Journal of Agriculture and Rural Development in the Tropics and Subtropics
Vol. 123 No. 1 (2022) 39–50

https://doi.org/10.17170/kobra-202201195571 ISSN: 2363-6033 (online); 1612-9830 (print) – website: www.jarts.info

Determinants of sustainable agricultural intensification adoption and impacts on household productivity and consumption in Rwanda

Jules Ngango [a,*], Fabrice Nkurunziza [b,c], Saidi Rumanzi Mbaraka [d],
Athanase Rusanganwa Cyamweshi [e]

[a] *Department of Economics, College of Business and Economics (CBE), University of Rwanda, Rwanda*
[b] *Department of Applied Economics, Institut d'Enseignement Superieur de Ruhengeri, Musanze, Rwanda*
[c] *The African Centre of Excellence in Data Science, University of Rwanda, Rwanda*
[d] *College of Agriculture, Animal Science and Veterinary Medicine (CAVM), University of Rwanda, Rwanda*
[e] *Rwanda Agriculture and Animal Resources Development Board (RAB), Kigali, Rwanda*

Abstract

Sustainable agricultural intensification (SAI) involves those farming systems that produce in ways that improve or maintain productivity with minimal effects on the environment so that critical farm resources can endure. The objective of this paper is to investigate 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 and consumption in Rwanda. We used data obtained from a survey of 327 households conducted in 2020 in the districts of Kirehe, Bugesera, and Nyagatare of the Eastern Province. The study uses 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, soil fertility, slope, 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 extension services that enable farmers to better understand the benefits of alternative sustainable agricultural intensification practices. To increase the adoption of SAI, policies should also geographically target regions that experience frequent droughts and that are characterised by steep slopes and good fertile soils since they determine the need for adoption.

Keywords: sustainable agricultural intensification, consumption, productivity, impact assessment, multinomial endogenous switching regression

1 Introduction

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 natural resources. In particular, conventional agricultural practices such as monoculture practices and slash-and-burn commonly used in Rwanda and other SSA countries gradually degrade the soil quality. Evidence from previous studies indicates that sustainable agricultural intensification (SAI) can provide a potential solution to improve agricultural productivity, rural incomes, and welfare while also preserving the natural environment in the agrarian economies of SSA (Teklewold *et al.*, 2013; Manda *et al.*, 2016; Marenya *et al.*, 2020; Oumer *et al.*, 2020; Zeweld *et al.*, 2020; Ngango & Hong, 2021c). 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 (Manda *et al.*, 2016). On the other hand, conventional farming refers to

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[*] Corresponding author – ngajules2@gmail.com

Published online: 31 January 2022 – Received: 9 August 2021 – Accepted: 11 January 2022

cropping systems that are characterized by specialised, capital intensive, and highly mechanized production systems. Conventional farming systems extensively use chemical fertilisers, herbicides, and pesticides (Rasul & Thapa, 2004). In general, it is expected that SAI practices can have social, economic, and environmental benefits for farmers and policymakers (Abdulai & Abdulai, 2017; Kotu *et al.*, 2017; Ngango & Hong, 2021c). However, the adoption rate of SAI practices in Rwanda is still very low (Ngango & Hong, 2021c). Moreover, there are no empirical studies that attempted to investigate the drivers of adopting SAI practices and their benefits in the case of Rwanda.

To encourage the adoption of SAI practices, more studies are needed to highlight the major factors that influence the adoption decisions to guide policymakers in designing appropriate strategies and programs for improving the use of SAI practices. Besides, more empirical studies are highly recommended for a better understanding of the benefits of SAI in terms of agricultural productivity, food security, and economic aspects. 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. In their study, Teklewold *et al.* (2013) indicated that the adoption of SAI practices improved maize income and reduced the use of nitrogen fertilisers. Using a multinomial endogenous switching regression model, Marenya *et al.* (2020) found that a combination of various SAI practices potentially had a positive impact on maize yield and income. Oumer *et al.* (2020) indicated that a combined use of SAI practices reduces the production cost. In Zambia, Manda *et al.* (2016) assessed the joint adoption of sustainable agricultural practices and their impacts on maize yields and incomes. Their findings revealed that the adoption of SAI practices such as improved maize varieties had a positive effect on maize yields, while residue retention and maize–legume rotation had a significant positive effect on incomes. 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 from the case of Rwanda.

Therefore, to address this research gap particularly in Rwanda, this study aims to empirically examine the determinants of adoption of SAI and whether the SAI practices improve household productivity and consumption outcomes in Rwanda. 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. We chose maize yield and income as productivity outcome-related indicators because maize is the major food crop in Rwanda (Ngango & Hong, 2021b). A multinomial endogenous switching regression approach is employed to model farmers' choice of SAI practices and examine the impacts of adopting the single and multiple SAI practices. As farmers might adopt a combination of alternative SAI practices instead of single SAI practice, the use of binary regression models such as logit and probit is not appropriate (Teklewold *et al.*, 2013). The multinomial endogenous switching regression model allows us to account for selection bias from both observable and unobservable factors[1]. Another contribution of this study relates to the analysis of the effects of adopting SAI practices on household consumption (i.e., household total expenditure and household food expenditure). To the best of our knowledge, this has not been done in Africa or elsewhere as most previous studies examined the link between SAI and income, poverty, and food security as measures of welfare (Shiferaw *et al.*, 2014; Kassie *et al.*, 2015; Abdulai, 2016; Khonje *et al.*, 2018; Marenya *et al.*, 2020).

2 Materials and methods

2.1 Study design and setting

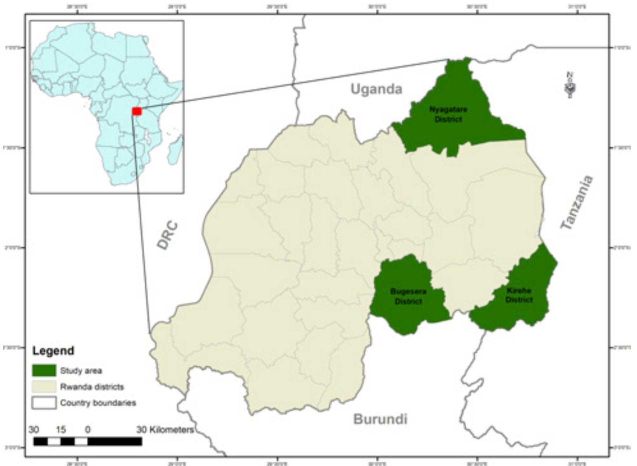

Fig. 1: *Maps of Africa and Rwanda showing study sites.*

Due to the limited resources to conduct a nationwide survey, our study was conducted in Kirehe, Bugesera, and

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[1] Observable factors/variables refer to all explanatory variables that are included in our econometric model. On the other hand, unobservable (or latent) factors/variables refer to the variables that may affect the dependent variable but were not included in our econometric model. Unobservable variables are captured by the error term.

Nyagatare districts in the Eastern Province of Rwanda. Eastern Province lies between latitudes 1°0'0" and 2°30'0" South of the equator and longitude 29°30'0" and 31°0'0" East (Fig. 1). The topography of this region is dominated by lowland semi-arid savannah grasslands and marshes. The semi-arid region is characterized by low average annual rainfall of less than 900 mm with frequent droughts (Jonah *et al.*, 2021). In general, Rwanda experiences two major agricultural seasons, supported by two rainy seasons. Season A is the most important and reliable rainy season that starts from September to December while Season B runs from March to May (Mikova *et al.*, 2015). Fig. 1 shows the three districts which are our study sites.

2.2 Data sources and sampling

This study uses the survey data collected from a total of 327 households randomly selected from three districts of 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 purposively selected. The second step involved the choice of villages in each district. This was done with the help of the Ministry of Agriculture and Animal Resources (MINAGRI) extension officers to identify potential villages with high dominance of SAI farming. A village is the lowest unit established by MINAGRI to coordinate and oversee the execution of extension services across the country. A total of 36 villages were selected in all three districts. In the third stage, maize-legume producers were randomly selected from each village. About 11 household farmers were selected from each village, giving a total sample size of 396 households. Afterward, we cleaned our data and end up with a total sample of 327 households. Experienced and trained enumerators conducted personal interviews with household heads.

The household questionnaire translated into Kinyarwanda language was used to elicit valuable information on socio-economic characteristics of households, crop yields, income, and expenditure on food and non-food items. We considered maize income as the income that farmers generate from sales of maize per year. In some instances, households got lower maize income because of using their harvest for own consumption, which is accounted for in our household food expenditure and household total expenditure outcome indicators. Household total expenditure was computed by adding all expenditure values on food and non-food items per year. Household food expenditure covers monetary expenditures on purchased food and the imputed values of consumption from own harvest per year. 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, soil fertility, and land slope were also collected. Additionally, the survey questionnaire captured information about extension services and membership in cooperatives.

2.3 Description of variables and hypotheses

The choice of explanatory variables used in this study is guided by previous literature on sustainable agricultural intensification (Kassie *et al.*, 2013; Teklewold *et al.*, 2013; Kassie *et al.*, 2015; Abdulai, 2016; Manda *et al.*, 2016; Khataza *et al.*, 2018; Khonje *et al.*, 2018; Kurgat *et al.*, 2018; Marenya *et al.*, 2020; Oumer *et al.*, 2020; Zeweld *et al.*, 2020; Ngango & Hong, 2021c) and the context of Rwanda. Household characteristics such as gender, age, education, and household size are considered as essential factors that determine the adoption of SAI practices. For instance, the uptake of agricultural technologies in SSA tends to be higher among male farmers compared to female farmers because men have better access, control, and use of the land resources, assets, and credit than women (Khataza *et al.*, 2018; Ngango & Hong, 2021a). Age may also influence the adoption of SAI practices because older farmers are likely to have more experience in farming and may have accumulated more physical and social capital (Manda *et al.*, 2016). Conversely, older farmers are less energetic and risk-averse compared to younger farmers which may reduce the likelihood of adoption (Kurgat *et al.*, 2018). The household size is another important determinant of adopting agricultural practices because in most rural areas larger families tend to have more labour is available for agricultural production. In general, SAI practices such as conservation tillage and crop residue retention in SSA agrarian communities are typically more labour-intensive (TerAvest *et al.*, 2019; Zeweld *et al.*, 2020). We also use education as an important factor that determines the adoption decisions. Better educated farmers are more efficient in agricultural production and have improved information-processing capabilities as well as innovation-seeking behaviour which may enhance the adoption of agricultural practices (Manda *et al.*, 2016; Khataza *et al.*, 2018; Kurgat *et al.*, 2018).

Livestock ownership and farm size are the major household assets in rural communities that may affect adoption decisions. Livestock provides a source of manure, draft power, and generate income for rural households (Kassie *et al.*, 2010). Consequently, land and livestock ownership could have a positive effect on the adoption of agricultural technologies. With regard to social capital and network variables, we use membership in farmers' groups and extension services as important factors that determine farmers' adoption decisions. As argued by Khataza *et al.* (2018), membership in farmers' groups tends to enhance the likelihood of adopting agricultural technologies because those groups enable farmers to share knowledge and get access to relevant information that can influence the adoption decisions. Similarly, extension services expose farmers to information on agricultural technologies and innovations which tend to increase the likelihood of adoption (Fatch *et al.*, 2020).

Previous studies indicated that farm characteristics such as soil fertility and slope of farmland play an important role in the adoption of agricultural technologies (Kassie *et al.*, 2013; Teklewold *et al.*, 2013; Kassie *et al.*, 2015; Manda *et al.*, 2016; Khonje *et al.*, 2018; Zeweld *et al.*, 2020). In particular, good soil fertility has the potential to influence the adoption of agricultural technologies (Manda *et al.*, 2016). Farmlands with steeper slopes are prone to water and wind erosion, thus those farmlands are more likely to influence the adoption of SAI practices (Manda *et al.*, 2016). Variables reflecting climatic and natural hazards are also included in our model and those include drought stress and pest shocks. Rainfall variability and drought occurrence in SSA adversely affect crop and livestock production leading to poverty and famines (Ayanlade *et al.*, 2018). Therefore, drought stress is hypothesised to influence positively the adoption of SAI practices. Similarly, we expect pest shocks to have a positive impact on the adoption of SAI practices because they are mostly used for weed management and reduce pests and diseases infestations (Kassie *et al.*, 2013).

2.4 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 practices that maximizes utility subject to land availability, labour, 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 modelled 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 choices of individual and combined SAI practices are modelled 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.

2.4.1 Multinomial adoption selection model

We conceptualized that the adoption decision for alternative SAI practices is modelled 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 $U_{ij} > U_i k$, $k \neq j$. 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}):

$$U^*_{ij} = X_i\beta_j + \epsilon_{ij} \tag{1}$$

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:

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

In the above, $\eta_{iJ} = \max_{(k\neq j)}(U_i k^* - U^*_{ij}) < 0$. Eq. (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 $\eta_{ij} = \max_{(k\neq j)}(U^*_{ij} - U^*_{ik}) > 0$. 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:

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

2.4.2 *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,. . . ,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 ($j = 2, \ldots, 8$). The outcome equation for each possible regime j is given as:

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

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 $E(u_{ij}|X,Z) = 0$ and $\text{var}(u_{ij}|X,Z) = \alpha_j^2$. 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 Eq. (4) using OLS will give biased results if the error terms of adoption (ϵ_{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 Eq. (4). Following Bourguignon *et al.* (2007), the multinomial endogenous switching model in Eq. (4) can be specified as in Eq. (5) below, which is also called the selection bias-corrected outcome equation or the second stage of multinomial endogenous switching regression.

$$\begin{cases} \text{Regime 1: } Y_{i1} \; = \; Z_{i1}\alpha_1 + \sigma_1\hat{\lambda}_{i1} + e_{i1} \quad \text{if} \;\; U = 1 \\ \vdots \qquad\quad \vdots \\ \text{Regime J: } Y_{iJ} \; = \; Z_{iJ}\alpha_J + \sigma_J\hat{\lambda}_{iJ1} + e_{iJ} \quad \text{if} \;\; U = J \end{cases} \tag{5}$$

where e_{iJ} is the error term with an expected value of zero, α_j is the covariance between ϵ_{ij}'s and u_{ij}'s, $\hat{\lambda}_{ij}$ is the inverse Mills ratio computed from the estimated probabilities in Eq. (3) as follows: $\hat{\lambda}_{ij} = \sum_{(k\neq j)}^{J} \rho_j \left[\frac{\hat{P}_{ik} ln(\hat{P}_{ik})}{1-\hat{P}_{ik}} + ln(\hat{P}_{ij} \right]$. Here, ρ is the correlation coefficient between ϵ_{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 Eq. (5) are bootstrapped to control the heteroscedasticity associated with the generated explanatory variables in the estimation procedure.

2.4.3 *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 Eq. (6) and Eq. (7), respectively.

Adopters with adoption decision (actual outcome):

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

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

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

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 Eq. (6) and Eq. (7) as:

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

where the first term (Z_{ij}) on the right-hand side of Eq. (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 Eq. (8) represents the selection term that captures all potential effects of difference in unobserved variables.

3 Results

3.1 *Description of farming practices and household characteristics*

Table 1 summarizes the joint adoption of SAI practices which led to eight combinations from which maize producers can choose. In the study area, crop residue retention appeared to be the most dominant SAI practice. The results show significant differences in maize yields between non-adopters and adopters of alternative SAI practices. On average, farmers who adopted a combination of minimum tillage and maize-legume diversification reported the highest yield followed by a combination of all three practices, while

Table 1: *Adoption of alternative combinations of SAI practices and maize yield: summary statistics (N=327).*

SAI practice	*Abbreviations*	*Percentage (%)*	*Maize yield (kg ha^{-1})* mean	*difference**	*Min.*	*Max.*
Non-adoption	$M_0R_0D_0$	12.42	2065		1820	2823
Minimum tillage only	$M_1R_0D_0$	14.75	2412	347^{***}	1992	3010
Residue retention only	$M_0R_1D_0$	25.38	2286	221^{**}	1997	2926
Maize-legume diversification only	$M_0R_0D_1$	6.37	2770	705^{***}	2005	2975
Minimum tillage and residue retention	$M_1R_1D_0$	20.23	2658	593^{***}	2014	3008
Minimum tillage and maize-legume diversification	$M_1R_0D_1$	4.86	2995	930^{***}	2485	3035
Residue retention and maize-legume diversification	$M_0R_1D_1$	10.85	2798	733^{***}	2090	3027
Minimum tillage, residue retention, and maize-legume diversification	$M_1R_1D_1$	5.14	2984	919^{***}	2261	3060

*SAI practice vs non-adoption; $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. The t test was used to compare the differences in the mean values between non-adopters and adopters of alternative SAI practices.

non-adopters reported low yield. A brief description and summary statistics of the major outcome and explanatory variables are given in Table 2. In the studied sample, the majority of farmers were males and appeared to be less educated. Social capital and information variables such as group membership and extension services were also included in this study and the results show that 34 % of the farm households were members of associations or cooperatives and the frequency of contacts with extension agents was not sufficient (with only 23 days per year). Concerning household wealth indicators, the results indicate that the average farm size (1.83 ha) in the studied sample appeared to be larger than the national cultivated land (0.70 ha)[2]. In this study, we considered the soil fertility and slope of the plot as measures of land/plot quality. These measures of farmland's quality are captured through farmers' perceptions and vary from flat to steep slopes and from very fertile to infertile soils. Of the total sample, 29 % reported that their plots were characterized by fertile soils while 21 % of the farmers perceived that their plots had poor soil quality. Regarding the shocks, 29 % of the farm households have reported that their crops were frequently affected by the prevalence of pests and diseases while 30 % of the farm households have reported that the drought occurred on their plots.

3.2 Factors explaining the adoption of SAI practices

Table 3 presents the results from the multinomial logit model in Eq. (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) rejected the null hypothesis that all regression coefficients were jointly equal to zero at 1 %, implying that the model fits the data very well. The results in Table 3 indicate that the estimated coefficients significantly differed across SAI practices. Farm household heads with a higher education level had an increased likelihood of adoption of most of the SAI practices except for the combination of minimum tillage and residue retention which was not statistically significant. The results further show that asset ownership variables such as farm size and livestock ownership significantly increased the likelihood of adoption of all alternative SAI practices as expected. With regard to social capital and network variables, the results show that group membership and extension services significantly enhanced the probability of adoption of all individuals and combinations of SAI practices.

Regarding the plot characteristics, the results show that plots with fertile soils were 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 decreased the likelihood of adoption of a combination of minimum tillage and residue retention. Finally, the occurrence of droughts significantly increased the likelihood of adoption of most of the SAI practices.

3.3 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

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[2] Data for the national cultivated land size was obtained from the fifth Integrated Household Living Conditions Survey (EICV 5) conducted in 2017.

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	65.30	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	Amount of livestock owned in 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
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
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
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

‡TLU: tropical livestock units are 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. *Plots with poor soil quality are treated as the base category. †Plots with a steep slope are treated as the base category.

yield and income from maize production) and consumption (i.e., household total expenditure and household food expenditure). The second stage regression (Eq. (5)) estimates are not reported due to space limitation but are available in the supplementary file. After controlling for selection bias originating from observed and unobserved heterogeneities, the average treatment effects on the treated (ATT) of SAI practices on maize yield, maize income, household total expenditure, and household food expenditure were both positive and significant (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 ($M_1R_0D_1$) was highly associated with a significant increase in maize yields (1015 kg/ha). Farmers adopting the combination of all three SAI practices ($M_1R_1D_1$) had 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). Regarding indicators for consumption, the results show that, on average, the adoption of all SAI practices was 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.

4 Discussion

This paper examined the major factors that determine the adoption of SAI practices and their impacts on household productivity and consumption. The study findings indicated that farm household heads with a higher education level had an increased likelihood of adoption of most of the SAI practices. This result is supported by Khonje *et al.* (2018) who found that education was important for farmers to adopt alternative combinations of agricultural technologies in

Table 3: *Parameter estimates of adoption of alternative sustainable agricultural intensification (SAI) practices.*

	SAI practices†						
	$M_1R_0D_0$	$M_0R_1D_0$	$M_0R_0D_1$	$M_1R_1D_0$	$M_1R_0D_1$	$M_0R_1D_1$	$M_1R_1D_1$
Gender	-0.268	-0.049	-0.051	-0.095	-0.114	0.006	-0.085
	(0.403)	(0.205)	(0.193)	(0.167)	(0.169)	(0.081)	(0.134)
Age	0.041	0.023	0.009	0.046	-0.074	-0.062	0.011
	(0.039)	(0.022)	(0.017)	(0.053)	(0.035)	(0.038)	(0.026)
Education	0.206^{***}	0.088^{***}	0.180^{**}	0.243^{*}	0.237^{**}	0.282^{***}	0.146^{**}
	(0.084)	(0.042)	(0.097)	(0.196)	(0.081)	(0.086)	(0.071)
Household size	0.059	0.044	0.135	0.080	-0.216	0.122**	0.008
	(0.210)	(0.169)	(0.157)	(0.093)	(0.273)	(0.079)	(0.105)
Farm size	0.275^{**}	0.149^{***}	0.167^{**}	0.271^{***}	0.091^{**}	0.218^{**}	0.147^{***}
	(0.124)	(0.055)	(0.086)	(0.102)	(0.035)	(0.087)	(0.053)
Livestock ownership	0.508^{***}	0.322^{***}	0.161^{**}	0.486^{***}	0.414^{***}	0.246^{***}	0.298^{**}
	(0.167)	(0.186)	(0.102)	(0.159)	(0.148)	(0.095)	(0.203)
Group membership	0.253^{***}	0.075^{*}	0.398^{**}	0.135^{***}	0.315^{***}	0.397^{**}	0.221^{**}
	(0.082)	(0.070)	(0.201)	(0.038)	(0.087)	(0.162)	(0.090)
Extension services	0.101^{**}	0.228^{***}	0.092^{***}	0.079^{**}	0.287^{**}	0.071^{***}	0.087^{***}
	(0.053)	(0.096)	(0.031)	(0.044)	(0.102)	(0.022)	(0.039)
Fertile soil	0.037	0.312^{**}	0.234^{***}	-0.554^{**}	0.461^{**}	0.237^{**}	0.124
	(0.126)	(0.109)	(0.071)	(0.296)	(0.223)	(0.095)	(0.392)
Medium fertile soil	-0.075	0.253^{**}	0.218^{**}	-0.426^{**}	0.703	0.261^{**}	-0.135
	(0.218)	(0.077)	(0.092)	(0.144)	(0.772)	(0.079)	(0.376)
Flat slope	-0.743^{***}	-0.634	-0.587	-0.213^{*}	-0.286	0.411	-0.307
	(0.188)	(0.572)	(0.647)	(0.121)	(0.356)	(0.473)	(0.498)
Medium slope	-0.594^{**}	0.406	0.786	-0.189^{*}	0.632	0.385	0.291
	(0.280)	(0.448)	(0.803)	(0.116)	(0.704)	(0.467)	(0.457)
Pest shocks	0.425	-0.251	-0.116	0.577^{**}	0.363	-0.222	-0.185
	(0.516)	(0.254)	(0.105)	(0.269)	(0.471)	(0.403)	(0.182)
Drought stress	0.810^{***}	0.706^{**}	0.255^{*}	0.935^{***}	0.477^{**}	0.874^{***}	0.519^{***}
	(0.378)	(0.515)	(0.209)	(0.292)	(0.158)	(0.381)	(0.103)
Constant	4.136^{***}	3.497^{***}	2.921^{**}	4.358^{***}	-0.621^{**}	2.426^{**}	-0.694^{**}
	(0.764)	(1.078)	(1.850)	(1.526)	(0.352)	(1.518)	(0.426)
Observations	327						
Wald $X^2 = 231.48$; $p > X^2 = 0.000$							

Figures in parentheses are robust standard errors. The reference category is $M_0R_0D_0$.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$. †See table 1 for the explanation of the abbreviations.

Zambia. 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). This implies that efforts should be directed towards education and training programmes as pathways to enhance the uptake of SAI systems in Rwanda. The results further showed that asset ownership variables such as farm size and livestock ownership significantly increased the likelihood of adoption of all alternative SAI practices. A plausible reason could be the benefits of SAI as labour-saving technologies (Teklewold *et al.*, 2013). Moreover, it has been argued that SAI practices require larger land which may discourage smallholder farmers to invest in SAI technologies (Khonje *et al.*, 2018). 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. However, Marenya *et al.* (2020) found a negative relationship between farm size and uptake of maize-legume intercropping system.

Social capital and network variables (i.e., group membership and extension services) significantly enhanced the probability of adoption of all individuals and combinations of SAI practices. A possible explanation for these findings could be that farmers' groups and extension services facilitate farmers to get access to the relevant information and experience. This reiterates the importance of farmers' groups and extension services in increasing the adoption of SAI systems in Rwanda. This result is consistent with the studies by Manda *et al.* (2016), Khataza *et al.* (2018), and Zeweld *et al.* (2020) that reported a positive effect of group membership and extension services on the adoption of sustainable agricultural practices.

We found evidence that plots with fertile soils increased the likelihood of adopting the residue retention, maize-legume diversification, the combination of minimum tillage

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

Outcome variables		Adoption status*		*ATT*
	SAI practice†	*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)

*The actual outcome (A) with the adoption of alternative sustainable agricultural intensification (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. †See table 1 for the explanation of the abbreviations.

and maize-legume diversification, and the combination of residue retention and maize-legume diversification system. However, good soil fertility decreased the likelihood of adoption of a combination of minimum tillage and residue retention. Our results indicated that the relationship between soil fertility and the adoption of maize-legume diversification is ambiguous because good soil fertility may be endogenous to the cereal-legume diversification system since that farming system can also enhance the fertility of the soil (Manda *et al.*, 2016). To avoid the issues of misleading results, it is important to have historical data of the farm. The results also revealed that the occurrence of droughts significantly increases the likelihood of adopting SAI practices. Typically, SAI practices (e.g., residue retention) improve soil fertility and retain moisture in the soil, particularly in regions that experience frequent droughts and dry spells (Manda *et al.*, 2016). Consequently, this implies that farmers whose plots experienced droughts may adopt SAI to mitigate the effects of droughts. This result is consistent with the findings of Manda *et al.* (2016) and Kassie *et al.* (2015) who argue that farms that have experienced drought are more likely to adopt SAI practices.

The main objective of the paper was to estimate the determinants and impacts of the adoption of SAI practices on household productivity and consumption. The average treatment effects on the treated (ATT) showed that SAI practices had a significant and positive impact on maize yield, maize income, household total expenditure, and household food expenditure. The results also indicated that the adoption of a combination of minimum tillage and maize-legume diversification system was highly associated with a significant increase in maize yields. Generally, the highest yield gain for farmers who adopted the combination of minimum tillage and maize-legume diversification system 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 (Manda *et al.*, 2016). The maize-legume diversification system can also prevent the development of unwanted weeds and interrupt the life cycle of pests (Khonje *et al.*, 2018). The adoption of a combination of all three SAI practices was associated with the highest income gain followed by the combination of minimum tillage and maize-legume diversification system. 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. The results further showed that the adoption of all SAI practices was 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.

5 Conclusions and policy implications

The likelihood of adopting the SAI practices was significantly determined by a set of household and plot-level characteristics. Indeed, our 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 extension services that enable farmers to better understand the benefits of alternative SAI practices. With regard to plot-level characteristics, our results suggest that site-specific characteristics (i.e., slope and soil fertility) have to be taken into consideration by policymakers and all stakeholders in the promotion and dissemination of SAI practices because they determine the need for adoption. In addition, the positive relationship between the occurrence of droughts and the adoption of SAI practices suggests that policymakers and development agencies should geographically target regions that experience frequent droughts and dry spells (e.g., Eastern Province) in the promotion of SAI practices.

This study also found 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 showed 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, since the results showed 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. However, we may not replicate our findings in the other rural communities because of the unique conditions prevailing in the Eastern province of Rwanda. Future research should consider assessing the effects of adopting SAI in all other rural communities of Rwanda, to capture the real picture of SAI impacts at the national level.

Acknowledgements

This study benefited from the comments of participants in the 31st Triennial International Conference of Agricultural Economists (ICAE), 17-31 August 2021. We are thankful to the respondents for their continued participation in the survey, and enumerators for their efforts in the data collection. The authors also thank the two anonymous reviewers for their valuable comments and suggestions.

Conflict of interest

The authors declare that they have no conflict of interest.

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