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Evaluation of the Effect of Stone Lines and Microdosing Adoption on Sorghum Yield and Income: A Case of Smallholder Farmers in Burkina Faso

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Abstract

This present study aims to investigate the factors influencing the combined adoption of stone lines and microdosing and its effect on sorghum yields and net income. By adjusting for biases in observable and unobservable factors, the multinomial endogenous switching regression (MESR) model was employed to estimate the net effects of adoption on outcomes. The average treatment effect on treated (ATT) was also employed to evaluate the effects of stone lines and microdosing adoption. For a more accurate estimation of farmer output and farming income, the inverse probability weighted regression adjustment (IPWRA) was also estimated. In achieving our purpose, we collected data from 420 farm households which had 1280 plots for four main crops. The total sample identified 368 sorghum plots with stone lines and microdosing adoption. The MESR results indicated that the number of extension visits, level of education, access to agricultural credit, access to subsidies, household size, family labour and tropical livestock unit (TLU), and perception of soil fertility all played significant roles in the adoption of the stone lines and microdosing combination. The ATT revealed that adopters of the stone lines and combined microdosing had a higher sorghum yield than their counterfactual. The adoption of the stone lines and microdosing increased sorghum yield and net sorghum income, respectively, by 70% ($p < 0.001$) and 60% ($p < 0.001$). This result shows a strong synergy in agricultural productivity between the stone lines and the microdosing. However, the sorghum yield was positively and significantly affected by the microdosing adoption, but the effect on net income was non-significant. The results demonstrate that adopting both techniques would be more effective, and this would let smallholder farmers improve their sorghum yield and income. The study recommends intensifying efforts to promote the use of both technologies simultaneously, educating smallholder farmers on the proper use of microdosing, and encouraging fertilizer subsidies for smallholder farmers in order to farm yield and maintain food security.

Keyword: stone lines, microdosing, sorghum yield, adoption, Burkina Faso

1. Introduction

1.1 Background and Purpose

Land degradation in Burkina Faso leads to a decrease in the amount of agricultural land and the availability of food, which tends to raise the prevalence of food insecurity (FAO, 2021). Furthermore, Bationo et al. (2018) revealed that a huge proportion of smallholder farmers suffer chronic food insecurity in combination to consistently low and irregular crop yields and incomes. In Burkina Faso, more than 60% of people rely on agriculture for food and income. Food insecurity and poverty are mostly caused by low productivity, related to rainfed farming, low yield enhancing inputs, and the preponderance of subsistence farming (Norton et al., 2014). Asfaw and Neka (2017), Kumar et al. (2021), and Mondal et al. (2018) demonstrated the soil and water conservation (SWC) structures significantly reduce soil erosion while improving crop yield. However, some studies have further investigated the benefits of optimizing fertility through microdosing on crop yields (Marenya et al., 2020; Ouedraogo et al., 2021; Timilsena et al., 2015; Traore et al., 2019). In addition, Kassie et al. (2011), Manda et al. (2016), and Zeeshan et al. (2021) showed that fertilizer management significantly improves household income. Then, Mujeyi et al. (2021), Setsoafia et al. (2022), and Sileshi et al. (2019)

demonstrated the positive effect of fertilizer management on smallholders' food security. Studies by Mujeyi et al. (2021), Setsoafia et al. (2022), and Sileshi et al. (2019) have shown that the adoption of the SWC structure significantly contributes to improving agricultural productivity and household welfare.

Additionally, sustainable land management projects in Burkina Faso have assisted smallholder farmers enhance their agricultural productivity by subsidizing them in the construction and innovation of stone lines in Burkina Faso. In order restore degraded soil in the farming crop field for sorghum, millet, and maize, these projects have encouraged smallholder farmers to actively promote the adoption of stone lines structure. Stone lines improve the physical structure of the soil by bringing in the passage and mineral elements of the soil and obstruct rainwater flow. Most of these programs, which involved significant financial investment from the Burkinabe government and its partners, were carried out between 2009 and 2017 to restore degraded lands (MAAH & KFW, 2020). In the Central and North Regions of Burkina Faso, these initiatives were mainly implemented on extremely degraded soils. In contrast, a few projects of the Burkinabe Ministry of Agriculture have developed and promoted the promotion of fertilization by using microdosing to solve this issue of land degradation.

In order to understand the concept of stone lines and microdosing fertilizer, a basic definition is provided by some authors. "In high-rainfall areas, stone lines can reduce runoff and have become popular among West African farmers for reducing erosion, collecting runoff water, and improving water use efficiency on farmlands" (Partey et al., 2018). According to Zougmoré et al. (2014), the stone lines are efficient ways to increase soil water content through runoff control when water is scarce. Hayashi et al. (2008) and ICRISAT (2009) define "the fertilizer microdosing or "micro-fertilization" as an application that consists of the application of a small quantity of mineral fertilizer together with seeds of the target crop in the planting hole at sowing or 2-4 weeks after sowing". The recommended amount of fertilizer that smallholder farmers should apply per hectare is significantly reduced by micro-dosing, going from 200 to 20 kg per hectare in the case of di-ammonium phosphate (Hayashi et al., 2008). In terms of the connection between both practices, Zougmoré et al. (2014) highlighted that combining stone lines with organic fertilizers boost their effectiveness. However, several technologies and technology combinations are widely used and promoted in order to improve the agricultural output and resilience of smallholder farmers to land degradation. Most of these technologies have been put through testing in greenhouses and experimental trials.

Previous studies by MAAH and KFW (2020) have evaluated the benefits of stone lines and were not clear enough and relevant to eliminate self-selection bias of adoption. Moreover, very few studies pointed out the interaction between the technology considered in this study: stone lines and microdosing. None of the studies (Ouedraogo & Sawadogo, 2001; Ouedraogo & Tiganadaba, 2015; Ouedraogo et al., 2020) have considered sample selection bias in order to assess accurated effect of stone lines and microdosing. We have element to believe that adoption of technology, such as stone lines and microdosing, is not random; farmers might make decision based on socioeconomic characteristics that are both observable and unobservable. This study wants to contribute to assessing adoption of technology taking into account the self-selection bias: otherwise, it might have an adverse effect on accuracy.

This study pretends to contribute to general knowledge the benefits that result from combining local technology such as stone lines and microdosing. We believe that productivity can be improved when these two different technologies are combined. Through this research, we want to evaluate the effect of microdosing adoption and the distribution of stone lines under the geographic and socioeconomic conditions in Burkina Faso. The results could provide theoretical and empirical support for policymakers in sustainable land management in Burkina Faso and give light on how effectively available technology in this region in West-Africa can be used together.

2. Materials and Methods

2.1 Sampling Procedures

This study was conducted in Plateau Central and North Regions (Passore and Oubritenga) of Burkina Faso. The annual average rainfall (600-900 mm) is still lower than in other areas. The rainy season only lasts three brief months in this region of Burkina Faso, with the heaviest rains falling in August. This area shown a highest population density (> 250 inhabitants/per square kilometer). In comparison to other areas, the yields of the cereal crops are also moderate (1 ton per hectare). At an average of 1,068.30 km^2 (6.51%), land degradation levels have been at their highest.

The power test (Note 1) was employed to justify sample size which performed by Yamane (2022) and experimented by Martey and Kuwornu (2021) using the formula: $n = N/[1 + N(e)^2]$, where, n denotes sample size, and e represents the sample's margin of error. N indicates number of farmers in the two regions, *i.e.*, 2,700,729, consisting of 1,722,115 from the North Region and 978,614 from the Plateau Central Region (Ministry of

Economy of Finance and Planning [MEFP], 2022). Using this test, we obtained more than 95% confidence (less than 5% margin error) when the sample was at least 400, and we decided to sample 420 farmers.

This study used data from a survey of 420 rural farmers in nine communes (Absouya, Loumbila, Dapeoloo, Zitenga, Ziniaré, Ourgou-Menaga, Bokin, Arbollé, and Kirsi) during the 2020-2021 cropping season. The survey was conducted from November 2021 to March 2022 using a multi-stage sampling technique. Nine communes were purposefully selected from two regions (northern and Plateau central) based on the adoption rate of SWC practices, soil degradation level, demography, and productivity. In the second stage, 18 villages were randomly selected, with six in the North and 12 in the Plateau Central Region, based on their high vulnerability to drought shock and low resilience to climate change adaptation. From the last stage, 20 smallholder farmers in the Plateau Central and 30 in the North Region were randomly chosen from the selected villages through government extension projects support. After that, 468 sorghum plots were found to have stone lines and microdosing adoption in the entire sample. From this, we obtained four different types of farm plots: 137 plots without the use of stone lines or microdosing (S_0M_0), 80 plots with stone lines (S_1M_0), 75 plots with microdosing fertilizer (S_0M_1), and 176 plots with both stone lines and microdosing fertilizer (S_1M_1).

A questionnaire was used to conduct interviews with all households, gathering data on the socioeconomic aspects of the farm, land use, food production, sustainable land management, farm equipment, chemical and organic fertilizers, credit availability, farm income, extension services, and food expenditure. The data on each household's production was checked and corrected using the records of national agricultural and research institutes, local organizations, and extension agents from NGOs. In order to evaluate the validity of the questionnaire and the logic and coherence of the questions, a pilot survey was conducted. Following the pilot survey, the questionnaire was modified to make it more accurate for the actual test. Before and after the pilot survey, the interviewers and supervisors received training to become proficient with the field components and questionnaire tools.

2.2 Econometric and Conceptual Framework

In order to illustrate the technical approach of technology packages more clearly in the framework of multiple technology adoptions, we adapted the conceptual analysis provided forward by Teklewold et al. (2013). This framework offered the advantage of evaluating alternative combinations of practices and individual practices. Farmers adopted sustainable land management technologies such as stone lines, microdosing, or a combination of both to address climate change and land degradation issues. We obtained four technological package alternatives (S_0M_0, S_1M_0, S_0M_1, and S_1M_1) displayed on Table 1. Each package adopted was based on the satisfaction of welfare provided by each technology option, due to the constraints of farmers budget and technical knowledge.

Then, we modeled those four technology packages and the outcome variables (sorghum yield and sorghum net income per hectare) in a multinomial endogenous switching regression (MESR) framework. From propensity score matching (PSM) approach, effect estimations were mainly determined by comparing similar variables (area, slope, soil type, soil fertility, and amount of animal manure applied) among plots adopting the different packages. According to Teklewold et al. (2013), this approach can be more appropriate for controlled experiments but not for empirical analysis using observational data due to self-selection. In order to avoid any biased effects from adoption influencing unobservable characteristics (*e.g.*, expectation of return gain from adoption, management skills, and motivation), we used an estimation method with a correction.

For that, we used a multinomial approach to the MESR treatment effect proposed by Dubin and McFadden (1984) (referred to as the D.M. model) and Bourguignon et al. (2007) to correct any selection bias from the model. The approach also considered self-selection bias and interactions between alternative packages, as mentioned by Zeweld et al. (2020).

From the estimation, in the first step, packages were modeled using a multinomial logit selection model while recognizing the interrelationships between packages. Using ordinary least squares (OLS) and a selectivity adjustment, the effects of each package on the outcome variables were evaluated in the second stage of estimation. We also employed the doubly robust estimator, inverse probability weighted regression adjustment (IPWRA), in the context of the propensity score framework in order to make an accurate effect of each package on the outcome variables. According to Danso-Abbeam and Baiyegunhi (2018), as a result of misspecification in propensity score models, IPWRA is a trustworthy countermeasure to potentially biased estimates (PBEs). According to Wooldridge (2010), IPWRA estimates would be accurate even if the treatment or result were incorrect, but not both. Due to IPWRA's dual robustness property, which enables treatment/outcome models to handle misspecification, consistent results can be ensured (Danso-Abbeam & Baiyegunhi, 2018).

2.2.1 Description of Agricultural Packages on Stone Lines and Fertilizer Microdosing

Table 1 tends to describe the different technological packages adopted by smallholder farmers. A definition, role, and function describe each package. This makes it easy to understand the importance and value of each choice that farmers adopt.

Table 1. Agricultural packages and their definition

Package	Definition	Description	Role /Function
S_0M_0	Non-adoption	No technological packages	Control
S_1M_0 (Bationo et al., 2018; Ouedraogo et al., 2018)	Stone lines practices	Construction of stones grouped in the shape of lines and placed in famers plot	i) Slow down runoff, slows down soil erosion and water erosion, maintaining soil humidity. ii) Strengthens the geophysical structure of the soil by preventing the movement of soil and its nutrients.
S_0M_1 (Sanogo et al., 2020; Traore et al., 2019)	Microdosing practices	To put a small amount of chemicals on sowing with seeds or without for optimizing fertilizer	i) Improve soil fertility and increase plant productivity. ii) Optimize the use of fertilizer by providing the plant with the minimum nutritional needs.
S_1M_1 (Korodjouma et al., 2017; Ouedraogo et al., 2018; Traoré et al., 2020)	Combination of stone lines and microdosing	Both techniques consist of gathering the effectiveness of using stone lines and microdosing	i) The same role observed on S_1M_0 and S_0M_1. ii) Improve yield more due to both techniques' adoption synergy.

2.2.2 Multinomial Adoption Selection Model

We assume that farmers choose the package that gives them the highest net benefit. This means comparing the net benefit of adopting package *k* with net benefit of using traditional methods. This comparison can be explained by $U_{ik} > U_{im}; m \neq k$ or equivalent $\Delta U_{im} = U_{ik} - U_{im} > 0; m \neq k$. As a result, the index function of package adoption:

$$U_{ik}^{*} = \varphi_k Z_i + \delta_{ik} \tag{1}$$

where, U_{ik}^{*} is a latent variable that shows the predicted net benefit of adopting the package k, φ_k is the coefficient of observed covariates, Z_i represents observed covariates (such as socioeconomic, biophysical characteristics among others) and δ_{ik} is an error term accounting for unobserved characteristics.

Let *J* be an index to represent the farmer's preference package, as follows:

$$J = \begin{cases} 1 \text{ if } U_{i1}^{*} > \max(U_{im}) \text{ or } \eta_{i1} < 0 \\ \qquad \text{for all } m \neq k \\ K \text{ if } U_{ik}^{*} > \max(U_{im}) \text{ or } \eta_{i1} < 0 \end{cases} \tag{2}$$

The index J in Equation 2 means that a sorghum farmer will adopt package k when the benefit U of using the package indicates greater expected benefit compared to benefit from the package m. According to Bourguignon et al. (2007) the benefit can be found when $\eta_{i1} < 0$.

We assumed that the error term (δ_{ik}) has an identical and Gumbel distribution (Bourguignon et al., 2007). The probability that i^{th} sorghum farmer would adopt package k can be expressed by a multinomial logit model (Note 2) according to McFadden (1973):

$$P_{ik} = \Pr(\eta_{ik} < 0/Z_i) = \frac{\exp(Z_i\beta_k)}{\sum_{m=1}^{k}\exp(Z_i\beta_m)} \tag{3}$$

The maximum likelihood function is used to estimate the parameters of the latent variable.

2.2.3 Multinomial Endogenous Switching Regression (MESR)

We used multinomial endogenous switching regression to address the bias selection and determine the relationship between the outcome variables (sorghum yield and net income) and set of covariables for the selected options. The base category, non-adoption of stone lines and microdosing (S_0M_0), is represented $k = 1$ while the remaining combination options are by $k = 2, 3$ and 4 where at least one option is adopted. The outcome equation for each possible regime is specified as follows:

$$\begin{cases} \text{regime 1: } Y_{i1} = \beta_1 X_i + \varepsilon_{i1} \text{ if } J = 1 \\ \text{regime k: } Y_{ik} = \beta_k X_i + \varepsilon_{ik} \text{ if } J = k \end{cases} \tag{4}$$

where, the terms X_i are vectors of exogenous covariates, the terms β_i are vectors of parameters; and the terms ε_{i1} and ε_{ik} are indicators of random disturbance. The distributions for the error terms $E(\varepsilon_{ik}/Z, X) = 0$ and variances $(\varepsilon_{ik}/Z, X) = \sigma_k^2$. $Y'_{ik}s$ are the outcome indicators for an i^{th} sorghum farmer in regime k. In this case, Y_{ik} is observed if and only if package k is adopted, where, $U_{ik}^* > \max_{m\neq k}(U_{im}^*)$. The D.M. model's linearity assumption can be expressed as follows:

$$E(\delta_{ik}/\varepsilon_{i1}, \ldots \varepsilon_{ik}) = \sigma_k \sum_{m\neq k}^{k} r_k [\varepsilon_{im} - E(\varepsilon_{im})] \quad (5)$$

where, $\sum_{m=1}^{j} r_k = 0$, by its performance, the correlation r_k between the two error terms δ and ε add up to zero. Thus, assuming this assumption is accurate, the multinomial endogenous switching regression can be written as follows:

$$\begin{cases} \text{regime 1: } Y_{i1} = \beta_1 X_1 + \sigma_1\lambda_1 + \varphi_{i1} \text{ if } J = 1 \\ \text{regime k: } Y_{ik} = \beta_k X_k + \sigma_k\lambda_k + \varphi_{ki} \text{ if } J = k \end{cases} \quad (6)$$

where, σ_j denotes covariance between the error terms δ of Equation 1 and ε of Equation 4; λ_k is the inverse Mills ratio (IMR) calculated from the multinomial logit model in Equation 2. The IMR (λ_k) is given as:

$$\lambda_k = \sum_{m\neq k}^{k} \rho_k \left[\frac{\hat{P}_{im} \ln(\hat{P}_{im})}{1 - \hat{P}_{im}} + \ln(\hat{P}_{ik})\right] \quad (7)$$

where, ρ_k defines the correlation coefficient of the three error terms, δ; ε and φ. The error terms have expected zero value. There is a possibility of heteroscedasticity in generating the regressor (λ_k) for the inverse Mills ratio. This was accounted for using standard bootstrap errors.

2.2.4 Estimation of Average Treatment Effect on the Treated (ATT)

The MESR presented above was used to estimate ATT. The effects of stone lines and microdosing on sorghum yield and net income were assessed by comparing the expected outcomes of adopters (Equation 8) with the hypothetical counterfactual case, which assumes that farmers did not adopt (Equation 9).

$$E(Y_{ik}/j{=}k) = \beta_2 X_{ki} + \sigma_k\lambda_k \quad (8)$$

$$E(Y_{i1}/j{=}k) = \beta_1 X_{ki} + \sigma_1\lambda_K \quad (9)$$

To calculate ATT, this study estimates the expected change in the mean outcome variables by Equation 10.

$$ATT = E(Y_{ik}/j{=}k) - E(Y_{i1}/j{=}k) = X_{ik}(\beta_k - \beta_1) + \lambda_1(\sigma_k - \sigma_1) \quad (10)$$

2.2.3 Estimation of Average Treatment Effect (ATE)

An approach similar to that used for ATT estimation can be used to estimate the average treatment effect (ATE).

$$ATE = E(Y_{ipk}/j{=}k) - E(Y_{ip1}/j{=}k) = X_{ipk}(\beta_k - \beta_1) + \lambda_{ipk}(\sigma_k - \sigma_1) \quad (11)$$

The second term (λ_1) in Equation 10 and the term λ_{ipk} in Equation 11 correct the selection bias and endogeneity from unobserved variables (Khonje et al., 2018).

3. Results and Discussion

3.1 Descriptive Statistics

Table 2 shows the summary statistics for all the variables included in the multinomial endogenous switching regression model. The results indicate that S_1M_1 has the highest yield with 1435.7 kg/ha and has the highest net income with 207,186.5 F.CFA (West African Financial Community franc) per hectare. In terms of agricultural output and net revenue, technology combination S_1M_1 seems to be the most effective. Regarding the number of extension visits, S_1M_1 adopters received more visits than other adopters, according to our data. In terms of female-headed households, S_0M_0 has the greatest proportion of households with a female household manager. It means they appear to be reluctant to adopt new technologies such as stone lines and microdosing. In terms of plot size, S_0M_0 has the smallest area of farmland. The most intriguing finding suggests that the larger the plot size, the more likely S_1M_1, S_1M_0, and S_0M_1 are to adopt new technologies, such as stone lines or microdosing, compared to S_0M_0.

Regarding land ownership, a significant percentage of S_0M_0 members own less land that is used for farming. These findings are consistent with Chianu et al. (2011), who state that the land owned by a household is a crucial driver in the adoption of agricultural technology. This is because farmers with larger farms are more likely to invest in farming technologies than their neighbors with smaller farms. Concerning off-farm income, we can notice that S_0M_0 participates in fewer activities that generate income. Several non-adopters provided an explanation of how this situation is frequently related to a lack of time and the availability of less opportunities to find additional activities generating revenue.

In terms of hired labor, both techniques may employ additional labor in the technology's application, which may be explained by the fact that both the stone lines and microdosing applications require a lot of labor. Considering the amount of fertilizer applied, we also noticed that S_1M_1 used the most chemical fertilizer, averaging 72 kg/ha. This amount of fertilizer applied was similar to the optimal amount recommended (62.5 kg/ha) by Ouedraogo et al. (2018), which is the optimal amount for boosting sorghum yield. Regarding the amount of organic fertilizer, S_1M_1 applied 742.7 kg/ha of compost, which satisfied the recommended amount of organic fertilizer (about 600 kg/ha) suggested by extension services.

Regarding subsidy access, S_1M_1 has the largest beneficiaries of improved seeds and chemical fertilizer. In addition, the tropical livestock unit (TLU) is highest for S_1M_1 with 58.2% which uses more animals for farm work. Owning cattle is beneficial for providing organic fertilizers and compost, improving soil fertility. That is consistent with Wawire et al. (2021) that illustrates livestock quantity had a bearing on manure use. This implies that cattle are a driving force and an engine of agricultural labour, necessary for planting, plowing, harvesting, and transporting cereals.

Table 2. Brief statistical analysis of the variables utilized in the study

Variables	Description	Average values for agricultural practices				
		S_0M_0	S_1M_0	S_0M_1	S_1M_1	Pooled sample
Sorghum yield	Yield in kg per hectare	823.1	1238.4	1011.5	1435.7	1154.6
Sorghum net income	Total gross production minus costs in F.CFA	128,226.4	180,854.4	139,836.8	207,186.5	168,777.7
Number of extension visits	Total number of Extension visits in 2020	0.08	1.84	0.36	2.62	1.39
Age of household head	Number of years	48.8	47.3	48.5	50.2	49.1
Female-headed household	If househead is a female	0.25	0.11	0.07	0.05	0.12
Education	Number of years in school	1.54	2.35	2.13	1.41	1.73
Household size	Number of persons	8.9	12.6	10.9	12.3	11.1
Land ownership	Dummy, yes = 1, 0 otherwise	0.60	0.70	0.93	0.86	0.77
Off-farm income	Dummy, yes = 1, 0 otherwise	0.52	0.76	0.67	0.76	0.67
Hired labour	Dummy, yes = 1, 0 otherwise	0.23	0.20	0.29	0.30	0.26
Plot size	Sorghum plot in ha	1.19	1.42	1.38	1.64	1.43
TLU per hectare	Index of TLU per hectare	0.28	1.20	0.49	0.58	0.59
Farm credit	Dummy, yes = 1, 0 otherwise	0.10	0.04	0.04	0.08	0.07
Amount of oxen plouwing	Draft power per plot (oxen days/ha)	6.26	31.79	8.23	12.36	13.23
Total number of trainings	Total number of trainings	0.06	1.81	0.32	2.24	1.22
Improved seeds	If received improved seeds	0.35	0.56	0.36	0.55	0.47
Access to subsidies	Dummy, yes = 1, 0 otherwise	0.01	0.45	0.08	0.61	0.32
Years of SWC adoption	Duration of SWC practices per plot	1.03	5.12	4.21	5.91	4.08
Amount of fertilizer	Amount of fertilizer NPK per plot (kg/ha)	21.49	35.18	62.53	72.95	49.76
Amount of fertilizer compost	Amount of fertilizer compost per plot (kg/ha)	26.90	358.58	205.76	742.78	381.48
Organic manure	Dummy, yes = 1, 0 otherwise	0.36	0.54	0.68	0.45	0.47
Flat ground	If plot is flat	0.49	0.26	0.41	0.31	0.37
August rainfall	Total August rainfall in 2020	266.27	261.25	251.12	257.58	259.71
Sandy loam	If soil is sandy loam	0.13	0.45	0.13	0.27	0.24
Sandy clay	If soil is sandy clay	0.24	0.29	0.28	0.32	0.29
Gravelly	If soil is gravelly	0.50	0.35	0.29	0.27	0.35
Perception of soil fertility	The main plot perceived as being fertile	0.13	0.85	0.29	0.90	0.57
Perception of SWC practices	SWC perceived as being improved	0.12	0.85	0.37	0.92	0.59
Distance to extension office	From plot to the extension office (km)	8.22	9.76	6.52	10.88	9.21
Number of observations		137	80	75	176	468

3.2 Determinants of Stone Lines and Microdosing Adoptions

We estimated the marginal effect of the variables affecting each adoption choice to assess the significance of each determinant and their probability of adopting each technology package category.

The determinant of the total number of visits has a significant and positive effect on S_1M_1. Farmers with more extension visits are especially likely to adopt stone lines and microdosing. The primary sources of knowledge for improved agricultural technologies are agricultural extension services. According to Beshir et al. (2012), most farmers get knowledge about new technology by getting in touch with the extension agent. Moreover, Zeweld et al. (2020) reported farmers who have frequent contact with extension agents are more likely to adopt alternative agricultural practices, either separately or jointly, because extension agents are expected to provide information to reduce uncertainty and improve awareness.

Household size has a significant and negative effect on S_0M_1, but it shows significant and positive effects on S_1M_0 and S_1M_1, indicating farmers with more family sizes are more likely to adopt stone lines practices. Families are a crucial supply of labor for farming operations and the construction of land management techniques. For instance, Miheretu and Yimer (2017) reported that household size seems to be positively and significantly affecting the adoption of soil lines and chemical fertilizer because the number of adults on the farm is a force of agricultural labor. Households with a larger size are more likely to adopt these sustainable land management technologies. Therefore, adopting these technologies requires a very high labor input and household size, as the adoption of these technologies remains very labor-intensive.

Land ownership has significant and positive effects on S_1M_0 and S_0M_1. Farmers who own land seem more likely to adopt stone lines and microdosing. It has been shown that land security is an essential factor affecting farmers' decisions to innovate and adopt technological practices. According to Amsalu and de Graaff (2007) and Bewket (2007), land users must have safe property ownership rights over the areas they utilize to invest in conservation efforts to gain long-term benefits. Farm Credit has a significant and positive effect on S_1M_1, suggesting that having access to farm credit may be more opportunity to adopt stone lines and microdosing. Credit availability is essential for farmers to purchase improved technologies and solve financial constraints. Kumar et al. (2021) and Yirga (2007) demonstrated that farm credit was highly correlated with adopting stone lines and chemical fertilizers. Households with access to a financing mechanism for agricultural inputs and equipment are more likely to adopt the new technologies. Credit makes it easier for smallholder farmers to access chemical fertilizers, and it seems essential to make them more motivated to adopt stone lines and microdosing.

Improved seeds have a significant and positive effect on both S_1M_0 and S_0M_1. This implies that farmers using improved seeds are more likely to adopt microdosing and stone lines. Ouedraogo and Tiganadaba (2015) and Sanogo et al. (2020) reported that the use of improved seeds contributes to improving grain productivity, and their use associated with the adoption of stone lines or microdosing remains more effective and contributes more to enhancing crop yield.

The amount of NPK and compost have a significant and positive effect for all three categories of adopters, suggesting that farmers who apply both chemical and organic fertilizers are more likely to adopt the stone lines, microdosing, and both combinations. Both chemical and organic fertilizers remain very important and influential in adopting the stone lines structure. These results remain consistent with the findings of Ouedraogo et al. (2018) and Traoré et al. (2020b), and Zougmoré et al. (2010), which showed that the joint use of organic fertilizers with the structure of the stone lines contribute to strengthen the devices and reinforce the soil structure.

The perception of soil fertility shows a significant and positive effect on S_1M_0 and S_0M_1. This implies that smallholders with a sense of perceived soil fertility are more likely to adopt the stone lines and microdosing. The findings are in line with Amadu et al. (2021) and Etsay et al. (2019), where the perception of fertility has a more significant influence on adopters' belief in the beneficial effects of adoption and a tendency to adopt the SWC structure more.

Table 3. The marginal effect of adoption of stone lines and microdosing (baseline is non-adopters S_0M_0)

Variables	Stones lines (S_1M_0)	Microdosing (S_0M_1)	Both techniques (S_1M_1)
Number of extension visits	-0.0078 (0.0119)	-0.0024 (0.0229)	0.0371*** (0.0113)
Age of household head	-0.0018 (0.0015)	0.0003 (0.0015)	0.0022 (0.0015)
Female-headed household	0.0488 (0.0529)	-0.0342 (0.0649)	0.0202 (0.0584)
Education	0.0162** (0.0065)	0.0064 (0.0064)	0.0151** (0.0069)
Household size	0.0081*** (0.0029)	-0.0028 (0.0031)	0.0057** (0.0028)
Land ownership	0.0888** (0.0414)	0.1458*** (0.0511)	0.0169 (0.0399)
Off-farm income	-0.0285 (0.0414)	0.0262 (0.0430)	0.0397 (0.0409)
Hired labour	-0.0492 (0.0392)	0.0939** (0.0382)	-0.0305 (0.0371)
Plot size	-0.0083 (0.0180)	0.0028 (0.0165)	0.0400** (0.0178)
TLU per hectare	0.0335*** (0.0095)	-0.0006 (0.0171)	0.0319*** (0.0114)
Farm credit	-0.0949 (0.0938)	-0.0884 (0.0927)	0.1350** (0.0633)
Improved seeds	0.1076*** (0.0388)	0.1120*** (0.0355)	0.0263 (0.0394)
Access to subsidies	0.0574 (0.0424)	-0.0291 (0.0716)	0.1036** (0.0405)
Years of SWC adoption	0.0027 (0.0041)	0.0073* (0.0039)	-0.0018 (0.0034)
Amount of NPK fertilizer	0.0026*** (0.0005)	0.0020*** (0.0004)	0.0022*** (0.0003)
Amount of compost	0.0001** (0.0001)	0.0002** (0.0001)	0.0001** (0.0001)
Flat plot	0.0747** (0.0360)	0.0342 (0.0345)	0.0205 (0.0358)
Rainfall August 2020	0.0029** (0.0014)	0.0040*** (0.0012)	0.0057*** (0.0015)
Sandy loam	0.1623*** (0.0334)	0.1393*** (0.0372)	0.0392 (0.0322)
Sandy clay	-0.0693 (0.0468)	-0.0128 (0.0423)	0.0333 (0.0412)
Gravelly	0.0383 (0.0348)	0.0012 (0.0367)	-0.0412 (0.0361)
Perception of soil fertility	0.2153** (0.1015)	0.2263*** (0.0597)	-0.0367 (0.0686)
Perception of SWC practices	-0.0722 (0.1027)	0.0023 (0.0625)	0.1560** (0.0722)
Number of observations	465	465	465

Note. robust standard error in parentheses, the significance levels of 10%, 5%, and 1% are denoted by the symbols *, **, and ***, respectively.

3.3 Impact Assessment on Sorghum Yield and Sorghum Net Income

The effect of sorghum yield and net income were estimated by the multinomial endogenous switching regression, which corrects for selection bias in order to have accurate and relevant estimators. The inverse probability weighted regression adjustment (IPWRA), which has a double robustness attribute, was used to strengthen these analyses. We estimate both ATT and ATE to boost the accuracy of the evaluation of the effects on outcome. The average treatment effect (ATE), as defined by Zakari et al. (2022), measures the average influence of a technology on the total population. It also indicates the expected effect on a person selected at random from the population. The average effect of an innovation on the subpopulation of the treated is determined by the average treatment effect on the treated (ATT). It also depicts the anticipated effect on a random selection person within in the treated population.

Table 4 shows the effect of each adoption category on sorghum yield and net income. We note that the overall effects remain significant and positive for all categories of adopters. Regarding sorghum yield, the average treatment of treated (ATT) is higher for S_1M_1 with an average gain of 598.6 kg/ha, which was 70% more compared to S_0M_0. This finding is in line with Ouedraogo et al. (2020), which showed that combining stone lines and microdosing is beneficial in increasing crop yield. Another important yield was observed on S_1M_0 (378.2 kg/ha), which was 45% better compared to S_0M_0. The adopters S_0M_1 have the lowest yield with 150.5 kg/ha and an increase of 18%.

Regarding net sorghum income, the ATT estimators are significant and positive for S_1M_1 and S_1M_0. Both stone lines and microdosing adopters S_1M_1 have the highest average net income, with an increase of 78,477 F.CFA/ha by 60%. The stone lines adopters S_1M_0 take second place in net income generated with 47,435.1 F.CFA/ha, with an increase of 36%. However, the microdosing adopters S_0M_1 show positive but insignificant ATT. It's possible that alone adopting microdosing offers less net income advantage than alternative combinations, which could support this. For the average treatment effect in population (ATE), we find that S_1M_1 has the highest yield with

596.8 kg/ha and an increase of 69%. As described earlier in Table 2, adopters of the S_1M_1 combination use an optimal amount of NPK chemical fertilizer and organic fertilizer recommended by extension services. Also, the adopters seem to have better access to input subsidies (see Table 2), and higher cattle ownership provides agricultural strength and reduces labor intensity. We also found that the average amount of NPK applied by S_1M_1 were close to the amount of chemical fertilizer recommended for microdosing by the research extension services of INERA (National Institute for Agricultural Research and Environment), and that reflects the fact that the optimal amount of applied fertilizer improves production and yields. When applied optimally, fertilizers are more efficient in reducing production costs and tend to raise smallholder farmers' net income. That ought to make them more economically viable and sustainable. This effect pointed out by the research of Zougmoré et al. (2010), which showed that adopting SWC, such as stone lines integrated with microdosing techniques, can improve smallholder sorghum yields.

Table 4. MESR effect estimate of stone lines and microdosing adoption using IPWRA

Outcome variable	Choice	ATT				ATE			
		Coef.	Std.Err	Z-value	Change	Coef.	Std.Err	Z-value	Change
Yield (kg/ha)	S_1M_0	378.2***	77.7	4.8	45%	379.1***	79.4	4.8	44%
	S_0M_1	150.5**	64.6	2.3	18%	131.1**	67.0	1.9	15%
	S_1M_1	598.6**	61.0	9.8	70%	596.8***	66.9	8.9	69%
Net income (F.CFA/ha)	S_1M_0	47,435.1***	13,673.5	3.4	36%	47,482.8***	13,830.1	3.4	36%
	S_0M_1	6,804.1	11,040.8	0.6	5%	3,329.8	11,626.8	0.3	2%
	S_1M_1	78,477.0**	10,714.6	7.3	60%	78,867.6***	11,775.4	6.8	59%

Note. ATT: estimate average treatment effect on the treated; ATE: estimate average treatment effect in population; Coef: coefficient, Std.Err: standard error; the significance levels of 10%, 5%, and 1% are denoted by the symbols *, **, and ***, respectively.

Cost-benefit analysis can show that new technology has a higher return on investment. This helps us understand the benefits of each technology better. We can use this study to evaluate the financial feasibility of different and show farm organizations which ones can increase their income, reduce land degradation, and have a good return on investment. For sorghum prices, we obtained the average annual prices from National Company for the Management of Food Security Stocks in Burkina Faso (SONAGESS), a state agency that collects and publishes cereal prices. The prices vary and are sensitive to small annual fluctuations. We considered only the direct cost to estimate the cost-benefit ratio in cross-sectional analysis data. The directs costs included all the prices of inputs such as fertilizer, improved seed, pesticides, hired labor, oxen plowing and weeding. The directs costs are all the prices of inputs such as fertilizer cost, improved seed costs, hired labor cost, oxen plowing costs. Table 5 shows a cost-benefit analysis that helped us evaluate how stone lines and microdosing improved the income and well-being of small farmers. Among all the categories, S_0M_0 has the lowest cost-benefit ratio (1.69). This can explain why, as fewer farmers adopt stone lines or microdosing, they improve their crop yield and net income. In addition, S_1M_1 showed the highest cost-benefit ratio (3.03). It implies that for each 100 F.CFA spent or invested on stone lines and microdosing adoption; farmers can gain 303 F.CFA on their income per hectare. This interesting finding illustrates that adopting stone lines and fertilizer microdosing remains more efficient and beneficial in terms of net income. To face land degradation, using stone lines and microdosing should be a better way to enhance soil fertility and improve net farm income.

Table 5. Cost-benefit analysis of stone lines and microdosing adoption for sorghum production (expressed in) F.CFA/ha)

	S_0M_0 (137)	S_1M_0 (80)	S_0M_1 (75)	S_1M_1 (176)
A. Yield (kg/ha)	829.69	1,241.16	1,011.54	1,435.72
B. Gross Production	144,365.69	215,961.14	176,007.09	249,815.11
C. Total production cost	53,691.41	74,236.41	61,855.77	61,966.78
D. Net value benefit (B-C)	90,674.28	141,724.73	114,151.32	187,848.33
E. Cost-benefit ratio (D/C)	1.69	1.91	1.85	3.03
F. Return on investment	168.9%	190.9%	184.5%	303.1%

Table 6 also shows the quartile distribution of S_0M_0, S_1M_0, S_0M_1, and S_1M_1 adopters. Among the quartiles, the third quartile indicates that S_1M_1 adopters have a higher average yield (1,807.3 kg/ha) than all other adopters. In the first quartile, S_1M_1 adopters also reported a higher sorghum yield of 943kg/ha among all adopted technologies. In the second quartile, adopters of the stone lines and microdosing combination also show high sorghum yields (1338 kg/ha), and these yields remained higher than non-adopters. Inter-quartile analysis shows that S_1M_1 has a high average yield of 864.3 kg/ha, followed by microdosing adopters with 803.6 kg/ha. Adopters in the top quartile (75%) report higher yields than the adoption distribution's first and second quartiles. The best sorghum yields are concentrated and held by most adopters regardless of the technology adopted, with the majority of 75% showing above average yields and better yields compared to the national average (907.8 kg/ha) and the S_0M_0 average. This indicates that most adopters of all three technologies are better able to benefit from the additional effects of adoption. Adopting new technologies remains effective and beneficial for most adopters, regardless of the technology adopted.

Table 6. Distributional summary statistics of sorghum yield (kg/ha) and sorghum net income (F.CFA/ha for stone lines, microdosing and combination between stone lines and microdosing

Outcome variables	Package	Mean	SD	First Quartile	Second Quartile	Third Quartile	Inter Quartile
Yield (kg/ha)	S_0M_0	823.1	391.2	575.3	763.3	1,002.3	425.3
	S_1M_0	1,238.4	620.5	795.8	1,038.0	1,526.9	731.1
	S_0M_1	1,011.5	489.5	625.0	839.6	1,428.6	803.6
	S_1M_1	1,435.7	594.8	943.0	1,338.0	1,807.3	864.3
Net income (F.CFA/ha)	S_0M_0	128,226.4	69,851.4	81,980.0	117,861.3	168,508.2	86,528.2
	S_1M_0	180,854.4	106,628.8	109,437.5	147,180.0	225,121.0	115,683.5
	S_0M_1	139,836.8	81,981.8	83,640.0	119,616.1	210,733.3	127,093.3
	S_1M_1	207,186.5	103,742.5	130,613.0	200,358.0	276,017.3	145,404.2

Note. SD: Standard deviation.

3. Conclusion

This paper evaluated the effect of stone lines, microdosing, and the synergistic relationship between stone lines and microdosing adoption. Sorghum yield and net sorghum income were used to assess agricultural productivity and smallholder welfare. A multinomial endogenous switching regression model was used to account for selection bias (unobserved variables) and understand the full effect of these actions on outcome variables.

Regarding the factors influencing the adoption of these different packages, the marginal effects show that households with a high number of extension visits were more likely to adopt the stone lines and microdosing in combination. Extension services are key factors in enabling households to have greater access to training, to master production techniques, to apply fertilizer optimally, and be in connection with information on the quality of inputs, information on market prices, and weather forecast information. This can prevent risks related to climatic variations, increase soil fertility, and avoid soil erosion. The results also indicated that households with access to improved seeds are more likely to adopt the combination of stone lines and microdosing. Improved seeds remain very useful and important for agricultural production. In the context of water scarcity, these seeds are highly adapted to water stress and short rainy season periods. Agricultural technologies incorporating improved seeds are actively adopted and promoted for agricultural productivity, and the fact that improved seeds also tend to adapt to harsh and arid soils, most of which are in continuous degradation.

Additionally, the findings revealed that households with access to subsidies are more likely to combine stone lines with microdosing. This demonstrates that the use of these technologies requires the availability of fertilizer. These subsidies benefit households that cannot purchase resources but adopt the stone lines and microdosing. Moreover, the quantity of NPK fertilizer and the amount of compost significantly influenced the adoption of these technology packages. This indicates that the availability of chemical and organic fertilizers is crucial for adopting these technologies. Combining chemical and organic fertilizers in adopting the stone lines and microdosing has the dual benefit of enriching the soil with organic matter and boosting agricultural productivity. The results of ATT show that the adopters of the combination of stone lines and microdosing have a sorghum yield indicating 598.6 kg/ha with an increase of 70% and the highest net sorghum income with 78,477.0 F.CFA /ha or a 60% increase. This suggests that there is a strong synergy in agricultural productivity between the stone lines and the microdosing. The combination provides a better boost to farm productivity and the net income of small households. On the other hand, the results of the microdosing ATT show a positive and significant effect on sorghum yield and a non-significant effect on net income. This suggests that the production costs of microdosing are very high in terms of labor, so the adoption of microdosing remains very labor-intensive.

At the end, we suggest some policy recommendations for both farmers and an extension program. The interesting findings showed that non-adopters are associated with low education, small plot size, lack of land tenure, and low off-farm income. For farmers who haven't adopted stone lines or microdosing yet, policymakers need to create a land tenure policy that encourages land owners to invest more in their land by using more stone lines and microdosing. Burkinabe extension services and NGOs need to put more financial support into long-term literacy education for adults and women because, according to the findings in our research. Non-adopters are also identified as having a very low income. A policy of training on off-farm income will greatly help non-adopters generate additional revenue. Considering the implications for the extension program, some strong actions need to be taken. First, adopting these technology combinations is known to be labor-intensive and requires investment in labor costs, especially for microdosing. It is critical to continue supporting sorghum farmers through training for optimal use of some resources to maximize productivity while minimizing agricultural costs. In addition, extension services could intensify support to producers through close follow-up of the applicability of technologies and through the supporting cooperatives or farm groups in the short term for a more efficient and complete application of technology packages. Finally, a policy is required for smallholder farmers who lack the resources to acquire resources for grain production. Moreover, some extension services, such as the National Institute for Research and the Environment, must motivate the subsidy scheme for production of improved seeds and compost.

Like other studies, this one had some moderate limitations, but they had no influence on the relevance of the results or the analysis. First, we used cross-sectional data, which didn't allow to visualize a dynamic assessment of the long-term effect. Secondly, producers estimated the entire production using measurement units which might overestimate or underestimate the real output. Third, we reported the amount of fertilizer applied by the farmer himself, but it was challenging to estimate the exact amount used on the plots depending on the type of chemical fertilizer. To account for this, we rely on the amounts of fertilizer purchased each season, assuming that farmers have applied all the fertilizer purchased as a result of the inadequate amount of fertilizer allowed to the plots.

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Notes

Note 1. The probability that the null hypothesis will be rejected in the event that it is false is the test's power (given that the alternative hypothesis is true). It is used to calculate the study's sample size (Martey & Kuwornu, 2021).

Note 2. For the Gumbel distribution, the cumulative distribution and density functions can read by respectively $G(\eta) = \exp(-e^{-\eta})$ and $g(\eta) = \exp(-\eta - e^{-\eta})$.