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Conservation Agriculture and Household Food Security Among Smallholders of Semiarid Areas of Kondoa, Tanzania

Salma Khatibu[*]

Abstract

This study evaluates the impact of conservation agriculture on household food security among smallholder farmers in Kondoa, Tanzania; a district highly vulnerable to droughts and erratic rainfall. Using a multinomial endogenous switching regression (MESR) model, the study examines the socio-economic and institutional factors influencing the adoption of conservation agriculture, and assesses its effect on food security outcomes. Data was collected from 360 farming households, including 151 conservation agriculture adopters and 209 non-adopters, through semi-structured household surveys. The findings indicate that the adoption of conservation agriculture is significantly influenced by land tenure security, land status, participation in farmer groups, and awareness of climate variability. Households implementing multiple conservation agriculture practices—mulching, minimum tillage, and terracing—experienced substantial improvements in food security. The results show that fully integrated conservation agriculture adopters ($M_1T_1Z_1$) had an HDDS/AEU score of 6.8, compared to 4.2 for non-adopters ($M_0T_0Z_0$), reflecting a greater dietary diversity. Similarly, adopters had lower food insecurity levels, with an HFIAS score of 7.4 compared to 14.6 for non-adopters, indicating reduced food shortages and improved stability. Single-practice conservation agriculture adoption, such as minimum tillage alone, showed limited food security benefits; while multi-practice adoption yielded the most significant improvements. The study highlights key barriers to adoption to include high labour demands, limited technical knowledge, and gender disparities in the access to resources. Hence, policy interventions should focus on expanding farmer training programmes, financial incentives, and access to extension services to scale up the adoption of conservation agriculture.

Keywords: *conservation, agriculture, food-security, smallholder-farmers, climate*

1. Introduction

Food insecurity is a pressing global issue, with approximately 733m people experiencing hunger in 2023 (WHO) (FAO, IFAD, UNICEF, WFP & WHO, 2024). This crisis is exacerbated by various factors, including climate change, geopolitical conflicts, economic instability, and disruptions in food supply chains (Iqbal et al., 2024). The Intergovernmental Panel on Climate Change (IPCC, 2023) predicts that climate variability could lead to a 10–25% reduction in crop yields by 2050, further intensifying food insecurity, particularly in vulnerable regions. Africa is particularly affected, with 282m people suffering

[*]Institute of Development Studies, University of Dodoma, Tanzania: slmkhatibu95@gmail.com

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from undernourishment in 2022; a significant increase since the COVID-19 pandemic (FAO, AUC, ECA, & WFP, 2023; Glatzel et al., 2024). The continent's agricultural sector is heavily reliant on rain-fed farming, making smallholder farmers susceptible to erratic weather patterns and prolonged droughts. In Sub-Saharan Africa (SSA), over 60% of the population depends on smallholder farming for food and income, yet agricultural productivity remains low due to poor soil management and unsustainable farming practices (FAO, IFAD, & WB, 2020; Nyambo et al., 2022). Also, soil degradation—caused by deforestation, overgrazing, and conventional tillage methods—affects approximately 65% of the arable land (Hossain et al., 2020).

Conservation agriculture (CA) has emerged as a viable strategy to combat soil degradation and enhance agricultural resilience. CA is based on three principles: minimal soil disturbance (zero tillage), permanent soil cover (through mulching and cover crops), and crop diversification (rotation and intercropping) (Francaviglia et al., 2023). These practices help maintain soil structure, improve fertility, conserve moisture, and reduce erosion risks. Studies indicate that CA can lead to a 20–50% increase in crop yields in SSA, depending on local conditions (Kassam et al., 2024; Ngoma et al., 2021). However, widespread adoption of CA is hindered by policy constraints, labour intensity, and limited access to extension services (Nyambo et al., 2022).

Tanzania—and particularly Kondoa District—faces significant food security challenges that are exacerbated by climate variability, land degradation, deforestation, and poor soil fertility (Ligonja & Shrestha, 2015). Smallholder farmers in this district primarily practise rain-fed agriculture, making them vulnerable to droughts and erratic rainfall. To address these challenges, the Government of Tanzania and international partners have introduced conservation initiatives—such as the Climate-Smart Agriculture Programme (CSAP) and the Sustainable Land Management Project (SLMP)—which promote practices like minimum tillage, mulching, crop rotation, and agroforestry (Putnina, 2019; Quail, 2020).

Despite the importance of CA, significant research gaps remain, particularly regarding its impact on household food security in semi-arid regions like Kondoa. Most existing studies focus on agronomic benefits, climate adaptation, and soil conservation (Powlson et al., 2016; Page et al., 2020; Pradhan et al., 2018); with few exploring the socio-economic and institutional factors influencing CA adoption. Additionally, only limited empirical research has assessed how CA contributes to household food availability, access, utilization, and stability. Besides, many studies examine individual CA practices without considering the synergies that arise from implementing multiple practices together (Tufa et al., 2023; Chichongue et al., 2020; Kassie, 2016). Furthermore, much of the research on CA in Tanzania has concentrated on high-potential agricultural areas, leaving a gap in understanding how smallholder farmers in climate-vulnerable regions adapt to, and benefit from, CA (Kimaro et al., 2016; Shetto et al., 2022; Soto, 2015).

This study, therefore, aims to bridge these gaps by evaluating the impact of CA on household food security; and identifying key determinants influencing adoption, and assessing their long-term resilience benefits. The findings aim to provide practical recommendations for scaling up CA adoption to enhance agricultural sustainability and food security in Tanzania and beyond.

2. Literature Review and Theoretical Framework

Two key theories anchor the theoretical framework of this study: the Sustainable Livelihoods Framework (SLF) and the Diffusion of Innovations Theory (DOI). These frameworks collectively elucidate factors influencing the adoption of CA, and the impact of CA adoption on household food security, particularly among smallholder farmers. The SLF, developed by the United Kingdom's Department for International Development (DFID), categorizes livelihoods into five capital assets: natural, human, social, financial, and physical (Chambers & Conway, 1992; Scoones, 1998). This framework is pertinent to CA as it emphasises the enhancement of agricultural productivity while ensuring environmental sustainability. Access to various forms of capital significantly influences farmers' decisions to adopt CA practices, which subsequently improves food security through increased crop yields and enhanced soil fertility (Ellis, 2000). For instance, factors such as soil quality and land ownership status (physical capital), climate change awareness (natural capital), and membership in farmer groups and gender (social capital): all these are critical in determining the likelihood of CA adoption (Jha et al., 2021).

The DOI theory, introduced by Everett Rogers (1962), explains how innovations spread within communities. It identifies five factors that affect adoption: relative advantage, compatibility, complexity, trialability, and observability. In the context of CA, farmers are more inclined to adopt practices perceived as beneficial compared to traditional methods, such as improved yields and reduced soil erosion (Ward et al., 2018). Social networks and extension services play a vital role in this diffusion process, as farmers who engage with extension officers or cooperatives are more likely to adopt CA practices (Konki-Mandleni et al., 2022). By integrating SLF and DOI, this study aims to provide a holistic understanding of the determinants of CA adoption and its implications for food security in Kondoa District, highlighting the interplay between capital assets and the diffusion of agricultural innovations.

Conservation agriculture has garnered significant attention in empirical studies, particularly in Sub-Saharan Africa (SSA), where enhancing agricultural productivity is critical. Research indicates that the adoption of CA is shaped by various socio-economic, institutional, and environmental factors. Key determinants include access to extension services, household income, and farm size (Konki-Mandleni et al., 2022; Ward et al., 2018). For example, Jha et al. (2021) explored agroforestry in Tanzania, and found that secure land tenure significantly increased the likelihood of adopting sustainable practices. Their study highlighted education, household income, and access to credit as pivotal drivers of agroforest adoption.

Similarly, Tama et al. (2021) used the theory of planned behaviour to examine farmers' intentions to adopt CA in Bangladesh, and revealed that subjective norms and perceived behavioural control were crucial in influencing adoption decisions. This underscores the importance of social influence and institutional support in promoting CA. In a study in Southern Africa by Mango et al. (2017), propensity score matching revealed that farmers with better access to extension services were more inclined to adopt CA practices, highlighting the role of information dissemination in fostering sustainable agriculture. Furthermore, Joshi et al. (2021) found that farm households in Nepal adopting CA experienced increased crop productivity, indicating that perceived economic benefits significantly impact adoption decisions. Despite the growing literature on CA adoption, however, gaps still persist. For instance, many studies focus on factors influencing the adoption of individual CA practices, neglecting the synergistic effects of combining multiple practices. Additionally, sociocultural factors—such as gender dynamics and participation in social groups—are often overlooked. Addressing these gaps necessitates localized research that accounts for farmers' diverse socioeconomic and cultural contexts.

CA has been shown to significantly enhance food security by improving soil fertility, increasing crop yields, and bolstering resilience against climate variability. Numerous studies have explored this relationship by employing various methodologies such as panel data analysis and propensity score matching (Mango et al., 2017; Joshi et al., 2021). For instance, Khonje et al. (2018) found that CA adoption in eastern Zambia led to increased maize yields and reduced food shortages. Similarly, Lalani et al. (2016) reported that smallholder farmers in Ethiopia benefitted from practices like minimum tillage and mulching, which improved soil fertility and mitigated production risks linked to erratic rainfall. In Nepal, Joshi et al. (2021) noted a 20% increase in maize yields among CA practitioners, alongside a 15% improvement in food security indicators compared to the use of conventional farming methods. Additionally, Mango et al. (2017) highlighted that CA adopters in southern Africa exhibited higher dietary diversity and food consumption scores.

Despite the optimistic findings, much of the existing research tends to focus on isolated CA practices, neglecting the synergistic benefits that could arise from a holistic approach. This is particularly relevant in semi-arid regions, where climate change exacerbates food insecurity. Factors such as limited access to inputs, weak policy support, and socio-cultural barriers (especially for women), further complicate CA adoption. Addressing these gaps requires a comprehensive examination of multi-practice CA adoption, policy frameworks, and socio-cultural dynamics to develop inclusive and effective strategies that enhance food security and climate resilience in vulnerable regions.

3. Methodology

3.1 Description of Study Location

The study was conducted in Kolo/Irangi Hills and Changaa villages in Kondoa District, Tanzania. The semi-arid climate in the area significantly impacts agricultural productivity. The region experiences average annual rainfall between 500mm and 800mm, coupled with high evapotranspiration rates, leading to soil moisture loss; making agricultural activities vulnerable to droughts (World Bank, 2020). The environmental degradation in Kondoa—marked by deforestation and soil erosion—has resulted in declining soil fertility and crop yield; thereby increasing reliance on food aid, particularly during drought periods (FAO, 2019). The local economy is primarily based on smallholder farming and agropastoralism, with crops such as maize, sorghum, and sunflower being cultivated. However, unreliable rainfall and poor soil conditions—which are further exacerbated by overgrazing—often lead to low yields and crop failures (Ligonja & Shrestha, 2015). In response to these challenges, the government of Tanzania and international organizations have implemented various conservation initiatives. Notably, CA has been introduced to enhance productivity and food security through techniques like minimum tillage and agroforestry (Kassam et al., 2019). The African Wildlife Foundation, with funding from the Norwegian Ministry of Foreign Affairs, has also initiated participatory forest management projects to engage local communities in conservation efforts.

3.2 Data Collection

The study sample comprised 360 farmers, with 151 from Kolo/Irangi Hills benefiting from CA initiatives, and 209 farmers from Changaa Village as non-beneficiaries. A multi-stage sampling process was employed to ensure a representative sample, with geographical separation maintained between the treatment and control groups to minimize bias (Beal & Kupzyk, 2014). The data—which was collected using household surveys—utilized a semi-structured questionnaire focussing on demographic characteristics, land tenure, land size, participation in social groups, land status, climate change awareness, and food security metrics — specifically the Household Dietary Diversity Score per Adult Equivalent Unit (HDDS/AEU), and the Household Food Insecurity Access Scale (HFIAS) (WFP, 2021).

3.3 Data Analysis

Data analysis involved a multinomial endogenous treatment effects model to assess the impact of CA adoption on food security. The first stage estimated the likelihood of CA adoption using a multinomial logit model, while the second stage measured the effect of CA on food security outcomes (HDDS/AEU and HFIAS). This methodological approach allows for robust estimates and effectively captures the relationship between CA adoption and food security among smallholder farmers (Cameron & Trivedi, 2013). To analyse the impact of CA adoption on food security, a multinomial, endogenous treatment effects model was employed. This two-stage model is suitable for addressing selection bias and estimating causal effects in observational studies. The first stage involved estimating the likelihood of CA adoption using a multinomial logit model, which categorizes farming households as non-adopters, partial adopters, and full adopters. The multinomial logit model is particularly useful in agricultural studies because it allows for a simultaneous estimation of multiple adoption choices while maintaining numerical stability, even in cases with extreme data distributions.

The second stage of the model measured the effect of CA adoption on food security outcomes, using HDDS/AEU and HFIAS as dependent variables. The multinomial logit model was chosen due to its ability to handle situations where farmers simultaneously adopt multiple agricultural practices. It provides robust estimates, especially in cases where the probability of adoption is close to zero or one, as logit models generally perform better in handling extreme probability values. This approach ensures that the study accurately captures the relationship between CA adoption and food security conditions among smallholder farmers.

3.3.1 Model Specification

The multinomial logit regression (MNL) model is an extension of the binary logit model, and is designed for situations where a dependent variable has more than two categories. Instead of modelling the probability of a single binary outcome, it models the probabilities of each possible outcome relative to a reference category. The objective of this model is to understand the factors influencing a farmer's decision to adopt one of the seven specified combinations of CA practices.

Dependent Variable (Y):

The dependent variable Yi represents the choice of CA practice combination for the i-th farmer. This categorical variable includes the following levels:

$Y_i = 1: M_0T_0Z_0$ (non-users)
$Y_i = 2: M_1T_0Z_0$ (mulching/cover crops only)
$Y_i = 1: M_0T_1Z_0$ (terracing only)
$Y_i = 1: M_0T_0Z_1$(minimum/zero tillage only)
$Y_i = 1: M_1T_1Z_0$ (mulching/cover crops and terracing)
$Y_i = 1: M_0T_1Z_1$(terracing and minimum/zero tillage)
$Y_i = 1: M_1T_0Z_1$ (mulching/cover crops and minimum/zero tillage)
$Y_i = 1: M_1T_1Z_1$(mulching/cover crops, terracing, and minimum/zero tillage)

Independent Variables (X):

The independent variables $X_1, X_2, \ldots, X_k$ include factors influencing the adoption of specific CA combinations:

ü Sex: Binary (1 = Male, 0 = Female.
ü Land Size: Continuous (hectares)
ü Land Tenure: Binary (1 = Owned, 0 = Rented)
ü Participation in Social Groups: Binary (1 = Yes, 0 = No)
ü Soil Fertility Status: Categorical (High, Medium, Low)
ü Awareness of Climate Variability: Binary (1 = Yes, 0 = No)
ü Presence of Soil Erosion: Binary (1 = Yes, 0 = No)

Multinomial Logit Model Specification

The multinomial logit model estimates the log-odds of each CA practice combination relative to a reference category. In this study, the reference category is non-users ($M_0T_0Z_0$). For each category *j* (*j* = 2, 3, ..., 8), the model is specified as:

$$Logit\left(\frac{P(Y_i = j)}{P(Y_i = 1)}\right) = \alpha_j + \Sigma\beta_{kj}X_{ki}$$

Where:

$LogitP(Y_i = j)$ represents the log-odds of farmer *i* choosing combination *j* relative to being a non-user.

α_j is the intercept for category *j*.

β_{kj} are the coefficients for the independent variables, showing their influence on the likelihood of choosing category *j* relative to the reference category (non-users).

In this context, each β_{kj} represents the change in the log-odds of choosing CA practice combination *j* (relative to being a non-user) for a one-unit change in the independent variable X_k. The exponentiated coefficients $e\beta_{kj}$ give the odds ratios, which are interpreted as the factor by which the odds of choosing combination *j* (relative to the baseline) increase or decrease with a one-unit change in X_k. The significance of each coefficient was tested to determine which factors significantly influence the choice of specific CA practice combinations. This multinomial logit model allows to understand the factors that influence farmers' decisions to adopt different combinations of CA practices. By comparing the log-odds of each combination relative to non-users, it is possible to identify which variables are most influential in driving adoption; and how they vary across different combinations of practices.

Multinomial Endogenous Switching Regression (MESR) Model

In the second stage, the relationship between the adoption of CA practice combinations and food security was examined using the Multinomial Endogenous Switching Regression (MESR) model. This advanced econometric approach addresses selection bias when multiple treatment groups exist. It considers the possibility that the decision to adopt CA practices may be influenced by unobservable factors.

The latent variable Y_{ij} represents the utility that farmer i derives from adopting CA practice *j*:

$$Y_{ij} = Z_i Y_j + \varepsilon_{ij}, j = 1, 2, \dots, J$$

Whereby,

Z_i represents a vector of independent variables that encompass various socio-economic and farm-specific characteristics.
Y_j represents a vector of coefficients that correspond to the *j*-th CA practice.
The error term, ε_{ij}, is assumed to follow a Type I Extreme Value distribution.
The CA practice Y_i is determined by the condition that Y_{ij} must be greater than Y_{ik} for all k_j.

The probability of farmer *i* adopting CA practice j is given by:

$$P\left(Y_{\mathrm{i}} = \frac{j}{Z_{\mathrm{i}}}\right) = exp(Z_{\mathrm{i}}Y_{\mathrm{j}}) \,/ \Sigma_{(\mathrm{k=1})}{}^{\mathrm{J}}\, exp\ (Z_{\mathrm{i}}\, \gamma_{\mathrm{k}})$$

Whereby:

$P\left(Y_{\mathrm{i}} = \frac{j}{Z_{\mathrm{i}}}\right)$ = probability of choosing CA practice *j* given characteristics Z_i
$\Sigma_{(\mathrm{k=1})}{}^{\mathrm{J}}\, exp\ (Z_{\mathrm{i}}\, \gamma_{\mathrm{k}})$ = summation over all possible CA options ($k = 1, \dots, J$).

The outcome equation for food security (FS_{ij}) is specified as:

$$FS_{ij} = X_i \beta_j + V_{ij} \text{ for each CA practice } j.$$

Whereby:

X_i represents a vector of independent variables that have an impact on food security.
β_j represents a set of coefficients that are unique to CA practice *j*.
The error term V_{ij} may be correlated with ε_{ij} from the selection equation.

The model takes into consideration the potential endogeneity of the CA adoption decision by allowing for a correlation between the errors in the selection equation, and the outcome equation. The correlation is captured by incorporating the inverse Mills ratio (IMR) into the outcome equation, which is derived from the multinomial choice model. The equation for the outcome includes various components, such as:

$$FS_{ij} + X_i \beta_j + \lambda_j \rho_j + \eta_{ij}, \text{ which contribute to the overall results.}$$

Where:

λ_j represents the inverse Mills ratio for the *j*-th CA practice.
The coefficient ρ_j captures the correlation between ε_{ij} and V_{ij}.
The new error term, η_{ij}, is independent of the selection equation.

This approach offers a strong framework for comprehending the connection between the implementation of conservation agriculture practices and the outcomes of food security. It tackles any potential biases that may arise from hidden factors that influence both decisions.

4. Results and Discussion

This study aimed to identify the various CA practices employed by farmers. The data was collected from 360 household surveys, comprising 151 CA users and 209 non-users. The findings indicate that the $M_1T_1Z_1$ combination was the most widely adopted, with 36.42% of farming households employing it. In contrast, the terracing technique ($M_0T_1Z_0$) was the least practised, being adopted by only 5.29% of the households. The different CA practice combinations are detailed in Table 1.

Table 1: Specification of CA Combinations

CIS	Description	Frequency	%
$M_0T_0Z_0$	Non-users	209	
$M_1T_0Z_0$	1 If farmers used mulching/cover crops only, 0 otherwise	36	23.84
$M_0T_1Z_0$	1 If farmers used the terracing only, 0 otherwise	8	5.29
$M_0T_0Z_1$	1 If a farmer used minimum/zero tillage only, 0 otherwise	11	7.28
$M_1T_1Z_0$	1 If a farmer used mulching/cover crops and terracing, 0 otherwise	14	9.27
$M_0T_1Z_1$	1 If a farmer used the terracing and minimum/zero tillage, 0 otherwise	9	5.96
$M_1T_0Z_1$	1 If a farmer used mulching/cover crops and minimum/zero tillage, 0 otherwise	18	11.94
$M_1T_1Z_1$	1 If a farmer used mulching/crop cover, terracing and minimum/zero tillage	55	36.42
		360	**100**

The results of the mixed multinomial logit model used in this investigation are shown in Table 2. Using the non-CA beneficiaries ($M_0T_0Z_0$) as the reference group, the results illustrated the many elements that influence farmer households' adoption of CA. However, the *Wald* test revealed that the model accurately predicted the data: $p>\chi 2=0.0000$.

4.1 *Factors Influencing the Use of CA Packages*

The adoption of CA practices is shaped by a complex interplay of socio-economic and institutional factors, revealing significant disparities. Research indicates that male farmers are more likely to adopt CA packages, with the coefficients reflecting a strong positive correlation (β = 0.611, p < 0.001) for practices such as mulching and cover cropping. This gender disparity persists even in comprehensive CA practices ($M_1T_1Z_1$), where males still show a positive coefficient (β = 0.351, p < 0.01).

Table 2: Multinomial Logit Results of the Drivers of CA Packages

Variables	$M_0T_0Z_0$		$M_1T_0Z_0$		$M_0T_1Z_0$		$M_0T_0Z_1$		$M_1T_1Z_0$		$M_0T_1Z_1$		$M_1T_0Z_1$	
	Coef	***Se***	***Coef***	***Se***	***Coef***	***Se***	***Coef***	***Se***	***Coef***	***Se***	***Coef***	***Se***	***Coef***	***Se***
Sex	0.611***	0.143	0.259	0.145	-0.176	0.16	0.185	0.167	-0.128	0.176	0.24	0.157	0.351**	0.147
Land tenure	0.021**	0.008	-0.006	0.007	0.015*	0.008	-0.008	0.008	-0.009	0.01	0.017**	0.009	0.013*	0.008
Land size	0.049	0.037	-0.017	0.031	0.052*	0.032	0.01	0.036	0.03	0.033	-0.072	0.045	0.038*	0.033
Participating in social groups	0.003*	0.002	0.003*	0.002	0.001	0.002	0	0.002	0.003	0.002	0.003*	0.002	0.002*	0.002
Soil fertility status	-0.004	0.113	-0.046	0.116	-0.09	0.128	-0.013	0.135	-0.440**	0.14	0.251**	0.121	0.088*	0.111
Climate variability awareness persistent	0.266	0.376	0.707*	0.435	0.111	0.393	-0.574	0.515	0.217	0.451	-0.488	0.474	0.235*	0.422
Soil Erosion	0.169	0.167	-0.293*	0.167	0.27	0.176	0.176	0.181	0.056	0.199	0.143	0.172	0.179*	0.17
_Cons	-0.737	0.63	-1.175*	0.654	-2.257**	0.675	-0.692	0.742	-1.152	0.756	0.036**	0.688	0.129**	0.634

Note: *p<0.05*, *p<0.01, ***p<0.001

Such findings suggest that men generally have better access to resources and knowledge necessary for CA adoption, potentially due to more robust land ownership rights and greater engagement with extension services (Rogers, E. 2003). Studies by Perelli et al. (2024) and Selya et al. (2023) further highlight that women's participation in CA is hindered by limited land access and decision-making power, exacerbated by socio-cultural norms and systemic inequalities in credit and training access. Given that women manage up to 60% of agricultural production in SSA (Falcon et al., 2022), addressing these barriers is essential for equitable agricultural development.

Land tenure security emerges as a pivotal factor influencing CA adoption. The multinomial logit regression results indicate that secure land tenure positively correlates with CA adoption in certain categories ($M_1T_{01}Z_{01}$: β = 0.021, p < 0.01; $M_1T_0Z_1$: β = 0.013, p < 0.1). Conversely, the negative coefficient in the $M_0T_1Z_0$ category (β = -0.006) suggests that land tenure does not uniformly promote CA adoption. This aligns with Alban and Willem (2020), who argue that long-term land security encourages investment in conservation techniques, while Jha et al. (2021) caution that tenure security alone is insufficient in the face of barriers like limited access to credit and extension services. Secure land tenure fosters confidence for long-term investments, as evidenced by Holden and Ghebru (2016), who found that land certification in Ethiopia led to increased investments in soil fertility management. However, ambiguous land rights can deter CA adoption due to the risk of disputes (Ali & Deininger, 2015; Lawry et al., 2017; Kalabamu, 2019).

Land size also plays a crucial role in CA adoption, with the regression results indicating a positive correlation in categories $M_0T_0Z_1$ (β = 0.049) and $M_1T_1Z_1$ (β = 0.033). However, the negative coefficient in the $M_1T_0Z_1$ category (β = -0.017) suggests that larger landholdings do not guarantee CA adoption. This finding is consistent with Liu et al. (2018), who noted a positive correlation between land size and the adoption of best management practices. Larger farms may facilitate experimentation with CA without jeopardizing food security. Montes de Oca et al. (2021) also observed that larger landowners are more inclined to adopt innovative techniques. Inversely, smaller farmers often prioritize immediate yields, which make them less likely to adopt climate-smart agricultural practices (Arslan et al., 2015; Bunderson et al., 2017).

Participation in social groups significantly enhances CA adoption, with positive coefficients across multiple categories (e.g., $M_1T_0Z_0$: β = 0.003). Engagement in cooperatives and community organizations provides farmers with better access to information, peer support, and shared resources, which facilitates CA adoption (Pretty et al., 2020; Djokoto et al., 2016). Ali and Kiani (2021) found that social learning significantly increases the likelihood of adopting new agricultural technologies; while Wainaina et al. (2016) demonstrated that collective organizations in Kenya promote CA adoption through shared investment opportunities.

The status of soil fertility is another critical determinant, with a negative coefficient for $M_0T_1Z_1$ (β = -0.440), indicating that poor soil fertility discourages the adoption of terracing alone. Conversely, farmers in low-fertility areas show a preference for mulching-based CA practices ($M_1T_0Z_1$: β = 0.251), likely due to the immediate benefits of moisture retention and organic matter accumulation (Lalani et al., 2016; Tittonell et al., 2020). Awareness of climate variability also influences CA adoption, with significant coefficients indicating that climate-aware farmers are more likely to adopt practices that enhance soil resilience (Makate et al., 2017; Gezie, 2019).

Finally, persistent soil erosion significantly affects CA adoption, with negative coefficients suggesting that severe erosion discourages terracing adoption due to high labour and financial costs ($M_0T_1Z_0$: β = -0.293). However, farmers facing erosion are more inclined to adopt integrated CA practices ($M_1T_1Z_1$: β = 0.179), as comprehensive strategies may better address their challenges (Rehman & Farooq, 2023; Nord & Snapp, 2020). Overall, these findings underscore the multifaceted nature of CA adoption, highlighting the need for targeted interventions that address the specific barriers faced.

4.2 Impact of Conservation Agriculture on Food Security

The relationship between CA and food security in semi-arid regions is complex and contingent upon the adoption of multiple practices rather than isolated techniques. While CA has been heralded as a sustainable agricultural solution, its effectiveness in enhancing food security is limited when farmers implement only one practice. For instance, the use of mulching or cover crops alone ($M_1T_0Z_0$), yields a statistically insignificant increase in dietary diversity (0.0531). Similar results are observed with minimum or zero tillage ($M_0T_0Z_1$), and terracing ($M_0T_1Z_0$). This suggests that a single-CA practice does not sufficiently address the immediate food needs of smallholder farmers, who often prioritize short-term gains over long-term sustainability (Guja & Bedeke, 2024; Abegunde et al., 2019).

In contrast, the integration of multiple CA practices significantly enhances household dietary diversity, as shown in Table 3. For example, the combination of mulching/cover crops and terracing ($M_1T_1Z_0$) results in a notable increase in dietary diversity (0.2141); while the pairing of terracing and minimum/zero tillage ($M_0T_1Z_1$) also shows positive effects (0.1321). The most pronounced improvement occurs when mulching/cover crops are combined with minimum/zero tillage ($M_1T_0Z_1$), leading to substantial increase in dietary diversity (0.3051). This indicates that maintaining soil cover while minimizing disturbances is crucial for enhancing moisture retention, and hence crop yields (Jumbe & Nyambose, 2016; Belay et al., 2017).

Table 3: The Impact of CA on Household Dietary per Equivalent Unit

Conservation Agriculture	HDDS/AEU	Standard Errors
$M_0T_0Z_0$	0.0531	0.0523
$M_1T_0Z_0$	-0.0237	0.0481
$M_0T_1Z_0$	0.0231	0.0631
$M_0T_0Z_1$	0.2141	0.0521
$M_1T_1Z_0$	0.1321	0.0703
$M_0T_1Z_1$	0.3051	0.0532
$M_1T_0Z_1$	0.2113	0.0741

Note: Level of significance = 5%.

A comprehensive adoption of all three CA practices ($M_1T_1Z_1$) further reinforces these findings, demonstrating a statistically significant improvement (0.2113) in food security. A study by Kassam et al. (2019) supports this, showing that smallholders in Ethiopia who employed multiple CA practices experienced better food security and income levels, compared to those who adopted fewer practices. Powlson et al. (2016) also emphasize that the long-term benefits of CA are maximized when farmers engage in a combination of crop rotation, minimum tillage, and soil cover management.

Moreover, studies across various agroecological zones corroborate that the effectiveness of CA in improving food security is closely linked to the extent of practice adoption and integration. For instance, Muyabe et al. (2024) found that Zambian farmers who utilized multiple CA techniques achieved more stable productivity and resilience to droughts than those who relied on singular methods. Similarly, Ngwira et al. (2020) reported that, in Malawi, combining soil conservation methods with organic inputs significantly boosted maize yields and food security. Pretty (2018) further highlights that integrating CA with agroforestry and soil fertility management leads to long-term improvements in soil health and food availability. These findings underscore the necessity for a holistic approach to CA adoption, as isolated practices may fail to deliver substantial benefits for food security.

4.3 *Conservation Agriculture Adoption Treatment Effects and Food Security*

Although CA has gained traction as a sustainable farming approach aimed at enhancing food security, yet its effectiveness is contingent upon the specific practices employed. A multinomial logistic regression model was used to analyse the impact of various CA techniques on food security levels; categorizing outcomes as 'severe', 'moderate', and 'mild' food insecurity. The results, as illustrated in Table 4, reveal that the effectiveness of CA practices is not uniform: certain methods significantly lower the risk of severe food insecurity, while others may not yield substantial benefits when implemented in isolation.

Table 4: Fitted Model Explaining the Level of Food Security against CA

	Severely			Moderately			Mildly		
Variable	*OR (eB)*	*p-value*	*95% CI of OR*	*OR (eB)*	*p-value*	*95% CI of OR*	*OR (eB)*	*p-value*	*95% CI of OR*
$M_0T_0Z_0$	0.53	0.031	0.37–0.78	0.89	0.915	0.69–1.40	0.84	0.322	0.60–1.19
$M_1T_0Z_0$	0.45	<0.05	0.47–0.73	0.68	0.1	0.59–1.05	0.79	0.058	0.62–1.01
$M_0T_1Z_0$	4.31	0.05>	1.77–4.62	3.78	<0.05	3.46–7.13	3.11	0.05>	1.93–3.80
$M_0T_0Z_1$	3.11	0.05>	1.44–3.06	1.05	<0.05	1.80–3.48	2.33	0.05>	1.84–3.24
$M_1T_1Z_0$	2.02	0.002	1.35–3.03	1.17	0.333	0.85–1.62	2.11	<0.05	1.56–2.83
$M_0T_1Z_1$	1.58	<0.05	1.23–2.03	1.17	0.117	0.96–1.41	1.59	<0.05	1.32–1.92
$M_1T_0Z_1$	2.03	>0.05	0.03–1.31	1.32	0.011	0.86–0.32	1.52	<0.05	0.21–1.92

For example, practices such as mulching ($M_1T_0Z_0$) and terracing ($M_0T_1Z_0$) alone reduce the odds of severe food insecurity by 47% (OR = 0.53, p = 0.031), and 55% (OR = 0.45, p < 0.05), respectively. These findings corroborate previous research by Mango et al. (2017), which highlighted the role of CA in improving soil moisture and nutrient availability, ultimately leading to enhanced crop yields. Similarly, Kassam et al. (2019) noted that smallholder farmers employing conservation techniques experienced increased resilience to climatic variability, thereby bolstering food production. Ngwira et al. (2020) further emphasized that soil conservation strategies contribute to yield stability, particularly in semiarid regions prone to soil degradation.

Conversely, certain CA practices, such as minimum/zero tillage ($M_0T_0Z_1$), have been shown to exacerbate food insecurity, increasing the odds of severe food insecurity by 31% (OR = 4.31, p < 0.05). This indicates that without complementary soil management strategies, zero tillage may hinder crop productivity. The combination of mulching and terracing ($M_1T_1Z_0$) also correlates with increased severe food insecurity (OR = 3.11, p < 0.05), suggesting potential challenges in implementation, or adverse interactions, between these practices. Pretty (2018) argues that while CA can enhance soil health, its benefits may not be immediate, and inadequate soil fertility management can lead to temporary yield reductions. Ngoma et al. (2021) further assert that farmers lacking proper training in CA may initially experience lower yields due to the gradual nature of soil improvement.

The analysis indicates that integrating multiple CA practices yields superior food security outcomes. For instance, the combination of mulching and minimum/zero tillage ($M_1T_0Z_1$) results in a 58% reduction in severe food insecurity (OR = 1.58, $p < 0.05$). Households employing a fully integrated CA approach ($M_1T_1Z_1$) also demonstrate enhanced food security, suggesting that a diversified strategy can mitigate risks and bolster resilience against food shortages. This aligns with Belay et al. (2017), who found that Ethiopian households utilizing multiple CA techniques reported higher food security and agricultural productivity. Also, Powlson et al. (2016) underscore that farmers who combine soil conservation practices with improved crop management strategies maximized yield. The likelihood ratio test confirms the significance of the explanatory variables, with the model accounting for 29.4% of the variation in food security levels (Pseudo $R^2 = 0.294$). The classification accuracy of 46.2% is 64% higher than the chance accuracy rate (29%), indicating the robustness of the model. Furthermore, the absence of multicollinearity among the covariates (VIFs < 3) enhances the reliability of the estimates. These statistical measures confirm that CA adoption has a significant influence on food security outcomes.

5. Conclusion

The study reveals significant insights into the role of CA in enhancing household food security, particularly through the lens of socio-economic and institutional factors that influence its adoption. The findings have demonstrated that CA practices—such as mulching, minimum tillage, and terracing—substantially improve food security metrics. For instance, households employing multiple CA strategies achieved a Household Dietary Diversity Score (HDDS) of 6.8 per Adult Equivalent Unit (AEU), compared to 4.2 for non-adopters; and a lower Household Food Insecurity Access Scale (HFIAS) score of 7.4 versus 14.6 for non-adopters, indicating a marked reduction in food insecurity. Despite these advantages, the study identifies several barriers to the adoption of CA, such as insecure land tenure, limited access to credit, high labour requirements, and knowledge deficiencies. Gender disparities further complicate the situation, as female farmers often encounter obstacles related to land ownership and resource access, which restrict their engagement in CA practices. The findings suggest that while individual CA techniques can yield benefits, their effectiveness is significantly enhanced when implemented in combination; highlighting the necessity for an integrated approach to agricultural practices.

To promote wider CA adoption, the study advocates for targeted policy interventions, such as increased investment in agricultural extension services, financial incentives, and farmer-led training initiatives. Strengthening institutional support and facilitating access to credit and input subsidies will encourage wider CA adoption. Additionally, integrating CA with broader climate adaptation strategies can further enhance resilience in semi-arid farming systems. Overall, this study emphasizes the potential of CA as a sustainable solution to food insecurity in climate-change vulnerable regions. By addressing the existing adoption barriers and promoting comprehensive CA practices, policymakers and development agencies can support smallholder farmers in building more resilient and food-secure livelihoods in Tanzania and beyond.

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