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Impact of Joint Adoption of Climate-Smart Agricultural Technologies on Sorghum Farmers' Performance in Mali

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Climate change remains a significant threat to food security, especially in developing countries of sub-Saharan Africa. We investigate the impact of farmers' joint adoption of climate-smart agricultural technologies (CSAT) on sorghum farmers' performance in Mali, where sorghum is one of the most important staple food crops. The empirical results indicate that adopting all the CSAT components as a package significantly increases sorghum yield compared to non-adopters and incomplete adopters. However, due to the higher cost associated with the package and insufficient yield enhancement by the package, incomplete adoption of CSAT components provides better income, particularly if farmers are educated.

Key words: technology adoption, climate-smart agricultural technologies (CSAT), staple food

1. Introduction

Sorghum is one of the most important staple crops produced and consumed in the Sahel region of West Africa. It is a strategic crop produced by more than half of the population and provides about 5 to 7% of full-time jobs in this region (Kaminski *et al*., 2013). Sorghum production is dominant in the drier zone of Mali and other Sahel countries due to its ability to resist severe weather, such as drought and poor soil conditions, which are prevalent in the Sahel.

Mali is a landlocked country in the Sahel that spans through the Sahara Desert. The country faces eccentric weather conditions, including sandstorms, high temperatures, and variability in rainfall. Sorghum plays a major role in food security in Mali due to its climate-resilient adaptive features. However, sorghum's productivity in Mali remains low, and farmers are producing below the potential yield. For instance, the average national yield of sorghum in the last decade (2011-2021) is less than 1,200 kg/ha (FAOSTAT, 2022). Sorghum's low yield has serious implications for poverty and food security in the drier zone of Mali, where farmers rely on sorghum for subsistence as well as a source of income. Several factors, including poor infrastructure, institutional issues, soil degradation, and abrupt climate conditions, have contributed to the challenges farmers encounter in Mali (Awotide *et al*., 2022). Climate change poses a significant threat to the Malian agricultural sector, as most farmers operate a rudimentary farming system with little or no advanced technology to adapt to extreme weather events.

To improve sorghum production and mitigate adverse climate change impacts, farmers are advised to adopt innovative and sustainable farming practices, collectively referred to as climate-smart agricultural technologies (CSAT). CSAT are rebranded innovations of agricultural practices and technologies proposed by the Food and Agricultural Organization (FAO) in 2010, to support farmers' adaptation to climate change and enhance productivity (CCAFS, 2022). Examples of CSAT include soil and water conservation, agroforestry, agrochemicals, and improved crop varieties. Although CSAT have the potential to reduce farmers' vulnerability to climate change and improve crop yield, its adoption rate in Mali is still low (Ouédraogo *et al*., 2019).

Recently, several studies have been conducted on CSAT adoption in various developing countries, including Mali (Awotide *et al*., 2022; Ho and Shimada, 2021; Kaliba *et al*., 2021; Singbo *et al*., 2021). However, most of these studies, except Ho and Shimada (2021), dealt with CSAT as a single technology, even though CSAT consists of multiple technologies. On the other hand, recent studies (Assefa *et al*., 2021; Ho and Shimada, 2021; Lu *et al*., 2021) have analyzed the impact of adopting incomplete packages (some of the multiple technologies). Our study is similar to Ho and Shimada (2021) in that we consider the adoption of incomplete packages and apply it to the case of CSAT. However, unlike Ho and Shimada (2021), our novelty is that we focus on the heterogeneous impact of CAST adoption among the farmers.

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Table 1. Definition and summary statistics of variables

Variables	Description	Mean (S.D.)
CSAT adoption (binary dummy)		
ISV	Adoption of any improved sorghum varieties	0.244 (0.24)
AGC	Adoption of herbicide, pesticide, and/or chemical fertilizer	0.496 (0.50)
SWM	Adoption of soil and water management practices	0.473 (0.47)
CSAT Non-adopters	Households adopting none of the CSAT components	0.286 (0.45)
CSAT incomplete adopters	Households adopting one or two of the CSAT components	0.603 (0.45)
CSAT package adopters	Households adopting all the CSAT components	0.111 (0.31)
Farm performance (outcome variables)		
Sorghum Yield	Sorghum output per hectare (kg/ha)	2,484 (3,880)
Sales Revenue	Sales of sorghum per hectare (1,000 FCFA/ha)	190.2 (220.6)
Production Cost	Production cost per hectare (1,000 FCFA/ha)	117.4 (184.1)
Sorghum Income	Output value minus paid-out cost per hectare (1,000 FCFA/ha)	139.3 (414.8)
Income/PC	Sorghum income per capita (1,000 FCFA/capita)	37.79 (152.5)
Farm characteristics (control variables)		
HHedu (dummy)	HH having formal education	0.363 (0.480)
HHage	Age of the HH (years)	57.9 (13.9)
HHfarmexp	Farming experience of HH (years)	39.1 (17.1)
Hsize	Number of household members	7.39 (5.22)
Prd_ast	Total value of farm productive asset (1,000 FCFA)	931 (1630)
Farm size	Total farm area (ha) under sorghum cultivation	7.97 (24.0)
TTLU	Total livestock holdings (TLU, tropical livestock unit)	13.6 (18.9)
FBO (dummy)	Farmers who belong to farmer-based organizations	0.793 (0.405)
Formal credit (dummy)	Farmers who have access to formal credit	0.118 (0.323)
Ext_contact (dummy)	Farmers who have access to extension services	0.717 (0.451)
Crop disease (dummy)	Farmers having experienced crop disease in the last three years	0.211 (0.408)
Drought (dummy)	Farmers having experienced drought in the last three years	0.614 (0.487)
Number of observations (*N*)		957

Note: PC denotes per capita; HH denotes Household Head; FCFA is the abbreviation of franc CFA, a common currency used in 14 countries in West and Central Africa (1USD = 590 FCFA during the survey period); S.D. denotes standard deviation.

With respect to the heterogenous impact of CSAT adoption, Awotide *et al*. (2022) show that the impact is generally higher for the poorest end of the welfare distribution. However, they do not explain why the poorest are less willing to adopt CSAT despite the higher return. Following Suri (2011), we consider that farmers' expected profit from adopting CSAT would be a key determinant of technology adoption and that its heterogeneity among farmers would explain the low adoption rate. In this regard, we hypothesize that the heterogeneity in education status will cause differential impacts.

Therefore, this study, focusing on sorghum production in Mali, analyzes the impact of CSAT adoption on farming performance, particularly its heterogeneity due to education status. Unlike Awotide *et al*. (2022), who investigate total crop/farm performance, this study focuses only on sorghum because of its strategic importance for poverty alleviation and enhancing food security under the climate change. Thus, obtaining policy implications for the improvement of sorghum production via CSAT adoption is vital for the region that is being threatened by climate change.

2. Data and Descriptive Statistics

This study utilizes cross-sectional data collected by the International Institute of Tropical Agriculture (IITA), Bamako, Mali, during the 2019 cropping season as the baseline data for the project titled "Climate-smart Agricultural Technologies for Improved Rural Livelihoods and Food Security in Mali (CSAT-Mali)." The survey was targeted at smallholder farmers cultivating several staple crops such as sorghum, millet, maize, rice, cowpea, groundnut, soybean, and vegetables. The primary aim of the survey was to obtain information on the livelihood status among heterogeneous farmers regarding the adoption/utilization of CSAT. For this study, we chose 957 sorghum farmers from the 2240 sample farmers in four regions in Mali.[1] The summary statistics of the sorghum farmers are in Table 1.

We consider CSAT as a package of three kinds of technology, namely, improved sorghum varieties (ISV), agrochemicals (AGC) including herbicide, pesticide, and chemical fertilizer, and soil and water management (SWM) practices/technologies such as trenches and bunds, minimum

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[1] Details of the survey and sampling procedure can be found in Awotide *et al*. (2022). The regions, namely Koulikoro, Kayes, Segou, and Sikasso cover the main agroecological areas in Mali. Among 2240 sample farmers, the share of sorghum growers is 47.8%, that of millet growers is 49.3%, and that of maize growers is 49.3%. However, their distribution is not even in the four regions: the sorghum share is the highest (79.3%) in the driest region and the lowest (6.1%) in the region where irrigation is developed. It suggests that sorghum is selected in relatively drought-prone areas because of its drought tolerance.

tillage, mulching compost, and water harvesting. As shown in Table 1, among the sampled farm households, 24.4% adopt IVS, 49.6% adopt AGC, 47.3% adopt SWM, and 28.6% do not adopt any of the three CSAT components (non-adopters of CSAT). On the other hand, 60.3% adopt any one or two of the three CSAT components (incomplete adopters of CSAT), and 11.1% adopt all the three CSAT components (package adopters of CSAT).

As for sorghum farming performance, we have five indicators, as shown in Table 1. The average yield of sorghum is 2,484 kg/ha, which is higher than the national average yield (FAOSTAT, 2022). Sample farmers are generating a positive income on average from sorghum production, i.e. 139,300 FCFA/ha and 37,800 FCFA/capita.

Farm characteristics are given in the lower part of Table 1. Most of the sample household heads are not educated; only 36.3% of them have at least one year of formal education.

Table 2. Mean comparisons of farm performance and characteristics based on CSAT adoption status

Variables	CSAT Non-adopters	CSAT Incomplete Adopters	CSAT Package Adopters
Outcome variables			
Sorghum Yield	1573	2766***	3309***
	(3696.96)	(3828.76)	(4223.01)
Sales Revenue	162.5	285.7***	341.8***
	(381.9)	(395.5)	(436.3)
Production Cost	41.7	134.1***	221.8***
	(67.1)	(194.2)	(249.8)
Sorghum Income	120.8	151.6	120.0
	(385.8)	(409.1)	(509.5)
Income/PC	34.4	42.4	21.5
	(98.7)	(165.8)	(187.8)
Control variables			
HHedu	0.30	0.36**	0.57***
HHage	58.5	57.6	58.6
HHfarmexp	42.6	37.5***	38.3*
Hsize	7.54	7.49	6.45
Prd_ast	598	974**	1,555**
Farm size	6.02	8.63	9.40***
TTLU	13.5	12.9	17.9
FBO	0.67	0.82***	0.94***
Formal credit	0.03	0.15***	0.20***
Ext_contact	0.49	0.78***	0.94***
Crop disease	0.26	0.18**	0.23
Drought	0.81	0.57***	0.38***
N	274	577	106

Note: CSAT non-adopters are compared with incomplete adopters of CSAT and package adopters of CSAT respectively. Standard deviations of outcome variables are in parenthesis.
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 2 compares the farm performance and farm characteristics of the sample farmers by CSAT adoption status. The difference in the means between CSAT non-adopters and CSAT adopters (incomplete CSAT adopters and package CSAT adopters respectively) is tested by the mean comparison t-test. The results show a significant difference in most of the variables between CSAT adopters and non-adopters. Specifically, CSAT adopters show not only better farming performance but also have higher endowment of physical as well as human capital than non-adopters. However, these descriptive findings do not imply any causal impact of CSAT adoption on farm performance. Moreover, it is highly likely that there are unobserved factors that are correlated with both CSAT adoption status and farming performance. Therefore, to assess the impact of CSAT adoption, we employ a multinomial endogenous treatment effect model, as presented in the next section.

3. Conceptual Framework and Estimation Strategy

Farmers will choose to adopt one or several components of CSAT based on observable (such as information access, literacy, and resource endowment) and unobservable (such as innate ability and skills) characteristics. We employ a multinomial endogenous treatment effect (METE) model with the inclusion of instrumental variables (IVs) to address the endogeneity issue. As proposed by Deb and Trivedi (2006), the METE is given as multinomial choice equation and outcome equation as below;

$$Pr(\mathcal{C}_{fj}|x_f, \mathcal{Z}_f, v_{fj}) = g(x_f'\gamma_1 + \alpha_1\mathcal{Z}_f + \delta_1 v_{f1},\ x_f'\gamma_2 + \alpha_2\mathcal{Z}_f + \delta_2 v_{f2}) \quad (1)$$

$$\mathrm{E}(\mathbb{Y}_f|x_f, \mathcal{C}_{fj}, v_{fj}) = x_f'\beta + \psi_1\mathcal{C}_{f1} + \psi_2\mathcal{C}_{f2} + \lambda_1 v_{f1} + \lambda_2 v_{f2} + \xi_f \quad (2)$$

where subscripts f and j represent sorghum farmers and the treatment statuses, respectively. j can take a value of 0 for non-adopters of CSAT, 1 for incomplete adopters of CSAT, and 2 for complete adoption of CSAT.

Equation (1) is to estimate the probability that the farmer chooses one of the three CSAT adoption statuses $\mathcal{C}_{fj}$, given the exogenous variables x_f, IVs[2] $\mathcal{Z}_f$ and unobserved factors v_{fj}, while γ_j, α_j, and δ_j are parameters to estimate. To estimate the above equations as a METE model, we apply a mixed multinomial logit structure to equation (1) as the

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[2] We use two binary dummy variables (crop disease and drought shocks in the last three years) as IVs because they can influence the adoption of CSAT in the survey year but not directly farmers' performance during the survey year. The instrument variables are excluded in equation (2).

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Equation (2) is for the impact of CSAT adoption on $\mathbb{Y}_f$, an indicator of farm performance such as yield, cost and income, where x_f is a vector of exogenous variables with associated parameter β. ψ_j refers to the impact of the choice of either of CSAT adoption statuses relative to the reference (non-adoption). υ_{fj} is to capture farmer and CSAT-specific unobserved factors that influence farmers' selection of CSAT adoption and the outcome variable. λ_j represents parameters estimating whether there is a positive or negative correlation between CSAT adoption status and the outcome variable via the unobserved characteristics.

To analyze the heterogenous impact depending on education, each CSAT adoption status is divided into two: one is with non-educated household heads, and the other is with educated household heads. Hence, by replacing C_{fj} with CE_{fk} $(k = 1 \cdots 6)$, equation (3) is obtained as below.

$$\mathrm{E}\left(\mathbb{Y}_f \middle| x_f, CE_{fk}, \upsilon_{fk}\right) = x_f'\beta + \mu_k CE_{fk} + \lambda_k \upsilon_{fk} + \xi_f \quad (3)$$

In estimating (3), one of the CE_{fk} will be dropped. For the same CSAT status (for example, package adoption), the difference in μ_k between "with education" and "without education" is the effect of education on the impact of CAST package adoption.

4. Impact of CSAT Adoption on Farm Performance

1) Determinants of CSAT adoption

The results of the mixed multinomial logit regression (the first stage of the METE model) are given in the second and third columns of Table 3. The results reveal that farmers' education has a positive effect on CSAT adoption, but only in the case of package adoption, implying that educated farmers know the benefit of package adoption of CSAT. The variables used as IVs, crop disease and drought production shock negatively influence CSAT adoption. The significant effects justify the use of these variables as IVs.[3]

2) Impact of CSAT adoption

The columns 4-8 of Table 3 are the results of the impact estimation (second stage of the METE model).[4] First, with respect to sorghum yield and sales revenue, CSAT adopters, either incomplete or package, show a significantly better performance than non-adopters. Among the CSAT adopters, package adopters are better off than incomplete adopters.[5] This result is consistent with Lu *et al*. (2021) and Khonje *et al*. (2018) for agricultural technology adopters in Ghana and Zambia, respectively. However, the cost of production of CSAT adopters is also significantly higher than that of non-adopters. Moreover, among the CSAT adopters, the production cost of package adopters is significantly higher than that of incomplete adopters.[5] This is not surprising as CSAT is known to be capital intensive due to more production input requirements (such as hired labour, agrochemical, and others). As a result, there is no statistical difference in sorghum income per hectare between the non-adopters and the package adopters, and the incomplete adopters have significantly higher income per hectare than the other two kinds of adopters.

On the other hand, with respect to sorghum income per capita used as a welfare indicator in this study, CSAT adoption has no statistically significant impact.

3) Heterogeneous impact of education

The results of the heterogeneity analysis (Table 4) reveal some important roles of education. First, among the CSAT incomplete adopters, educated farmers tend to realize significantly higher sorghum income than non-educated farmers. Second, among CSAT package adopters, the production cost of educated farmers is significantly lower than that of non-educated farmers. Third, within the same CSAT adoption status, education does not create a significant difference in sorghum yield.

5. Conclusion

This study investigates the causal effect of adopting CSAT on sorghum farming performance in Mali. We extend the literature by taking account of different degrees of CSAT adoption and considering the heterogeneity of its impact.

Our regression analyses reveal that CSAT package adopters realize the highest sorghum yield and sales revenue per hectare than incomplete adopters and non-adopters. However, package adopters' income per hectare is not different from that of non-adopters and is significantly lower than that of incomplete adopters due to the high production cost of adopting CSAT package relative to the yield gain of

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[3] We conducted a falsification test, as proposed by Di Falco and Veronessi (2013) and confirmed the efficacy and validity of the selected IVs in the model.

[4] We conducted a robustness check using the ordinary least square regression. The coefficients for the CSAT combinations (incomplete and package) in the OLS were lower than those of the METE model. These could be due to the sensitivity of OLS to endogeneity.

[5] We conducted an equality test of the estimated coefficient of both CSAT dummies and confirmed that the differences in yield, sales revenue, and production cost between package adopters and incomplete adopters are statistically significant.

package adoption. Instead, the income of incomplete adopters is the highest among the three. Although the heterogeneity analysis shows that education helps CSAT package adopters to reduce production costs significantly, the sorghum yield of package adopters is not sufficiently high even if farmers are educated. On the other hand, the highest income of CSAT incomplete adopters even becomes higher if farmers are educated. The results indicate a vital role of education in CSAT adoption, but on the other hand, the necessity of further improvement of sorghum yield.

The results also imply that educated farmers will probably choose appropriate combinations of CSAT components to enjoy higher income. Our data include several combinations of CSAT components, but unfortunately, due to the insufficient number of each combination, we cannot compare farming performance between combinations in this study.

Another limitation of this study is that its impact assessment is based on single-year cross-sectional data. The availability of multiple-year panel data will be helpful not only to control for unobserved heterogeneity but also to assess CSAT's effect on the stabilization of crop production under highly variable climate conditions.

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Table 3. Impact of CSAT adoption on farm performance by multinomial endogenous treatment effect model

	Determinant		**Impact**				
Variables	**CSAT Incomplete Adopters**	**CSAT Package Adopters**	**Sorghum Yield (kg/ha)**	**Sales Revenue (1,000 FCFA/ha)**	**Production Cost (1,000 FCFA/ha)**	**Sorghum Income (1,000 FCFA/ha)**	**Sorghum Income (1,000 FCFA/capita)**
CSAT Incomplete Adopters			886.35***	134.09***	27.56**	90.64***	20.32
			(335.14)	(15.64)	(12.54)	(30.10)	(12.35)
CSAT package Adopters			1,247.26***	232.17***	109.10***	-53.82	19.55
			(445.56)	(25.08)	(26.24)	(53.10)	(21.17)
HHedu (dummy)	0.077	0.89***	583.5*	-16.1	-13.6	81.0**	13.1
	(0.21)	(0.31)	(328.0)	(13.3)	(13.6)	(38.1)	(11.3)
ln(HHage)	0.61	1.14*	-162.0	-69.7**	-37.5	23.2	0.91
	(0.42)	(0.67)	(580.4)	(27.9)	(26.1)	(62.6)	(23.7)
ln(HHfarmexp)	-0.53**	-0.46	-342.2	0.72	-21.7*	-11.1	-1.88
	(0.24)	(0.31)	(346.9)	(10.8)	(12.3)	(40.2)	(9.72)
ln(HSzc)	-0.063	-0.39	-66.4	-40.1**	-13.5	4.57	-43.0**
	(0.19)	(0.25)	(238.4)	(18.8)	(10.2)	(25.6)	(16.7)
ln(Prd_ast)	0.32***	0.43***	165.7**	14.1**	4.63	12.3	2.40
	(0.091)	(0.15)	(83.3)	(5.79)	(5.47)	(9.86)	(3.58)
ln(Farm_Size)	-0.12	0.17	148.7	-2.21	8.97**	8.87	-1.00
	(0.10)	(0.16)	(104.7)	(6.15)	(4.32)	(11.6)	(3.81)
ln(TTLU)	0.35*	0.53**	-137.2	40.8***	52.0***	-65.0***	-14.9*
	(0.19)	(0.26)	(213.6)	(11.7)	(10.8)	(24.3)	(7.91)
FBO (dummy)	0.71***	1.99***	318.5	-37.4**	25.7***	10.4	0.020
	(0.22)	(0.51)	(262.1)	(17.1)	(9.66)	(27.7)	(13.7)
Formal credit (dummy)	1.35***	1.35**	715.0	26.6	100.8***	-27.7	-17.1
	(0.48)	(0.59)	(434.8)	(28.3)	(31.5)	(53.5)	(17.9)
Ext_contact (dummy)	1.34***	2.81***	350.4	23.7*	11.5	26.7	6.86
	(0.21)	(0.53)	(251.6)	(13.4)	(12.1)	(29.8)	(10.4)
Crop disease (dummy)	-0.59**	-0.13					
	(0.26)	(0.39)					
Drought (dummy)	-1.15***	-2.09***					
	(0.22)	(0.33)					
Number of Observations	577	106	957	957	957	957	957

Note: Variables headed with ln are converted into logarithms. A multinomial endogenous treatment effect model is used for each outcome variable. Robust standard errors clustered at the village level are in parenthesis. 100 Halton sequence-based quasi-random draws per observation are used for the outcome variable models.

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

Table 4. Heterogeneity impact of CSAT adoption by education status of the farmers

Variables	**Sorghum Yield (kg/ha)**	**Sales Revenue (1,000 FCFA/ha)**	**Production Cost (1,000 FCFA/ha)**	**Sorghum Income (1,000 FCFA/ha)**	**Sorghum Income (1,000 FCFA/capita)**
CSAT Non-adopters	512.04	-71.29***	-12.48	51.71	-17.45
(Educated n = 81 vs Non-educated n = 193)	(681.57)	(16.64)	(13.71)	(71.51)	(20.55)
CSAT Incomplete Adopters	446.29	-19.66	-13.36	117.99**	18.21
(Educated n = 207 vs Non-educated n = 370)	(396.21)	(19.98)	(21.75)	(49.01)	(20.46)
CSAT package Adopters	16.23	54.98	-111.11**	97.78	42.95
(Educated n = 59 vs Non-educated n = 47)	(813.13)	(44.28)	(45.73)	(105.52)	(36.91)
Controls	YES	YES	YES	YES	YES
Number of Observations	957	957	957	957	957

Note: Controls are the same as Table 3, with the exclusion of the education dummy, which is combined with CSAT adoption status. The estimation procedure is the same as Table3. Robust standard errors clustered at the village level are in parenthesis.

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