3800-7887
Marcos A. Lana http://orcid.org/0000-0002-1733-1100
Johannes Michael Hafner http://orcid.org/0000-0003-2447-6268
Stefan Sieber http://orcid.org/0000-0002-4849-7277

Availability of data and material

The data supporting this study's findings are available on request from the corresponding author.

References

Abegunde, V. O., M. Sibanda, and A. Obi. 2019. The dynamics of climate change adaptation in Sub-Saharan Africa: A review of climate-smart agriculture among small-scale farmers. *Climate* 7 (11):132. doi: 10.3390/cli7110132.

Addisu, D. A., M. A. Husen, and M. A. Demeku. 2015. Determinants of adopting techniques of soil and water conservation in Goromti Watershed, Western Ethiopia. *Journal of Soil Science* 6:168–77.

Altieri, M. A., C. I. Nicholls, and R. Montalba. 2017. Technological approaches to sustainable agriculture at a crossroads: An agroecological perspective. *Sustainability* 9 (3):349. doi: 10.3390/su9030349.

Aluku, H., H. C. Komakech, A. Van Griensven, H. Mahoo, and S. Eisenreich. 2021. Seasonal profitability of soil and water conservation techniques in semi-arid agro-ecological zones of Makanya catchment, Tanzania. *Agricultural Water Management* 243:106493. doi: 10.1016/j.agwat.2020.106493.

Amare, D., and D. Darr. 2020. Agroforestry adoption as a systems concept: A review. *Forest Policy and Economics* 120:102299. doi: 10.1016/j.forpol.2020.102299.

Andrieu, N., and Y. Kebede. 2020. Agroecology and climate change: A case study of the CCAFS research program. *CCAFS Working Paper*.

Antoh, E. F., A. A. Arhin, S. Edusah, and K. Obeng-Okrah. 2021. Prospects of agroforestry as climate-smart agricultural strategy in cocoa landscapes: Perspectives of farmers in Ghana. *Sustainable Agriculture Research* 10 (1):10. doi: 10.5539/sar.v10n1p20.

Awoke, M. D., J. Hafner, A. A. Kimaro, M. A. Lana, K. Löhr, and S. Sieber. 2023. Development of an integrated assessment framework for agroforestry technologies: Assessing sustainability, barriers, and impacts in the semi-arid region of Dodoma, Tanzania. *International Journal of Agricultural Sustainability* 21 (1):2285161. doi: 10.1080/14735903.2023.2285161.

Awoke, M. D., K. Löhr, A. A. Kimaro, M. Lana, B. D. Soh Wenda, K. Buabeng, J. M. Hafner, and S. Sieber. 2025. Exploring gender dynamics in climate-smart agriculture adoption: A study in semi-arid Dodoma, Tanzania. *Frontiers in Sustainable Food Systems* 8:1507540. doi: 10.3389/fsufs.2024.1507540.

Bongole, A., K. Kitundu, and J. Hella. 2020. Usage of climate smart agriculture practices: An analysis of farm households' decisions in Southern Highlands of Tanzania. *Tanzania Journal of Agricultural Sciences* 19:238–55.

Brüssow, K., A. Faße, and U. Grote. 2017. Implications of climate-smart strategy adoption by farm households for food security in Tanzania. *Food Security* 9 (6):1203–18. doi: 10.1007/s12571-017-0694-y.

Bukhari, S. A. R. 2020. Bukhari sample size calculator. *Research Gate GMBH*. doi: 10.13140/RG.2.2.27730.58563.

Darkwah, K. A., J. D. Kwawu, F. Agyire-Tettey, and D. B. Sarpong. 2019. Assessment of the determinants that influence the adoption of sustainable soil and water conservation practices in Techiman Municipality of Ghana. *International Soil & Water Conservation Research* 7 (3):248–57. doi: 10.1016/j.iswcr.2019.04.003.

Dumont, A. M., A. C. Wartenberg, and P. Baret. 2021. Bridging the gap between the agroecological ideal and its implementation into practice. A review. *Agronomy for Sustainable Development* 41 (3):32. doi: 10.1007/s13593-021-00666-3.

Fané, S., D. K. Agbotui, S. Graefe, L. Sanou, S. Sanogo, and A. Buerkert. 2024. Adoption of agroforestry systems by smallholders' farmers in the Sudano-Sahelian zones of Mali and Burkina Faso, West Africa. *Agroforestry Systems* 98 (7):2385–96. doi: 10.1007/s10457-024-01020-8.

Fanzo, J., D. Hunter, T. Borelli, and F. Mattei. 2013. *Diversifying food and diets*. London: Routledge.

FAO (Food Agriculture Organization). 2010. *Climate smart agriculture: Policies, practices and financing for food security, adaptation and mitigation*. Rome, Italy: Food Agriculture Organization.

Fischer, J., D. J. Abson, A. Bergsten, N. French Collier, I. Dorresteijn, J. Hanspach, K. Hylander, J. Schultner, and F. Senbeta. 2017. Reframing the food–biodiversity challenge. *Trends in Ecology & Evolution* 32 (5):335–45. doi: 10.1016/j.tree.2017.02.009.

Gamba, A., A. Kimaro, and K. Mtei. 2020. Effects of climate smart agricultural practices and planting dates on maize growth and nutrient uptake in Semi-Arid Tanzania. *International Journal of Biosciences | IJB |* 16:98–109.

Gliessman, S., and P. Tittonell. 2015. Agroecology for food security and nutrition. *Agroecology & Sustainable Food Systems* 39 (2):131–33. doi: 10.1080/21683565.2014.972001.

Hafner, J., J. Steinke, G. Uckert, S. Sieber, and A. Kimaro. 2021. Allometric equations for estimating on-farm fuel production of Gliricidia sepium (Gliricidia) shrubs and Cajanus cajan (pigeon pea) plants in semi-arid Tanzania. *Energy, Sustainability and Society* 11 (1):1–14. doi: 10.1186/s13705-021-00310-8.

HLPE. 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the high level panel of experts on food security and nutrition of the committee on world food security.

Hrabanski, M., and A. Fallot. 2017. Comparative analysis of four concepts for adapting agriculture to climate change: Resilience, agroecology, climate-smart agriculture (CSA) and nature-based solutions (NbS).

Jat, M. L., H. S. Jat, T. Agarwal, D. Bijarniya, K. S. Kumar, K. M. Choudhary, K. C. Kalvaniya, N. Gupta, M. Kumar, and L. K. Singh. 2020. *A compendium of key climate smart agriculture practices in intensive cereal based systems of South Asia*. New Delhi, India: CIMMYT.

Jensen, J. R., R. H. Bernhard, S. Hansen, J. Mcdonagh, J. P. Møberg, N. E. Nielsen, and E. Nordbo. 2003. Productivity in maize based cropping systems under various soil–water–nutrient management strategies in a semi-arid, alfisol environment in East Africa. *Agricultural Water Management* 59 (3):217–37. doi: 10.1016/S0378-3774(02)00151-8.

Jones, K., A. Nowak, E. Berglund, W. Grinnell, E. Temu, B. Paul, L. L. R. Renwick, P. Steward, T. S. Rosenstock, and A. A. Kimaro. 2023. Evidence supports the potential for climate-smart agriculture in Tanzania. *Global Food Security* 36:100666. doi: 10.1016/j.gfs.2022.100666.

Kaczan, D., A. Arslan, and L. Lipper. 2013. Climate-smart agriculture? A review of current practice of agroforestry and conservation agriculture in Malawi and Zambia.

Kelemewerk Mekuria, Z., A. Kassegn Amede, E. Endris Mekonnen, and F. Yildiz. 2020. Adoption of rainwater harvesting and its impact on smallholder farmer livelihoods in Kutaber district, South Wollo Zone, Ethiopia. *Cogent Food & Agriculture* 6 (1):1834910. doi: 10.1080/23311932.2020.1834910.

Kimaro, A. A., M. Mpanda, J. Rioux, E. Aynekulu, S. Shaba, M. Thiong'o, P. Mutuo, S. Abwanda, K. Shepherd, H. Neufeldt, et al. 2016. Is conservation agriculture 'climate-smart'for maize farmers in the highlands of Tanzania? *Nutrient Cycling in Agroecosystems* 105 (3):217–28. doi: 10.1007/s10705-015-9711-8.

Kizito, F., R. Chikowo, A. Kimaro, and E. Swai. 2022. Soil and water conservation for climate-resilient agriculture. In *Sustainable agricultural intensification: A handbook for practitioners in East and Southern Africa*, 62–79. Wallingford, UK: CABI.

Knowler, D., and B. Bradshaw. 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. *Food Policy* 32 (1):25–48. doi: 10.1016/j.foodpol.2006.01.003.

Kurgat, B. K., C. Lamanna, A. Kimaro, N. Namoi, L. Manda, and T. S. Rosenstock. 2020. Adoption of climate-smart agriculture technologies in Tanzania. *Frontiers in Sustainable Food Systems* 4:4. doi: 10.3389/fsufs.2020.00055.

Lasco, R. D., R. J. P. Delfino, D. C. Catacutan, E. S. Simelton, and D. M. Wilson. 2014. Climate risk adaptation by smallholder farmers: The roles of trees and agroforestry. *Current Opinion in Environmental Sustainability* 6:83–88. doi: 10.1016/j.cosust.2013.11.013.

Liingilie, A. S. 2019. Effects of grilicidia sepium intercropping, rainwater harvesting and planting times on maize performance in Kongwa District, Tanzania. MSc thesis, Sokoine University of Agriculture.

Lipper, L., P. Thornton, B. M. Campbell, T. Baedeker, A. Braimoh, M. Bwalya, P. Caron, A. Cattaneo, D. Garrity, K. Henry, et al. 2014. Climate-smart agriculture for food security. *Nature Climate Change* 4 (12):1068–72. doi: 10.1038/nclimate2437.

Mahmood, M. I., and M. Zubair. 2020. Farmer's perception of and factors influencing agroforestry practices in the Indus River Basin, Pakistan. *Small-Scale Forestry* 19 (1):107–22. doi: 10.1007/s11842-020-09434-9.

Mayaya, H., G. Opata, and E. Kipkorir. 2015. Understanding climate change and manifestation of its driven impacts in the semi arid areas of Dodoma Region, Tanzania. *Ethiopian Journal of Environmental Studies Management of Environmental Quality: An International Journal* 8 (4):364–76. doi: 10.4314/ejesm.v8i4.2.

Mazibuko, D. M., H. Gono, S. Maskey, H. Okazawa, L. Fiwa, H. Kikuno, and T. Sato. 2023. The sustainable niche for vegetable production within the contentious sustainable agriculture discourse: Barriers, opportunities and future approaches. *Sustainability* 15 (6):4747. doi: 10.3390/su15064747.

Mkonda, M. Y. 2021. Agricultural sustainability and food security in agroecological zones of Tanzania. In *Sustainable agriculture reviews 52*, ed. E. Lichtfouse, 309–334. Cham: Springer International Publishing.

Mugabe, P. A.2020. Assessment of information on successful climate-smart agricultural practices/innovations in Tanzania. In *Handbook of Climate Change Resilience*, 2721–2741. Switzerland: Springer Nature. doi: 10.1007/978-3-319-71025-9_180-1.

Nicolétis, É., P. Caron, M. El Solh, M. Cole, L. O. Fresco, A. Godoy-Faúndez, M. Kadleciková, E. Kennedy, M. Khan, and X. Li. 2019. Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition. A report by the high level panel of experts on food security and nutrition of the committee on world food security.

Nyasimi, M., P. Kimeli, G. Sayula, M. Radeny, J. Kinyangi, and C. Mungai. 2017. Adoption and dissemination pathways for climate-smart agriculture technologies and practices for climate-resilient livelihoods in Lushoto, Northeast Tanzania. *Climate* 5 (3):63. doi: 10.3390/cli5030063.

Pello, K., C. Okinda, A. Liu, and T. Njagi. 2021. Factors affecting adaptation to climate change through agroforestry in Kenya. *The Land* 10 (4):371. doi: 10.3390/land10040371.

Pimbert, M. 2015. Agroecology as an alternative vision to conventional development and climate-smart agriculture. *Development* 58 (2–3):286–98. doi: 10.1057/s41301-016-0013-5.

Rioux, J., E. Lava, and K. Karttunen. 2017. *Climate-smart agriculture guideline for the United Republic of Tanzania: A country-driven response to climate change, food and nutrition insecurity*. Rome: FAO.

Rosenstock, T. S., C. Lamanna, S. Chesterman, P. Bell, A. Arslan, M. B. Richards, J. Rioux, A. Akinleye, C. Champalle, and Z. Cheng. 2016. The scientific basis of climate-smart agriculture: A systematic review protocol. *CCAFS Working Paper*.

Rowhani, P., D. B. Lobell, M. Linderman, and N. Ramankutty. 2011. Climate variability and crop production in Tanzania. *Agricultural and Forest Meteorology* 151 (4):449–60. doi: 10.1016/j.agrformet.2010.12.002.

Schaller, M., E. I. Barth, D. Blies, F. Röhrig, and M. Schümmelfeder. 2017. Climate smart agriculture (CSA): Climate smart agroforestry.

Scherr, S. J., S. Shames, and R. Friedman. 2012. From climate-smart agriculture to climate-smart landscapes. *Agriculture & Food Security* 1 (1):1–15. doi: 10.1186/2048-7010-1-12.

Shilomboleni, H., M. A. Radeny, T. Demissie, J. J. Osumba, J. W. Recha, and D. Solomon. 2020. Building transformative change in Africa's smallholder food systems: Contributions from climate-smart agriculture and agroecology.

Sileshi, M., R. Kadigi, K. Mutabazi, and S. Sieber. 2019. Determinants for adoption of physical soil and water conservation measures by smallholder farmers in Ethiopia. *International Soil & Water Conservation Research* 7 (4):354–61. doi: 10.1016/j.iswcr.2019.08.002.

Sinclair, F., A. Wezel, C. Mbow, S. Chomba, V. Robiglio, and R. Harrison. 2019. *The contribution of agroecological approaches to realizing climate-resilient agriculture*. Rotterdam, The Netherlands: GCA.

Spicka, J., T. Hlavsa, K. Soukupova, and M. Stolbova. 2019. Approaches to estimation the farm-level economic viability and sustainability in agriculture: A literature review. *Agricultural Economics (Zemědělská ekonomika)* 65 (6):289–97. doi: 10.17221/269/2018-AGRICECON.

Suresh Ramanan, S., and A. Arunachalam. 2021. Introspection of agroecology for food systems from agroforestry perspective. *Indian Journal of Agroforestry* 23:141–45.

Swamila, M., D. Philip, A. M. Akyoo, S. Sieber, M. Bekunda, and A. A. Kimaro. 2020. Gliricidia agroforestry technology adoption potential in selected dryland areas of Dodoma region, Tanzania. *Agriculture* 10 (7):306. doi: 10.3390/agriculture10070306.

Tanzania, T. U. R. O., and M. O. Fisheries. 2017. Climate - smart agriculture guideline. Dodoma, Tanzania.

Thorlakson, T., and H. Neufeldt. 2012. Reducing subsistence farmers' vulnerability to climate change: Evaluating the potential contributions of agroforestry in western Kenya. *Agriculture & Food Security* 1 (1):1–13. doi: 10.1186/2048-7010-1-15.

Tittonell, P. 2015. Agroecology is climate smart. Climate-Smart Agriculture, Global Science Conference. Montpellier, France: CIRAD.

Uckert, G., K. Löhr, F. Graef, and S. Sieber. 2018. *The trans-sec book of participative research: Approaches for implementing food securing upgrading strategies*. Müncheberg, Germany: Leibniz Centre for Agricultural Landscape Research (ZALF).

Van Zutphen, K. G., S. Van Den Berg, B. Gavin-Smith, E. Imbo, K. Kraemer, J. Monroy-Gomez, M. Pannatier, H. Prytherch, J. Six, C. Thoennissen, et al. 2022. Nutrition as a driver and outcome of agroecology. *Nature Food* 3 (12):990–96. doi: 10.1038/s43016-022-00631-7.

Wassie, A., and N. Pauline. 2018. Evaluating smallholder farmers' preferences for climate smart agricultural practices in Tehuledere District, northeastern Ethiopia. *Singapore Journal of Tropical Geography* 39 (2):300–16. doi: 10.1111/sjtg.12240.

Were, K., A. M. Gelaw, and B. R. Singh. 2016. Smart Strategies for Enhanced Agricultural Resilience and Food Security Under a Changing Climate in Sub-Saharan Africa. In *Climate Change and Multi-Dimensional Sustainability in African Agriculture*, 431–53. doi: 10.1007/978-3-319-41238-2_23.

Wezel, A., B. G. Herren, R. B. Kerr, E. Barrios, A. L. R. Gonçalves, and F. Sinclair. 2020. Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development* 40 (6):40. doi: 10.1007/s13593-020-00646-z.

Yusuph, A. S., E. F. Nzunda, S. K. Mourice, and T. Dalgaard. 2023. Usage of agroecological climate-smart agriculture practices among Sorghum and maize smallholder farmers in semi-arid areas in Tanzania. *East African Journal of Agriculture and Biotechnology* 6 (1):378–406. doi: 10.37284/eajab.6.1.1490.

Zerihun, M. F., M. Muchie, and Z. Worku. 2014. Determinants of agroforestry technology adoption in Eastern Cape province, South Africa. *Development Studies Research* 1 (1):382–94. doi: 10.1080/21665095.2014.977454.