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by Jules Ngango and Fabrice Nkurunziza

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Abstract:

This paper investigates the determinants and impacts of the adoption of three interdependent sustainable agricultural intensification practices (crop residue retention, minimum tillage, and maize-legume diversification) and their combinations on household productivity (i.e., maize yield and income from maize production) and consumption (i.e., household total expenditure and household food expenditure) in Rwanda. We use a multinomial endogenous switching regression model to control for selection bias and endogeneity arising from observable and unobservable factors. The results reveal that the adoption decisions are driven by factors such as education; farm size, livestock ownership; group membership, extension services; distance from home to the farm; land tenure, soil fertility, soil depth, slope; rainfall index; and drought stress. The adoption of interdependent and a combination of sustainable agricultural intensification practices increases maize yields, maize income, household total expenditure, and household food expenditure. From a policy perspective, the findings of this study suggest that government and other development partners should promote the adoption of these practices through the provision of innovative extension services that enable farmers to better understand the benefits of alternative sustainable agricultural intensification practices.

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This paper investigates the determinants and impacts of the adoption of three interdependent sustainable agricultural intensification practices (crop residue retention, minimum tillage, and maize-legume diversification) and their combinations on household productivity (i.e., maize yield and income from maize production) and consumption (i.e., household total expenditure and household food expenditure) in Rwanda. We use a multinomial endogenous switching regression model to control for selection bias and endogeneity arising from observable and unobservable factors. The results reveal that the adoption decisions are driven by factors such as education; farm size, livestock ownership; group membership, extension services; distance from home to the farm; land tenure, soil fertility, soil depth, slope; rainfall index; and drought stress. The adoption of interdependent and a combination of sustainable agricultural intensification practices increases maize yields, maize income, household total expenditure, and household food expenditure. From a policy perspective, the findings of this study suggest that government and other development partners should promote the adoption of these practices through the provision of innovative extension services that enable farmers to better understand the benefits of alternative sustainable agricultural intensification practices.

1. Background

Recently, the most important challenge facing sub-Saharan African (SSA) countries is to find solutions to increase productivity and food security, while simultaneously preserving the soil quality and natural resources. The literature also indicates that there has been an increasing interest in sustainable agricultural intensification (SAI) as a potential solution to improve productivity and preserving the natural environment in the agrarian economies of SSA (Manda et al., 2016; Marenya et al., 2020). The SAI involves the farming systems that produce in ways that improve or maintain productivity with minimal effects on the environment so that critical farm resources can endure. In general, it is believed that SAI practices can have social, economic, and environmental benefits for farmers and policymakers (Abdulai & Abdulai, 2017; Kotu et al., 2017; Ngango & Hong, 2021). In developing countries, it has been recognized that conventional agricultural practices such as monoculture practices and slash-and-burn gradually degrade the soil quality and natural resources (Khataza et al., 2017; Kurgat et al., 2018). To protect and preserve the soil quality, the adoption of conservation agriculture practices should be prioritized (El-Shater et al., 2016; Kotu et al., 2017; Manda et al., 2016; Teklewold et al., 2013).

In Rwanda, there are five components of SAI technologies that are being widely promoted because of their environmental, agronomic, social, and economic benefits. These components include the use of improved varieties, compost and animal manure, cereal association or rotation with legumes, crop residue retention (i.e., covering farm surface with maize Stover and legume straw), and minimum tillage (i.e., minimum soil disturbance). In general, cereal association or rotation with legumes (mixed cropping system) can offset the cost of inorganic fertilizers and pesticides, while also contributing to the mitigation of climate change (Manda et al., 2016). Crop residue retention is also a widely accepted practice for maintaining the soil surface cover and protecting the soil from nutrient losses and erosion. Moreover, crop residue retention protects the soil from wind and rain erosion, conserves soil moisture, and improves aeration within the soil profile (Sarkar et al., 2020). Minimum tillage has more benefits in terms of enhancing the fertility of the soil and land productivity by reducing soil temperatures, soil, and water losses, as well as improving infiltration (Manda et al., 2016).

To encourage the adoption of SAI practices, more studies are needed for a better understanding of the benefits of SAI in terms of social, economic, and environmental aspects. To date, no study has examined the impacts of SAI practices on household productivity and consumption in Rwanda. Only a few empirical studies in SSA, mostly in Zambia and Ethiopia have attempted to examine the adoption and impact of SAI on productivity, consumption, and welfare outcomes. Teklewold et al. (2013), Marenya et al. (2020), and Oumer et al. (2020) assessed the adoption and impacts of SAI practices on yields, incomes, agrochemical use, and welfare among smallholder maize farmers in Ethiopia. Similarly, Manda et al. (2016) assessed the joint adoption of sustainable agricultural practices and their impacts on maize yields and incomes in Zambia. However, Zambia and Ethiopia have different agro-ecological conditions relative to Rwanda. Thus, the impact of SAI in these countries is likely to be different in the case of Rwanda. To address this research gap, this study aims to empirically test whether the SAI practices improve household productivity and consumption outcomes in Rwanda. The study particularly focuses on three practices of SAI in this study: (i) minimum tillage; (ii) crop residue retention; and (iii) maize-legume diversification system. Maize yield and income from maize farming are used as a proxy for productivity outcomes, while household total expenditure and household food expenditure are used as indicators for household consumption outcomes in this study.

This study makes a contribution to the existing literature on the relationship between SAI and household productivity and consumption outcomes in SSA. In this regard, a multinomial endogenous switching regression approach is employed to model farmers' choice of SAI practices (i.e., alternative combinations of minimum tillage, crop residue retention, and maize-legume diversification cropping system) and examine the effects of adopting the single and multiple SAI practices. The multinomial endogenous switching regression model allows us to account for selection bias from both observable and unobservable factors.

The remainder of the paper is organized as follows. Section 2 presents the conceptual framework and analytical methods. Section 3 provides a brief description of the data and variables. In section 4, the results are presented and discussed, while section 5 concludes and draws policy implications.

2. Conceptual framework and analytical methods

As established in the introduction, the analysis of this study is based on three practices of SAI (i.e., crop residue retention, maize-legume diversification system, and minimum tillage). In a multiple adoption setting, farmers' simultaneous adoption of these three practices leads to eight alternative combination options that a farmer could choose. Those combination options include: (i) Non-adoption; (ii) minimum tillage only; (iii) crop residue retention only; (iv) maize-legume diversification only; (v) minimum tillage and crop residue retention; (vi) minimum tillage and maize-legume diversification; (vii) crop residue retention and maize-legume diversification; and (viii) minimum tillage, crop residue retention, and maize-legume diversification system. We postulate that a farmer selects the combination of SAI practice that maximizes utility subject to land availability, labor, input costs, and other constraints. Generally, farmers self-select into the adoption or non-adoption categories. In this regard, observed and unobserved factors associated with the outcomes of interest can influence the decisions of farmers. Consequently, following Teklewold et al. (2013), Kassie et al. (2015), Khonje et al. (2018), and Marenya et al. (2020), the adoption and impacts of SAI practices on household productivity and consumption are modeled using a multinomial endogenous switching/treatment effect regression approach. The major motive for this method is that it can allow us to account for selection bias arising from observable and unobservable factors.

The endogenous switching regression model involves a two-step estimation technique. In the first step, farmer's choice of individual and combined SAI practices are modeled using a multinomial logit selection model, while accounting for unobserved heterogeneity. In the second step of estimation, the effects of individual and combined SAI practices on household productivity and consumption are examined using ordinary least squares (OLS) with selectivity correction terms.

2.1. Multinomial adoption selection model

We conceptualized that the adoption decision for alternative SAI practices is modeled in a random utility framework. According to Teklewold et al. (2013), in a multinomial adoption selection model, we assume that maize producers have an objective of maximizing their profit, U_i, by comparing the profit obtained from different m SAI practices. Thus, the maize producer i will choose a particular practice j, over an alternative practice k, if $U_{ij} > U_{ik}$, $k \neq j$. The expected profit, U_{ij}^*, that the producer derives from the adoption of practice j is the latent variable determined by observed demographic, social-economic, and farm-level variables (X_i) and unobserved characteristics (ε_{i1}):

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

where X_i is observed exogenous variables (demographic, social-economic, and farm-level variables) and ε_{ij} is unobserved characteristics. Let (U) be an index that denotes the producer's choice of SAI practice, such that:

$$U = \begin{cases} 1 \ \text{ iff } \ U_{i1}^* > \max_{k\neq j}(U_{ik}^*) \ \ or \ \ \eta_{i1} < 0 \\ \vdots \qquad \vdots \qquad\qquad\quad \vdots \qquad\quad \text{for all } k \neq j \\ J \ \text{ iff } \ U_{iJ}^* > \max_{k\neq J}(U_{ik}^*) \ \ or \ \ \eta_{iJ} < 0 \end{cases} \quad (2)$$

In the above, $\eta_{ij} = \max_{k\neq j}\left(U_{ik}^* - U_{ij}^*\right) < 0$. Equation (2) suggests that the i^{th} maize producer will adopt SAI practice j, to maximize his expected profit if the practice j provides greater expected profit than any other practice $k \neq j$, that is, if $\eta_{ij} = \max_{k\neq j}\left(U_{ij}^* - U_{ik}^*\right) > 0$.

Following McFadden (1973), the probability that a maize producer i with characteristics X_i will choose the SAI practice j can be specified by a multinomial logit model as:

$$P_{ij} = Pr\left(\eta_{ij} < 0 \middle| X_i\right) = \frac{exp\left(X_i\beta_j\right)}{\sum_{k=1}^{J} exp(X_i\beta_k)} \quad (3)$$

2.2. Second stage: Multinomial endogenous switching regression

In the second stage of multinomial endogenous switching regression, we estimate the relationship between outcome variables and a set of explanatory variables (Z) for each selected SAI practice. In the model's specification for the three SAI practices, maize producers are expected to have eight alternative combination options ($j = 1, 2, \dots, 8$). The present study assumes that the non-adoption decision of SAI practice denoted by $j = 1$ is the base category, while at least one practice is adopted in the remaining choices ($j = 2, \dots, 8$). The outcome equation for each possible regime j is given as:

$$\begin{cases} \text{Regime 1: } Y_{i1} = Z_{i1}\alpha_1 + u_{i1} \quad if\ U = 1 \\ \vdots \qquad\qquad \vdots \\ \text{Regime J: } Y_{iJ} = Z_{iJ}\alpha_J + u_{iJ} \quad if\ U = J \end{cases} \tag{4}$$

where Y_{ij}'s denote the productivity and consumption outcome variables of the ith farmer in regime j, and the error terms ($u_{ij}'s$) are distributed with $E\left(u_{ij} \middle| X, Z\right) = 0$ and $\text{var}\left(u_{ij} \middle| X, Z\right) = \sigma_j^2$. $Y_{ij}'s$ are observed if a particular SAI practice j is adopted. In addition, the error term (u_{ij}) involves the unobserved individual effects and a random error term. Consequently, estimating Equation (4) using OLS will give biased results if the error terms of adoption ($\varepsilon_{ij}'s$) and outcome ($u_{ij}'s$) equations are not independent. To get consistent estimates of α_j, it is necessary to include the selection correction terms derived from Equation (4). Following Bourguignon et al. (2007), the multinomial endogenous switching model in Equation (4) can be specified as in Equation (5) below, which is also called the selection bias-corrected outcome equation or the second stage of multinomial endogenous switching regression.

$$\begin{cases} \text{Regime 1: } Y_{i1} = Z_{i1}\alpha_1 + \sigma_1\hat{\lambda}_{i1} + e_{i1} \quad if\ U = 1 \\ \vdots \qquad\qquad \vdots \\ \text{Regime J: } Y_{iJ} = Z_{iJ}\alpha_J + \sigma_J\hat{\lambda}_{iJ} + e_{iJ} \quad if\ U = J \end{cases} \tag{5}$$

where e_{ij} is the error term with an expected value of zero, σ_j is the covariance between $\varepsilon_{ij}'s$ and $u_{ij}'s$, $\hat{\lambda}_{ij}$ is the inverse Mills ratio computed from the estimated probabilities in Equation (3) as follows: $\hat{\lambda}_{ij} = \sum_{k \neq j}^{J} \rho_j \left[\frac{\hat{P}_{ik}\ln(\hat{P}_{ik})}{1-\hat{P}_{ik}} + \ln\left(\hat{P}_{ij}\right)\right]$. Here, ρ is the correlation coefficient between $\varepsilon_{ij}'s$ and $u_{ij}'s$. In the multinomial choice setting, there are $J - 1$ selection correction terms to be included in the outcome equations, one for each alternative SAI practice. The standard errors in Equation (5) are bootstrapped to control the heteroscedasticity associated with the generated explanatory variables in the estimation procedure.

2.3. Estimating average treatment effects

The multinomial endogenous switching regression framework stated above can be used to estimate the average treatment effects on the treated (ATT) by comparing the expected values of outcomes of adopters and non-adopters of SAI practices in actual and counterfactual scenarios—given by Equation (6) and (7), respectively.

Adopters with adoption decision (actual outcome):

$$E\left(Y_{ij} \middle| U = j; Z_{ij}, \hat{\lambda}_{ij}\right) = \alpha_j Z_{ij} + \sigma_j \hat{\lambda}_{ij} \tag{6}$$

Adopters who had decided not to adopt (counterfactual outcome):

$$E\left(Y_{i1} \middle| U = j; Z_{ij}, \hat{\lambda}_{ij}\right) = \alpha_1 Z_{ij} + \sigma_1 \hat{\lambda}_{ij} \tag{7}$$

Equations (6) and (7) are used to compute the ATT, which is derived as the difference between the actual and counterfactual expected values, i.e., the difference between Equations (6) and (7) as:

$$\begin{aligned} ATT &= E\left(Y_{ij} \middle| U = j; Z_{ij}, \hat{\lambda}_{ij}\right) - E\left(Y_{i1} \middle| U = j; Z_{ij}, \hat{\lambda}_{ij}\right) \\ &= \left(\alpha_j - \alpha_1\right) Z_{ij} + \left(\sigma_j - \sigma_1\right) \hat{\lambda}_{ij} \end{aligned} \tag{8}$$

where the first term (Z_{ij}) on the right-hand side of Equation (8) represents the expected change in adopters' mean outcome variable if adopters had similar characteristics as non-adopters. The second term ($\hat{\lambda}_{ij}$) on the right-hand side of Equation (8) represents the selection term that captures all potential effects of difference in unobserved variables.

3. Data and description of variables

3.1. Data sources and sampling

This study uses the survey data collected from a total of 327 households randomly selected from Kirehe, Bugesera, and Nyagatare districts in the Eastern Province of Rwanda. The survey was conducted from July to September 2020. Before the survey, enumerators who speak the local language were trained to understand the questionnaire. The three-stage sampling method was used to select villages and respondents. In the first stage, based on their maize-legume production potential, the three districts were selected. The second step involved the choice of villages in each district. A village is the lowest unit established by the Ministry of Agriculture and Animal Resources (MINAGRI) to coordinate and oversee the execution of extension services across the country. In the third stage, maize-legume producers were randomly selected from each village and enumerators conducted personal interviews with household heads.

The household questionnaire was designed to elicit valuable information on socio-economic characteristics of households, crop yields, income, and expenditure on food and non-food items. The survey also gathered information on the use of SAI practices such as minimum tillage, crop residue retention, and maize-legume diversification system. Data on farm-level characteristics such as farm size, land tenure, soil fertility, depth of the soil, land slope, and the distance from home to the farm were also collected. Additionally, the survey questionnaire captured information about farmers' access to credit, markets, and extension services as well as membership in cooperatives.

3.2. Description of variables and summary statistics

Table 1 summarizes the joint adoption of SAI practices which led to eight combinations from which maize producers can choose. The descriptive statistics indicate that of 327 farm households, 12.4% did not adopt any SAI practice while 5.14% simultaneously adopted all the three SAI practices. Table 1 also shows that crop residue retention only, minimum tillage only, and maize-legume diversification system only were practiced by 25.38%, 14.75%, and 6.37% of farm households, respectively.

A brief description of the major outcome and explanatory variables is given in Table 2. According to the data, the results presented in Table 2 indicate that the average maize yield is about 2575 kg/ha, while the average maize income is 202010 RWF/ha.[1] The results for household consumption-related indicators show that the average household total expenditure is roughly 289690 RWF per year and the average household food expenditure is approximately 140130 RWF per year.[2] Regarding the demographic and household characteristics, Table 2 indicates that the average age of the household head is approximately 53 years and 61% of the studied households are headed by males. The average household size is around 7 members and the average level of education in the sample area is about 6.4 years. Social capital and information variables such as group membership and extension services are also included in this study and the results show that

[1] Maize income denotes the monetary value or cash obtained from maize sales.
[2] Household expenditure is computed by adding the expenditure on non-food and food items.

34% of the farm households are members of associations or cooperatives and the frequency of contacts with extension agents is about 23 days per year.

Concerning household wealth indicators, the results reveal that the average farm size is 1.83 ha and the average number of livestock owned by farmers is 2.17 TLU.[3] About 45% of the farm households have access to off-farm activities and 36% of the farm households have access to credit. The average distance from home to the market is estimated at approximately 60–65 minutes and the average distance from home to the farm is around 15–20 minutes. In this study, we consider the soil fertility, soil depth, and slope of the plot as the measures of land/plot quality. These measures of farmland's quality are captured through farmers' perceptions and vary from shallow to deep soils and from flat to steep slopes. They also vary from very fertile to infertile soils. In the study's sample, 29% of the farm households perceive that their plots have fertile soils while 50% and 21% of the farmers perceive that their plots have medium and poor soil quality. On average, 31% of farm households have plots characterized by shallow depth of soil while 52% and 17% of farm households have plots with moderately deep and deep soils, respectively. About 27% of the farm households have plots characterized by flat slopes while about 35% and 38% of the farm households have plots characterized by medium and steep slopes, respectively. Regarding the shocks, 29% of the farm households have reported that their crops are frequently affected by the prevalence of pests and diseases while 30% of the farm households have reported that the drought occurred on their plots.

[3] TLU stands for tropical livestock unit and it is used to determine livestock density from various categories of livestock. The TLU value is computed as follows: 0.7 for cows; 0.45 for heifers; 0.1 for goats; 0.1 for sheep; 0.01 for chicken; and 0.2 for pigs.

Table 1. Adoption of alternative combinations of SAI practices and maize yield.

SAI practice	Abbreviations	Number of observations	Frequency (%)	Maize yield (kg/ha)	Yield difference (SAI practice vs non-adoption)	Minimum	Maximum
Non-adoption	$M_0R_0D_0$	41	12.42	2065		1820	2823
Minimum tillage only	$M_1R_0D_0$	48	14.75	2412	347***	1992	3010
Residue retention only	$M_0R_1D_0$	83	25.38	2286	221**	1997	2926
Maize-legume diversification only	$M_0R_0D_1$	21	6.37	2770	705***	2005	2975
Minimum tillage and residue retention	$M_1R_1D_0$	66	20.23	2658	593***	2014	3008
Minimum tillage and maize-legume diversification	$M_1R_0D_1$	16	4.86	2995	930***	2485	3035
Residue retention and maize-legume diversification	$M_0R_1D_1$	35	10.85	2798	733***	2090	3027
Minimum tillage, residue retention, and maize-legume diversification	$M_1R_1D_1$	17	5.14	2984	919***	2261	3060
Total		327					

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 2. Description and summary statistics of variables used in the analysis.

Variable	Description	Sample mean	Std. Dev.	Min.	Max.
Outcome variables					
Maize yield	Amount of maize produced in kilograms per hectare (kg/ha)	2575	1437	1820	3060
Net maize income	Value of maize harvested (‘000 RWF$^{\$}$/ha)	202.01	78.46	172.41	318.65
Household total expenditure	Household total expenditure (‘000 RWF)	289.69	326.53	250.32	390.70
Household food expenditure	Household food expenditure (‘000 RWF)	140.13	127.82	129.01	216.74
Independent variables					
Gender	1 if the household head is male, 0 otherwise	0.61	0.47	0	1
Age	Age of household head (years)	53.40	17.43	22	81
Household size	Number of persons in the household	6.96	3.26	2	11
Education	Number of years of formal education	6.44	3.68	0	16
Livestock ownership	Amount of livestock owned in tropical livestock units (TLU)	2.17	1.95	0.10	4.20
Farm size	The size of land under maize production (ha)	1.83	1.40	0.15	9.50
Group membership	1 if a farmer is a member of an association of farmers, 0 otherwise	0.34	0.41	0	1
Extension services	Frequency of contacts with extension agents (number of days per year)	23.14	7.51	0	36
Off-farm income	1 if a farmer has access to off-farm activities, 0 otherwise	0.45	0.39	0	1

Credit access	1 if a farmer has access to credit, 0 otherwise	0.36	0.32	0	1
Distance to market	Distance from home to the market (walking minutes)	62.72	58.60	10.25	90.50
Distance to farm	Distance from home to the farm (walking minutes)	19.92	21.07	4.00	30.25
Land tenure	1 if the farmer owns the land, 0 if the land is rented	0.86	0.83	0	1
Fertile soil♣	1 if the plot is characterized by good soil quality	0.29	0.34	0	1
Medium fertile soil♣	1 if the plot is characterized by medium soil quality	0.50	0.56	0	1
Shallow soils♦	1 if the plot is characterized by shallow depth of soil	0.31	0.45	0	1
Medium deep soils♦	1 if the plot is characterized by a medium depth of soil	0.52	0.48	0	1
Flat slope♠	1 if the plot is characterized by a flat slope	0.27	0.20	0	1
Medium slope♠	1 if the plot is characterized by a medium slope	0.35	0.26	0	1
Rainfall index	1 if there is enough rainfall	0.36	0.49	0	1
Pest shocks	1 if plot experienced pests and diseases	0.29	0.23	0	1
Drought stress	1 if drought occurred on a plot	0.30	0.27	0	1

Notes: [$]RWF is the Rwandan Franc currency unit and the exchange rate was 938.55 RWF to a US Dollar in December 2020.

♣Plots with poor soil quality are treated as the base category.

♦Plots with deep soils are treated as the base category.

♠Plots with a steep slope are treated as the base category.

4. Results and discussion

4.1. Factors explaining the adoption of SAI practices

This section presents the parameter estimates from the multinomial logit model in Equation (3). The reference category is the non-adoption of SAI practices against which the results are compared. The test of goodness-of-fit (Wald chi-square test) rejects the null hypothesis that all regression coefficients are jointly equal to zero at 1%, implying that the model fits the data very well. The results indicate that the estimated coefficients significantly differ across SAI practices. Farm household heads with a higher education level have an increased likelihood of adoption of most of the SAI practices. In general, education plays a vital role in technology adoption because farm households with better education can interpret the received information about new agricultural technologies and understand the benefits of adopting such technologies (Manda et al., 2016). Khonje et al. (2018) also found that education was important for farmers to adopt alternative combinations of agricultural technologies in Zambia. The results further show that asset ownership variables such as farm size and livestock ownership significantly increase the likelihood of adoption of all alternative SAI practices. Similarly, farm households owning full property rights to the land (i.e., land tenure) are more likely to adopt the SAI practices than those who rented pieces of land. Similar findings have been reported by Manda et al. (2016), Teklewold et al. (2013), and Kassie et al. (2013) in their studies on technology adoption in Zambia, Ethiopia, and Tanzania.

Social capital and network variables (i.e., group membership and extension services) significantly enhance the probability of adoption of all individuals and combinations of SAI practices. The distance from home to the farm decreases the likelihood of adoption of residue retention, maize-legume diversification, and the combination of minimum tillage, residue retention, and maize-legume diversification system. With regard to the plot characteristics, the results show that plots with fertile soils are more likely to adopt the residue retention, maize-legume diversification, the combination of minimum tillage and maize-legume diversification, and the combination of residue retention and maize-legume diversification system. But, good soil fertility decreases the likelihood of adoption of a combination of minimum tillage and residue retention. From a policy perspective, it is very important to have historical data of the farm as the cereal-legume intercropping system can also enhance the fertility of the soil.

Concerning the soil depth, the results show that the probability of adoption of most of the SAI practices is greater on farms with medium-deep soils. The likelihood of adoption of SAI practices such as residue retention, maize-legume diversification, and the combinations of minimum tillage and residue retention, and minimum tillage and maize-legume diversification system decreases with the rainfall index. Finally, the occurrence of droughts significantly increases the likelihood of adoption of most of the SAI practices.

Table 3. Parameter estimates of adoption of alternative SAI practices.

Variable	$M_1R_0D_0$	$M_0R_1D_0$	$M_0R_0D_1$	$M_1R_1D_0$	$M_1R_0D_1$	$M_0R_1D_1$	$M_1R_1D_1$
Gender	–0.142	–0.087	–0.081	–0.126	-0.165	–0.098	–0.124
	(0.217)	(0.255)	(0.230)	(0.209)	(0.194)	(0.303)	(0.221)
Age	0.053	0.029	–0.033	0.061	–0.038	–0.046	–0.035
	(0.045)	(0.034)	(0.026)	(0.095)	(0.023)	(0.017)	(0.020)
Education	0.231***	0.166**	0.183**	0.316	0.268**	0.304**	0.176*
	(0.098)	(0.095)	(0.104)	(0.332)	(0.089)	(0.125)	(0.087)
Household size	0.088	0.061	0.158	0.114*	–0.203	0.130*	–0.117
	(0.232)	(0.176)	(0.165)	(0.060)	(0.299)	(0.108)	(0.146)
Farm size	0.312**	0.154***	0.196***	0.268**	0.097**	0.243**	0.151**
	(0.139)	(0.063)	(0.089)	(0.115)	(0.038)	(0.092)	(0.069)
Livestock ownership	0.546***	0.333***	0.168**	0.507***	0.421***	0.264***	0.310**
	(0.184)	(0.195)	(0.110)	(0.168)	(0.157)	(0.104)	(0.213)
Group membership	0.265**	0.079	0.438**	0.151**	0.326***	0.415**	0.247**
	(0.088)	(0.087)	(0.213)	(0.054)	(0.096)	(0.171)	(0.093)
Extension services	0.107*	0.241**	0.094**	0.089*	0.341**	0.075***	0.090**
	(0.066)	(0.120)	(0.043)	(0.067)	(0.118)	(0.028)	(0.054)
Off-farm income	0.049	–0.080	0.087	0.032	–0.073	–0.127	0.182
	(0.051)	(0.081)	(0.098)	(0.043)	(0.078)	(0.115)	(0.208)
Credit access	0.183	0.056*	0.135	–0.322	0.086	0.062	0.126
	(0.195)	(0.039)	(0.221)	(0.279)	(0.104)	(0.083)	(0.128)

Distance to market	–0.242	0.074	–0.123	–0.050	–0.146	0.098	–0.204
	(0.235)	(0.098)	(0.184)	(0.106)	(0.145)	(0.083)	(0.212)
Distance to farm	–0.069	–0.127*	-0.102**	0.049	-0.060	0.014	-0.097**
	(0.197)	(0.083)	(0.059)	(0.115)	(0.071)	(0.065)	(0.043)
Land tenure	1.211***	0.825*	1.147**	1.066	0.958***	1.141***	1.473**
	(0.453)	(0.608)	(0.519)	(1.132)	(0.274)	(0.406)	(0.714)
Fertile soil	-0.048	0.366**	0.250***	-0.547*	0.495**	0.254**	0.130
	(0.151)	(0.135)	(0.075)	(0.328)	(0.269)	(0.096)	(0.415)
Medium fertile soil	-0.061	0.298***	0.235**	-0.402**	0.747	0.284**	-0.124
	(0.230)	(0.084)	(0.102)	(0.176)	(0.814)	(0.109)	(0.387)
Shallow soils	0.215	0.268	0.197	-0.188*	0.092	0.085	0.204
	(0.220)	(0.324)	(0.203)	(0.114)	(0.129)	(0.084)	(0.296)
Medium deep soils	0.183**	0.561***	0.638**	0.299	0.535**	0.508*	0.223**
	(0.088)	(0.214)	(0.352)	(0.321)	(0.247)	(0.386)	(0.095)
Flat slope	-0.757***	-0.626	0.813	-0.190*	-0.275	0.439	0.293
	(0.224)	(0.588)	(0.798)	(0.125)	(0.361)	(0.477)	(0.507)
Medium slope	-0.581*	0.449	0.817	-0.183*	0.676	0.408	0.295
	(0.285)	(0.460)	(0.818)	(0.107)	(0.713)	(0.470)	(0.484)
Rainfall index	-0.219	-0.155**	0.120**	-0.095*	0.088*	0.136	-0.182
	(0.212)	(0.086)	(0.078)	(0.051)	(0.052)	(0.140)	(0.189)
Pest shocks	0.471	-0.248	-0.093	0.607**	0.391	-0.203	-0.173
	(0.533)	(0.256)	(0.106)	(0.280)	(0.479)	(0.411)	(0.185)

Drought stress	0.836**	0.714*	0.257	0.986***	0.483**	0.912**	0.537***
	(0.454)	(0.590)	(0.288)	(0.314)	(0.160)	(0.416)	(0.114)
Constant	3.168***	3.461***	2.864*	4.395**	-0.714*	2.355*	-0.842
	(0.957)	(1.103)	(2.021)	(2.946)	(0.587)	(1.760)	(0.966)
Observations	327						
Wald test $\chi^2 = 247.65; p > \chi^2 = 0.000$							

Notes: Figures in parentheses are standard errors. The reference category is $M_0R_0D_0$ (non-adoption of SAI practices). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.2. Impacts of SAI practices on household productivity and consumption

Table 4 reports the results for the multinomial endogenous switching regression-based average treatment effects of adopting SAI practices on household productivity (i.e., maize yield and income from maize production) and consumption (i.e., household total expenditure and household food expenditure). The second stage regression (Equation (5)) estimates are not reported due to space limitation but are available upon request from the author. The average treatment effects on the treated (ATT) of SAI practices on maize yield, maize income, household total expenditure, and household food expenditure after controlling for selection bias originating from observed and unobserved heterogeneities (Table 4). The results in the last column (ATT column) of Table 4 indicate that the adoption of a combination of minimum tillage and maize-legume diversification system ($M_1R_0D_1$) is highly associated with a significant increase in maize yields (1015 kg/ha). Generally, the highest yield gain for farmers who adopted $M_1R_0D_1$ indicates the presence of synergy between minimum tillage and maize-legume diversification system. Besides, the maize-legume diversification system is more advantageous in terms of nitrogen fixation. The maize-legume diversification system can also prevent the development of unwanted weeds and interrupt the life cycle of pests (Khonje et al., 2018).

Farmers adopting the combination of all three SAI practices ($M_1R_1D_1$) have the highest maize income gain (16480 RWF/ha) followed by the combination of minimum tillage and maize-legume diversification system ($M_1R_0D_1$) (14514 RWF/ha). This finding is consistent with Manda et al. (2016) who found that the SAI practices adopted in combination have a significantly positive effect on maize yield and income compared to the SAI practices adopted in isolation. Regarding the other indicators for consumption, the results show that, on average, the adoption of all SAI practices is associated with increased household total expenditure and food expenditure. Overall, the household total expenditure and food expenditure increased for farmers adopting a combination of SAI practices compared to those adopting each SAI practice in isolation. These results corroborate the study of El-Shater et al. (2016) on the impacts of the adoption of zero tillage on farm income and wheat consumption.

Table 4. Multinomial endogenous switching regression-based average treatment effects of SAI practices on productivity and consumption.

Outcome variables	SAI practice	Adoption status♥	ATT

		A($j > 0$)	C($j = 0$)	(A–C)
Maize yield (kg/ha)	$M_1R_0D_0$	2461 (107)	2037 (79)	424*** (41)
	$M_0R_1D_0$	2340 (101)	1995 (78)	345*** (37)
	$M_0R_0D_1$	2884 (75)	2122 (82)	762*** (76)
	$M_1R_1D_0$	2597 (114)	2060 (73)	537*** (49)
	$M_1R_0D_1$	3073 (68)	2058 (58)	1015*** (103)
	$M_0R_1D_1$	2705 (85)	2104 (110)	601*** (44)
	$M_1R_1D_1$	2978 (53)	2128 (95)	850*** (87)
Maize income (RWF/ha)	$M_1R_0D_0$	183156 (2661)	175870 (3742)	7286** (1573)
	$M_0R_1D_0$	194354 (3275)	184720 (4338)	9634*** (976)
	$M_0R_0D_1$	200805 (1533)	189378 (1872)	11427*** (2464)
	$M_1R_1D_0$	202469 (5860)	191218 (4993)	11251*** (2300)
	$M_1R_0D_1$	211732 (7209)	197218 (8536)	14514*** (6452)
	$M_0R_1D_1$	201340 (6635)	189285 (7268)	12055*** (7816)
	$M_1R_1D_1$	215977 (4721)	199497 (4975)	16480*** (5265)
Household total expenditure (RWF)	$M_1R_0D_0$	290738 (12370)	265475 (12682)	25263* (13419)
	$M_0R_1D_0$	281451 (14968)	260378 (15610)	21073 (15942)
	$M_0R_0D_1$	277285 (9027)	257649 (9448)	19636*** (8716)
	$M_1R_1D_0$	291844 (5350)	266048 (5741)	25796*** (6307)
	$M_1R_0D_1$	293486 (5065)	267385 (5867)	26101*** (6283)
	$M_0R_1D_1$	293512 (6528)	266672 (6900)	26840*** (7410)
	$M_1R_1D_1$	292417 (7193)	264282 (7535)	28135*** (5998)
Household food expenditure (RWF)	$M_1R_0D_0$	139149 (1732)	133706 (2526)	5443*** (1834)
	$M_0R_1D_0$	136863 (2264)	131036 (2408)	5827*** (2635)
	$M_0R_0D_1$	135920 (2817)	131259 (3253)	4661*** (3007)
	$M_1R_1D_0$	140026 (2493)	133394 (2638)	6632*** (2900)
	$M_1R_0D_1$	140855 (1208)	132206 (1385)	8649*** (1522)
	$M_0R_1D_1$	142631 (2364)	131311 (2719)	11320*** (1846)
	$M_1R_1D_1$	141528 (3040)	131686 (2871)	9842*** (2461)

Notes: ♥The actual outcome (A) with the adoption of alternative SAI practices and counterfactual outcome (C) with non-adoption of SAI practices are reported as the adoption status in our case.

The difference between actual and counterfactual outcomes is the ATT. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Standard errors are in parenthesis.

5. Conclusions and policy implications

In SSA, the low soil fertility is a major problem that limits rural farm households to enhance crop yields, income, and food security. This study uses survey data to examine the determinants and impacts of the adoption of three interdependent SAI practices (minimum tillage, crop residue retention, and maize-legume diversification) and their combinations on household productivity (i.e., maize yield and income from maize production) and consumption (i.e., household total expenditure and household food expenditure) in Rwanda. The study employs the multinomial endogenous switching regression model to control the selection bias and endogeneity arising from observable and unobservable factors.

The results from the multinomial logit model indicate that likelihood of adopting the SAI practice is determined by a set of household and plot-level characteristics. Some of these factors include education; farm size, livestock ownership; group membership, extension services; distance from home to the farm; land tenure, soil fertility, soil depth, slope; rainfall index; and drought stress. In particular, these findings have policy relevance for government and development partners aimed at increasing the adoption rates of multiple and interdependent SAI practices. For instance, the significant and positive relationship between extension services and the adoption of SAI practices suggests that efforts aimed at promoting the adoption of SAI practices should focus on the provision of innovative extension services that enable farmers to better understand the benefits of alternative SAI practices. In addition, the positive relationship between the occurrence of droughts and the adoption of SAI practices suggests that farmers may be using SAI practices to alleviate the effects of weather-related risks.

This study also finds that the adoption of SAI practices significantly increases maize yields, maize income, household total expenditure, and household food expenditure. The multinomial endogenous switching regression results show that when unobservable factors are ignored, the effects of the adoption would be overestimated. This suggests that in the assessment of the impact of development projects, unobservable variables should be taken into consideration. Consequently, as we have found that the adoption of SAI practices has positive impacts on maize yield, income, and household consumption, efforts should be directed towards sensitizing farmers to adopt alternative SAI practices. It is also important for researchers, extension agents, and policy-makers involved in the research and diffusion of SAI practices to find the proper combination of these practices that will guarantee an increment in maize yield, income, and household consumption.

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