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Effects of infrastructure on the adoption of sustainable agricultural practices in sub-Saharan Africa

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Abstract

Adopting sustainable agricultural practices (SAPs) is critical for achieving circular agricultural systems (CAS) in sub-Saharan Africa, as these practices emphasize resource efficiency, waste reduction, and sustainable management of natural resources. Infrastructure, including irrigation and produce/product storage facilities, play a vital role in enabling the effective implementation of SAPs by improving resource use efficiency, reducing post-harvest losses, and supporting the recycling and reuse of agricultural inputs—key principles of CAS. However, investment in infrastructure by African governments remains low, raising concerns about its role in driving the adoption of SAPs and the necessary transformations for sustainable agricultural development. Using a panel dataset from sub-Saharan Africa and advanced econometric techniques—including a correlated random effect with a multivariate probit (CRE-MVP), a control function approach (CRE-CFA), and an ordered probit with endogenous treatment (CRE-OPRETRE) models—this study accounts for potential interrelationships between SAPs and endogeneity due to observed and unobserved heterogeneity. The analysis examines the effects of irrigation and produce/product storage infrastructure on the adoption and extent of adoption of SAPs. The results reveal that, in addition to influencing the decision to adopt SAPs, each type of infrastructure significantly increases the proportion of households adopting SAPs at higher levels. These findings underscore the importance of investing in production and post-production infrastructure to promote SAPs, aligning with CAS principles by fostering sustainable resource use, enhancing resilience, and minimizing environmental impact.

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Introduction

Improving smallholder adoption of sustainable agricultural practices (SAPs) is crucial for development in Africa. This is because SAPs are not only environmentally friendly but economically beneficial to society[1] (SAPs include conservation tillage, legume intercropping, legume crop rotations, improved crop varieties, the use of animal manure, the complementary use of inorganic fertilizers, soil, and stone bunds for soil and water conservation among others[2]). For these reasons, several packages of SAPs are largely promoted by many governments and researchers in sub-Saharan Africa[1−3]. However, despite the benefits of SAPs and the efforts of government and researchers to promote take-up among households, the adoption rate is still very low[1].

Physical infrastructure offers a potential solution to the low adoption rate because it can enhance the adoption of SAPs[4,5]. Infrastructure plays a pivotal role in fostering the adoption of sustainable agricultural practices (SAPs), which are foundational to circular agricultural systems (CAS). CAS emphasizes resource efficiency, waste reduction, and the recycling of agricultural inputs, all facilitated by infrastructure development. By enabling farmers to adopt SAPs such as residue retention, crop rotation, and zero tillage, infrastructure development directly contributes to creating resilient agricultural ecosystems. As shown in Section S2 of the Supplementary File 1 to this study, the presence of physical infrastructure may enhance production and increase farm income[4]. In turn, increased farm income may ease financial constraints, thereby allowing the adoption of SAPs[6]. However, despite the potential role of physical infrastructure in improving the adoption of SAPs in Africa, investment in the region has been very low[6] and challenging in Africa (see Secion S1 of the Supplementary File 1 for details of the challenges). This mismatch in low investment in Africa and the potential role of infrastructure in improving the adoption of SAPs raises questions about whether infrastructure enhances SAPs. Yet empirical information about the effect of infrastructure on SAP adoption is scanty despite the policy relevance of such information. Although robust evaluation of the impact of infrastructure has been conducted by past studies[4,5,7,8], the questions of adoption effects of infrastructures on SAPs in Africa remained unanswered despite its policy relevance in Africa. Moreover, past studies focused on a single infrastructure even though multiple infrastructures can be used in an integrated manner to improve livelihoods. Additionally, the existing studies on the effect of infrastructure only focused on single countries: Alhassan et al.[4], and Mumin et al.[8] in Ghana; and Wubale et al.[5] in Ethiopia; etc. Thus, results from these studies are far from general since ecological conditions and agricultural policies at a national level cannot be generalized to Africa.

This study builds on past studies by examining the plot-level adoption effect of multiple infrastructures among maize farmers in Africa. The infrastructure considered includes irrigation and produce/product storage facilities. Our contribution comes from several angles. First, given our objective of investigating the adoption effect of multiple infrastructures in sub-Saharan Africa over time, we employed a unique panel dataset from the intensification project of sub-Saharan Africa. The dataset is unique because it covers eight countries and documents over time (i.e., Afrint round I and Afrint round II), information on household characteristics, institutional conditions, production, adoption of SAPs, and use of infrastructure. Second, we examine the role of multiple infrastructures in the adoption of SAPs with special reference to irrigation and produce/product storage facilities in Africa. Knowledge of how these infrastructures affect the adoption of SAPs could be relevant

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for designing policies for holistic adoption in Africa. The SAPs considered include crop rotation (CR), animal manure (AM), minimum tillage (MT), residue incorporation (RR), pesticides/herbicides (PH), improved seeds (IS), chemical fertilizer (CF), and rainwater harvesting (RH). Thus, aside from the study's uniqueness in terms of location of coverage and how multiple infrastructures affect the adoption of SAPs, the study is also unique in terms of an attempt to explore how rainwater harvesting is related to other SAPs. Rainwater harvesting (RH) facilitates the take-up of other SAPs[9]. Nonetheless past empirical studies did not examine how it interrelates with other SAPs. Third, we extend the analysis to the implication of the multiple physical infrastructures on the level of adoption of SAPs in Africa since there are several adoption levels and the possibility that different infrastructures may not affect them differently. By examining the effect of infrastructure on adoption and levels of adoption of SAPs, this study bridges the gap between infrastructure development and circular agricultural systems, emphasizing the critical role of integrated infrastructure investments in accelerating the transition to sustainable agricultural systems in sub-Saharan Africa.

Methods and materials

Modeling the link between infrastructure and SAP adoption

Given the study's focus, we draw from the random utility framework, and literature on infrastructure and adoption to provide deeper insights into the conceptual links between infrastructure and the adoption of SAPs in Africa. Following Pitt[10], we assumed that a variable net benefit (π), revenue (P_iQ_i) , and cost (C_i) are associated with any decision on the farm. Consequently, the variable net benefit for households' adoption of any of the SAPs, π_A, and non-adoption of SAPs, π_{NA} may be respectively specified as: $\pi_A = Q_iQ_A - C_A$ and $\pi_{NA} = P_iQ_{NA} - C_{NA}$; where P_i is the per unit market price of maize produced; Q_A and Q_{NA} are the respective quantities of maize produced under the adoption and non-adoption of SAPs; C_A and C_{NA} are the respective costs associated with the adoption and non-adoption of SAPs. Thus, while receiving benefits for adoption decisions, the household will have a higher cost of adoption to contend with as compared with non-adoption. Such a cost may eventually reduce the net variable benefits and consequently discourage the adoption of SAPs. With the information given, the household must decide between the adoption and non-adoption of SAPs. If the net benefits from the adoption of SAPs π_A could be higher or equal to the net benefits from non-adoption π_{NA}, i.e., $\pi_A \geq \pi_{NA}$ or $\pi_A - \pi_{NA} \geq 0$, the farmer will adopt SAPs. In this regard, the adopting farmer must devise strategies that will increase maize income (P_iQ_A) for adoption, decrease cost (C_A) for adoption, or hold it fixed and consequently make $\pi_A \geq \pi_{NA}$ or $\pi_A - \pi_{NA} \geq 0$.

Aside from the influence of changing dynamics of household/farm, agroecological/location, and institutional characteristics on adoption[2], the use of infrastructure including irrigation and produce/product storage facilities also affects the adoption of SAPs. For instance, irrigation facilities can directly increase output from Q_A to $Q_A^{'}$ [11−14].

Although the effect of produce/product storage facilities may be direct, the indirect effects are notable, especially, through total revenue, and can be explored by the farmer to make $\pi_A \geq \pi_{NA}$ or $\pi_A - \pi_{NA} \geq 0$. For instance, households may employ produce/product storage facilities to reduce losses and increase surpluses for sale (as reflected in Q_A) or maximize market output. The use of produce/product storage facilities may also allow farmers to wait for prices P_i increases to P_j. The increase in market output or prices can therefore lead to an increase in net variable benefits π_A for adoption than nonadoption π_{NA}. Consequently, the change in market prices P_i and output Q_A, associated with the use of irrigation and storage infrastructure may cause some increase in income P_iQ_A, thereby increasing the net variable benefits π_A for adoption than nonadoption π_{NA} and hence may enhance the adoption and level of adoption of SAPs. However, several challenges may also increase transaction costs for adoption. For instance, some irrigation and produce/product storage facilities are publicly owned and managed, and therefore exhibit some degree of externalities[15]. This can therefore raise the transaction cost for all users any time an additional user is added. Consequently, such high transaction costs may lead to low benefits for adoption and hence may discourage adoption.

Data analysis strategy

Following the discussions above, the following equation with multiple and nonlinear functions of endogenous explanatory variables is specified to test the effects of the different infrastructures on the adoption of SAPs:

$$A^*_{ikt} = \delta_i I_{ikt} + \vartheta_i X_{ikt} + \mu_{ikt} \quad (1)$$

Where A^*_{ik} represents a latent variable for adoption decisions or level of adoption of household i in SAPs k (i.e., CR, AM, MT, RR, IS, RH PH, and CF) at time t; X_i is a vector of household/plot, institutional, and agroecological/locational conditions including agricultural potential, rainfall, soil, and location variables; I_i is a vector of the different infrastructures including irrigation and storage, facilities; the $\boldsymbol{\vartheta}_i$ is the coefficient of X_i; μ_{ikt} is a random term. Further, Eqn (1) implies that δ_i can be the effect of the multiple infrastructures on the latent variables for adoption and level of adoption of SAPs A^*_{ik} at time t. This is possible if the following econometric issues are addressed. First, adoption decisions on CR, AM, MT, RR, IS, RH, PH, and CF may be interrelated. For instance, RH has the potential to capture and supplement water, address water scarcity, increase agricultural production, and enhance the adoption of other SAPs[16]. MT improves water conservation and may be chosen over less tillage-demanding practices such as residue retention[2]. Rainwater harvesting, agrochemicals, and animal manure are both resource demanding, and practicing rainwater harvesting may lead to less labour and income available for the application of agrochemicals, and animal manure. Second, some storage and irrigation facilities are public goods by nature and therefore have no excludability, nor rivalry of use. Thus, farmers may self-select into the use of such infrastructure based on their wealth status. Given such potential interrelation and self-selection, $\rho = \text{corr}\,(\mu_{ik}, I_{ik}) \neq 0$, δ_i in Eqn (1) cannot be taken as the true effect of infrastructure if these problems are not accounted for. Fourth, the error term μ_{ik} is made of unobserved time-invariant factors (e_{ikt}) for household j in plot i and the usual error terms for household $j(v_{ijt})$ that affect infrastructure and may be correlated with the outcome A^*_{ik} [17].

To solve the problems enumerated above, we combined the correlated random effects (CRE)[18,19] with (i) multivariate probit (MVP) model (hereinafter, CRE-MVP) to account for potential interrelationships between SAPs, time-constant unobserved factors, and to determine the effects of the multiple infrastructures on the adoption of SAPs and (ii) ordered probit regression with endogenous treatment and random effects (OPRETRE) model (hereinafter, CRE-OPRETRE)[20] to control for both time-constant and time-varying unobserved factors, endogeneity of the infrastructure and to determine the effects of different infrastructure on level of adoption of SAPs.

For the effect of the irrigation and storage infrastructure on the adoption of potentially interrelated SAPs, we employed CRE-MVP (The pooled MVP model is estimable under the assumption of no correlation between unobserved heterogeneity and observed explanatory variables). For the effect of irrigation and storage infrastructure on the level of adoption of SAPs, we employed CRE-OPRETRE. In the following sections, we present the data and CRE-MVP and CRE-OPRETRE models employed for estimating the effect of the irrigation and storage infrastructures on adoption and the level of adoption.

Data and descriptive statistics

The data employed for this study is panel data which comes from sub-Saharan Africa's Intensification (Afrint) project. The project was born out of the tenets of Boserupian intensification and the zeal to determine models of Asian Green Revolutions for Africa, as well as economic and political drivers of intensification in Africa[21]. The data was gathered through a multistage sampling technique. The sampling consists of the selection of Ghana, Kenya, Malawi, Nigeria, Tanzania, Ethiopia, Uganda, Zambia, and Mozambique based on the potential to produce cereals and tubers; selection of 2−5 regions from each country based on agroecological potential; selection of 2−10 villages from each region based on resource endowment; and random selection of 300−400 households from each village for the survey. The survey consisted of three waves, namely Afrint I, II, and III. Afrint I traced household demographic and socio-economic characteristics, production, marketing conditions, infrastructure, and institutional conditions of households in 2002/04. Afrint II and III repeated the cross-sectional survey made in Afrint I in over 100 villages during 2008/10 and 2013 respectively. The information used for this analysis is from Afrint I and II since Afrint III was not available at the time of the study. Afrint I and II dataset employed in this study consists of a balanced panel of 2,388 households cultivating 4,776 plots in sub-Saharan Africa. It was employed because of our interest in knowing how multiple infrastructures affect the adoption of SAPs over time. Afrint I covered 3,537 households in the 2002/2004 period and Afrint II covered 2,368 households in 2008/2010. Thus, an attrition rate of 15% was recorded. This was caused by death, migration, and omission of some observations. Data from Uganda, for instance, is excluded from this study because the data has a high rate of attrition. We test for non-randomness of attrition by regressing our outcome variables and other covariates against attritors = 1 and non-attritors = 0 using probit. However, no significant differences between attritors and non-attritors were recorded. The results can be provided upon request. In Table 1, the definitions/measurements of SAPs and other explanatory variables are presented. It is widely documented in both theoretical and empirical literature that the adoption of agricultural technologies is influenced by household/plot, institutional, and agroecological/location characteristics[1] as well as infrastructure[12]. Our household/plot explanatory variables include sex, age, education of the household head, labour use, livestock holding, assets, membership status of the head in FBOs, dependency ratio, and plot size (Asset index variable is a latent indicator variable of assets constructed from ownership of utilities including phone, radio, television, motorbike, and bicycle using principal component analysis). Of the sample households, 67% represent male-headed households with each controlling an average of 7 hectares of land and having three dependents. On average, the age of a household head in the sample is about 40 years. The average number of schooling years and the number of members working on the farm are 4 years and three members, respectively. Thus, the adoption of skill- and labour-intensive practices is likely to be affected given that education and labour—implied in schooling years and members working on the farm - are low. On average, about 32% of the sampled households are members of farmer-based organisations (FBOs). Participation in FBO membership is expected to improve both the adoption and use of infrastructure since information on agricultural-related activities is provided by such organisations. However, it may be argued that FBO membership is endogenous to the adoption of SAPs. The social network literature[22,23], in particular, argues that social networks, implied in FBO membership, can be influenced by sex, age, and education. However, these variables can also influence the adoption of SAPs[23]. To circumvent this problem, we include FBO membership and its residuals from first-stage CRE probit models of FBO membership in second-stage CRE-probit models for each of the SAPs considered. Here, we instrument FBO membership with the presence of any agriculture-related organisation in farmers' villages. This variable was expected to influence membership in FBO but not infrastructure and adoption. Overall, the results indicated that FBO membership is not endogenous to the use of infrastructure and adoption as we did not find the generalized residuals from FBO membership to be significant. To capture institutional conditions, we employed contract farming, credit access, tenure security, and extension advice. It is often argued that contract farming, tenure security, access to credit, and extension advice are potentially endogenous to the adoption of agricultural technologies[24−27]. However, these variables are captured at the village level, which is arguably beyond a households own decision. Finally, we captured agroecological characteristics in terms of country and rainfall status of farmers' villages. As mentioned previously, adoption decisions may be influenced by agroecological differences. In forest areas where rainfall is abundant, farmers may choose MT over tillage and AM since livestock/draught animals responsible for tillage and manure cannot survive in forests harboring trypanosomiasis spreading tsetse flies[2]. This situation may be different in the savannah areas of Africa because such areas are drought-stressed due to less rain and less accommodating for tsetse flies and may therefore influence the adoption of tillage and AM or RR. The statistics of variables are summarized in Table 1. In this study, the adoption of SAPs regards the application of CR, AM, MT, RR, IS, RH PH, and CF. These are also presented in Table 1.

The infrastructures considered in this study include the use of irrigation and produce/product storage facilities. The use of these infrastructures, as shown in Table 2, varies across the two rounds of the survey period. However, the variations are not extremely high or low across the survey periods. Between 2002/04 and 2008/10, the use of irrigation rose from 67% to 72% while the use of produce/product storage facilities declined from 93% to 81%. Thus, households tend to change the status of the use of infrastructure by increasing and decreasing the use of irrigation and produce/product storage facilities. We think this is fair because compared to produce/product storage facilities, irrigation facilities are sources of water supply for production and other important livelihoods and therefore likely to be welcomed by farmers in most of Africa.

Table 3 gives summary statistics of adoption decisions and level of adoption by infrastructure and survey year. Compared to nonusers, the rate of adoption for users of irrigation facilities is 54% in 2002/04 and 70% in 2008/10 for CR, 60% in 2002/04 and 64% in 2008/10 for AM, 42% in 2002/04 and 48% in 2008/10 for MT, 64% in 2002/04 and 80% in 2008/10 for RR, 41% in 2002/04 and 65% in 2008/10 for CF, 65% in 2002/04 and 69% in 2008/10 for PH, 9% in 2002/04 and 20% in 2008/10 for RH, and 5% in 2002/04 and 22% in 2008/10 for IS. Compared to nonusers of product/produce storage facilities, adoption rate of users is 64% in 2002/04 and 57% in 2008/10 for CR, 40% in 2002/04 and 46% in 2008/10 for AM, 25% in 2002/04 and 33% in 2008/10 for MT, 49% in 2002/04 and 55% in 2008/10 for RR, 46% in 2002/04 and 40% in 2008/10 for CF, 48% in 2002/04 and 42% in 2008/10 for PH, 15% in 2002/04 and 9% in 2008/10 for RH, and 6% in 2002/04 and 19% in 2008/10 for IS. Thus,

Table 1. Measurements and summary statistics of the variables used in the analysis.

Variable	Definition/measurements	Pool sample
Crop rotation (CR)	1 if the farmer applied CR on his plots; 0 if otherwise	0.58 (0.49)
Animal manure (AM)	1 if the farmer applied AM on his plots; 0 if otherwise	0.43 (0.49)
Minimum tillage (MT)	1 if the farmer applied MT on his plots; 0 if otherwise	0.32 (0.46)
Residue retention (RR)	1 if the farmer applied RR on his plots; 0 if otherwise	0.43 (0.50)
Chemical fertilizer (CF)	1 if the farmer applied CF on his plots; 0 if otherwise	0.54 (0.50)
Pesticides/herbicides (PH)	1 if pesticides/herbicides are applied to the plots; 0 if otherwise	0.44 (0.50)
Rainwater harvesting (RH)	1 if the farmer applied RH on his plots; 0 if otherwise	0.10 (0.30)
Improved seeds (IS)	1 if the farmer applied IS on his plots; 0 if otherwise	0.24 (0.17)
Number of SAPs	Number of SAPs adopted per plot	5.13 (3.14)
Household/plot characteristics		
Sex_HHH	Sex of the household head (1 if male; 0 if otherwise)	0.67 (0.47)
Age_HHH	Age of the head of the household (years)	39.89 (21.88)
Education_HHH	Education of head (years)	4.33 (4.20)
Labour use	Number of household members working on the farm	3.03 (3.16)
TLU*	Total livestock holding in Tropical Livestock Units (TLU)	5.12 (1.60)
FBO membership status	1 if the head is a member of any local farmer organisation dealing with agriculture; 0 if otherwise	0.32 (0.47)
Asset index	Household asset index	1.18 (1.02)
Dependency ratio	The ratio of household members aged below 15 and above 61 to those aged 15–61	3.01 (0.72)
Plot_size	Size of plot cultivated (hectares)	7.62 (12.68)
Plot_title	1 if the plot is registered; 0 if otherwise	0.41 (0.49
Plot_distance	Plot distance to the nearest market outlet/crop depot (km)	6.39 (3.78)
Institutional conditions		
Contract farming	1 if there are any contract farming/outgrower schemes present in the village; 0 if otherwise	0.14 (0.35)
Credit	1 if credit is available in the village for farmers; 0 if otherwise	0.29 (0.45)
Tenure security	1 if there is the presence of small-scale farmers in the village who hold a formal title to land; 0 if otherwise	0.62 (0.45)
Extension advice	1 if the village at present has access to extension services; 0 if otherwise	0.75 (1.10)
Agroecological/location characteristics		
Above_average***	1 if rainfall in the village is perceived as above average; 0 if otherwise	0.48 (0.30)
Average***	1 if rainfall in the village is perceived as average; 0 if otherwise	0.54 (0.50)
Below_average***	1 if rainfall in the village is perceived as below average; 0 if otherwise	0.55 (0.50)
Ethiopia#	1 if Ethiopia is the location of the household; 0 if otherwise	0.13 (0.33)
Ghana#	1 if Kenya is the location of the household; 0 if otherwise	0.15 (0.36)
Kenya#	1 if Tanzania is the location of the household; 0 if otherwise	0.08 (0.27)
Malawi#	1 if Ghana is the location of the household; 0 if otherwise	0.10 (0.31)
Nigeria#	1 if Nigeria is the location of the household; 0 if otherwise	0.11 (0.32)
Tanzania#	1 if Malawi is the location of the household; 0 if otherwise	0.10 (0.31)
Zambia#	1 if Zambia is the location of the household; 0 if otherwise	0.11 (0.32)
Mozambique#	1 if Mozambique is the location of the household; 0 if otherwise	0.11 (0.31)
Instruments		
Knowledge of irrigation	1 if the household head has the knowledge to practice irrigation; 0 if otherwise	0.52 (0.50)
Individual_HH**	1 if the irrigation facility is managed by individual households; 0 if otherwise	0.37 (0.48)
Association_HH**	1 if the irrigation facility is managed by associations of households at the local level; 0 if otherwise	0.37 (0.48)
Supravillage_organisation**	1 if the irrigation facility is managed by supravillage organisations at the district/state level; 0 if otherwise	0.25 (0.43)
Agric_organisation	1 if there is the presence of any agriculture-related organisation in the village; 0 if otherwise	0.53 (0.50)
Modern_grain store	1 if modern grain stores are available in the village; 0 if otherwise	0.20 (0.40)
Food_storage_org	1 if the organisation in-charge of food storage is available in the village; 0 if otherwise	0.13 (0.32)

* For TLU in sub-Saharan Africa, rate of conversion for cattle = 0.5, sheep = 0.1, goats = 0.1, pigs = 0.2, camel = 0.7, chicken = 0.01. ** The reference categories for management of irrigation facility is Individual_HH. *** The reference categories for rainfall conditions is Below_average. # The reference categories for country of location of household is Mozambique.

the patterns of application of SAPs vary between users and nonusers of irrigation and produce/product storage facilities in 2002/04 and 2008/10. Such variation may be due to survey factors that were beyond our control as users of secondary data. In the next sections, the empirical models to disentangle and quantify the pure effects of the irrigation and storage infrastructure on the adoption and level of adoption of SAPs are presented.

Estimating the effect of infrastructure on the adoption of interrelated SAPs

As stated earlier, the adoption decisions of SAPs are potentially interrelated, and the use of infrastructure is potentially endogenous due to plot and household observed and unobserved heterogeneity. Neglecting such potential interdependences between the techniques, and the endogeneity of infrastructure can result in biased estimates. To avoid biased estimates, we augment a multivariate probit (MVP) model with the correlated random effects (CRE) model where mean values of size of the plot, plot title, access to extension, labour used, age of household head, and rainfall variables are included in an MVP model along with the endogenous (i.e., use of irrigation and produce/product storage facilities) and other explanatory variables to minimize unobserved heterogeneity. The inclusion of the mean values of the time-varying explanatory variables in the MVP model is the correlated random effects (CRE)[17–19] which has been employed in controlling unobserved heterogeneity[2]. Specifically, the MVP model estimates the relationship between explanatory variables and the choice of adoption, allowing for the correlation between unobserved disturbances, and the different adoption choices[28]. The MVP model is specified as:

Table 2. Use of infrastructure by survey wave.

Infrastructure	Definition/measurements	Mean		
		2002/04	2008/10	Pooled sample
Use of irrigation facilities	1 if the household produces with a privately owned well, river diversion, community-owned irrigation system, or government-owned irrigation scheme; 0 if otherwise)	0.67 (0.47)	0.72 (0.45)	0.71 (0.45)
Use of product/produce storage facilities	1 if household stores produce with bags inside the house, proper store, or granary; 0 if otherwise	0.93 (0.26)	0.81 (0.29)	0.88 (0.28)

Figures in parentheses are the standard deviations.

Table 3. Adoption of SAPs by status of use of infrastructure and survey wave.

SAPs	Use of irrigation facility				Use of storage facility			
	2002/04		2008/10		2002/04		2008/10	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
CR	0.54	0.50	0.70	0.46	0.64	0.48	0.57	0.50
AM	0.60	0.49	0.64	0.48	0.40	0.49	0.46	0.49
MT	0.42	0.50	0.48	0.50	0.25	0.44	0.33	0.47
RR	0.64	0.48	0.80	0.40	0.49	0.51	0.55	0.59
CF	0.41	0.49	0.65	0.48	0.46	0.50	0.40	0.49
PH	0.65	0.48	0.69	0.46	0.48	0.50	0.42	0.50
RH	0.09	0.29	0.20	0.40	0.15	0.32	0.09	0.29
IS	0.05	0.23	0.22	0.41	0.06	0.23	0.17	0.35
No. of SAP	5.39	3.48	5.13	2.78	5.41	3.47	5.17	2.78

Crop rotation (CR), animal manure (AM), minimum tillage (MT), residue incorporation (RR), improved seeds (IS), rainwater harvesting (RH), pesticides/herbicides (PH), and chemical fertilizer (CF).

$$A^*_{ikt} = \delta_0 + \delta_1 I_{it} + \delta_2 X_{it} + \delta_3 \overline{X}_i + \varepsilon_{it} k = \mathrm{CR, AM, MT, RR, CF, PH, IS, RH} \quad (2)$$

$$A_{ikt} = \begin{cases} 1 \ if \ A^*_{ikt} > 0 \\ 0 \ if \ A^*_{ikt} \leq 0 \end{cases} \quad (3)$$

where, A_{ikt} is the adoption decision related to the latent variable A^*_{ikt} for each of the SAPs k in plot i at time t; X_i is a vector of exogenous covariates of household/plot i; I_i is the vector of potentially endogenous infrastructure (i.e., use of irrigation and produce/product storage facilities). $\overline{X}$ is the index of the averages of household/plot varying explanatory variables that help account for time-invariant unobserved heterogeneity; δ_js are the coefficients of X_i, I_i, and $\overline{X}$. If the ε_i in Eqn (2) jointly follow a multivariate normal distribution with 0 as the mean and 1 as the variance, then the covariance matrix Σ can be stated as:

$$\sum = \begin{bmatrix} 1 & \rho_{CRMT} & \rho_{CRAM} & \rho_{CRRR} & \cdots & \rho_{CRINM} \\ \rho_{MTCR} & 1 & \rho_{MTAM} & \rho_{MTRR} & \cdots & \rho_{MTINM} \\ \rho_{AMCR} & \rho_{AMMT} & 1 & \rho_{AMRR} & \cdots & \rho_{AMINM} \\ \rho_{RRCR} & \rho_{RRMT} & \rho_{RRAM} & 1 & \cdots & \rho_{RRINM} \\ \vdots & \vdots & \vdots & \vdots & 1 & \vdots \\ \rho_{INMCR} & \rho_{INMMT} & \rho_{INMAM} & \rho_{INMRR} & \cdots & 1 \end{bmatrix} \quad (4)$$

Where, the off-diagonal elements [$rho(\rho)$] in Eqn (4) represent the unobserved correlation between the stochastic components of the different types of SAPs. The specification in Eqn (4) allows for correlation across the unobserved components of the error terms that affect the choice of alternative SAPs in the several latent equations. A positive correlation is interpreted as a complementary relationship, while a negative correlation is interpreted as a substitute. This assumption means that Eqn (2) generates an MVP model that jointly represents decisions to adopt a particular component of SAP[28].

On the other hand, the CRE controls for endogeneity due to time-constant unobserved heterogeneity[18,19]. Fixed effects procedures could be used for solving such problems. However, the fixed effects would require the estimation of single-equation models and can lead to incidental parameter problems. The CRE approach assumes that if explanatory variables, influencing the adoption of SAPs, are correlated with unobserved variables (ϵ_{it}), they are correlated only with the time-invariant component of the unobserved variables (e_{it}) which is a linear function of averages of the household/plot-varying explanatory variables i.e., $e_{it} = \pi_i \overline{X}_i + \omega_{it}$ with $\omega_i IID(0, \sigma^2)$, $E\left(\omega_i | \overline{X}_i\right) = 0$ and $\overline{X}_i$ is the vector of the mean values of time-varying explanatory variables of plot i and π_i is the corresponding index of coefficients, and ω_i is a normally distributed error term[18,19]. It is, however, worth noting that the CRE does not control time-varying unobserved heterogeneity. Thus, if the unobserved plot/time-varying heterogeneity is correlated with the adoption of SAPs or other observed explanatory variables, our estimate of the effect of multiple infrastructures will be inconsistent. We minimize potential bias from unobserved plot-varying heterogeneity by including detailed information about the plot - plot size, the title of registration, and distance to the nearest market outlet/crop depot. Although these variables are likely to correlate positively with the unobserved plot-varying heterogeneities and might help reduce unobserved heterogeneities, we cannot claim to have accounted for all unobserved heterogeneities. We address potential problems from time-varying unobserved factors using CRE with CFA (CRE-CFA) where the first stage is a set of CRE-probit models for each infrastructure and the second stage is CRE-probit models for each of the SAPs[29]. The CFA controls endogeneity due to time-varying unobserved heterogeneity when the outcome and endogenous independent variables are both discrete.

Estimating the effect of infrastructure on the level of adoption of SAPs

As indicated already, the SAPs considered include CR, AM, MT, RR, IS, RH, PH, and CF. Based on households' adoption decisions in these practices, the number of SAPs adopted was constructed as (i) Category j = 0, for non-adoption SAPs; (ii) Category j = 1, for the adoption of only one of the SAPs; (iii) Category j = 21, for the adoption of a combination of any two of the SAPs; (iv) Category j = 31, for the adoption of a combination of any three of the SAPs: (v) Category j = 41, for the adoption of a combination of any four of the SAPs; and (vi) Category j = 51, for the adoption of a combination of any five or more of the SAPs. Our approach to the classification of SAPs has been employed by Midingoyi et al.[30]. Because the outcome variable is ordered, we draw from the latent response model of adoption in Eqn (3) to specify an ordered probit model as:

$$A_{ikt} = \begin{cases} 0, \ if \ A^*_{ikt} \leqslant c_1 \\ 1, \ if \ c_1 < A^*_{ikt} \leqslant c_2 \\ \vdots \\ J, \ if \ A^*_{ikt} > c_J \end{cases} \quad (5)$$

where, c is defined as the boundaries of moving from one level of adoption of the SAPs to another level; and A_{ik} and A^*_{ik} are as defined previously. Thus, the model for A_{ik} consists of the error term with random effect and normally distributed error terms at plot level for households. Following Greene[31], the probabilities of the six observed results for the ordered probit model are expressed as:

$$prob(A_{ikt} = 0|X_{it}, I_{it}) = \Phi(c_1 - \delta_i I_{it} - \vartheta_i X_{it}) \quad (6a)$$

$$prob(A_{ikt} = 1|X_{it}, I_{it}) = \Phi(c_2 - \delta_i I_{it} - \vartheta_i X_{it}) - \Phi(c_1 - \delta_i I_{it} - \vartheta_i X_{it}) \quad (6b)$$

$$prob(A_{ikt} = 2|X_{it}, I_{it}) = \Phi(c_3 - \delta_i I_{it} - \vartheta_i X_{it}) - \Phi(c_2 - \delta_i I_{it} - \vartheta_i X_{it}) \quad (6c)$$

$$prob(A_{ikt} = 3|X_{it}, I_{it}) = \Phi(c_4 - \delta_i I_{it} - \vartheta_i X_{it}) - \Phi(c_3 - \delta_i I_{it} - \vartheta_i X_{it}) \quad (6d)$$

$$prob(A_{ikt} = 4|X_{it}, I_{it}) = \Phi(c_5 - \delta_i I_{it} - \vartheta_i X_{it}) - \Phi(c_4 - \delta_i I_{it} - \vartheta_i X_{it}) \quad (6e)$$

$$prob(A_{ikt} = 5|X_{it}, I_{it}) = 1 - \Phi(c_5 - \delta_i I_{it} - \vartheta_i X_{it}) \quad (6f)$$

where, the standard normal distribution function is represented by $\Phi(\cdot)$; X_{it} is as defined earlier in Eqn (2) but here, it also includes the averages of all plot-varying explanatory variables to control for unobserved time-invariant heterogeneity. I_{it} is the index of the use of irrigation and storage infrastructure at time t; δ_i and ϑ_i are coefficients of X_{it} and I_{it}. Of particular interest in this study is the proper estimation of δ_i in Eqns (6a)–(6f). As explained previously, the index of infrastructure I_{it} is endogenous due to the potential correlation between unobserved plots and household heterogeneities. Thus, proper estimation of δ_i require accounting for such endogeneity. A combination of the CRE with OPRETRE (CRE-OPRETRE) model can accommodate endogeneity and as well estimate the effect of each infrastructure on the level of adoption. The OPRETRE model is one of the ERMs that allows ordered outcomes with endogenous treatment and random effects. However, the OPRETRE assumes that random effects are not correlated with observation-level error terms, yet correlation may exist between the unobserved and observed variables. To control any potential bias due to the correlation between observed and unobserved household heterogeneity, we again employed the CRE within the framework of OPRETRE (CRE-OPRETRE). The CRE-OPRETRE model for the effect of each infrastructure is estimated in two stages. First, we estimated an OPRETRE model for the use of each infrastructure and level of adoption where X_{ik} in Eqn (6) includes the means of time-varying explanatory variables to capture unobserved time-constant heterogeneity (We estimate OPRETRE model using the 'xteoprobit' command in STATA 17[20]). In the second stage of the CRE-OPRETRE models, the effect of the infrastructure under consideration is then estimated as in the potential-outcomes framework. Thus, for each treatment level I_i observed, the adoption level A_{ijt} is specified as:

$$A_{kit} = \sum_{j=1}^{I} 1(I_{ijt} = a_i X_{it} + \psi_i Z_{it} + \eta_i) A_{it} \quad (7)$$

Where, A_{ik} is as defined in Eqn (5); I_i is an index of a binary treatment (i.e., infrastructure under consideration) that takes the values {0, 1} and related to household/plot, institutional conditions, agroecological/location characteristics, and means of time-varying explanatory X_{it}, and instruments Z_{it}. Equation (7) further implies that for each plot, we observe only the level of adoption of SAPs asso ciated with the infrastructure I_i employed at time t. Thus, the average treatment effect on the treated (ATET) for using a particular infrastructure j in the treatment group I_i is defined as the difference in the outcome for plots using that infrastructure instead of not using it (For each infrastructure, the ATET was estimated with 'estat teffects' command available in STATA 17[20]). We instrumented the treatment equations for the different infrastructures with the following variables but excluded them in the outcome equations of OPRETRE. For the use of irrigation facilities, we employed variables concerning whether the household knows how to practice irrigation and whether the irrigation system is managed by (i) individual households, (ii) associations of households at the local level, and (iii) supravillage organisation at district or state level. Every irrigation infrastructure consists of subsystems with functions linked hierarchically and continuously to deliver water to the end user. However, the function of each subsystem in the process of delivering water to the end-user depends on management[32] which includes maintenance of irrigation canals and disputes among water users, and regulation of water application in a way that satisfies water requirements without waste. Thus, the knowledge and level of management of irrigation systems are important determinants of access and use of irrigation systems[33] and are likely to affect the adoption of SAPs through irrigation infrastructure. For produce/product storage facilities, we used the village-level availability of modern grain stores and the organisation in charge of food storage as instrumental variables. Although the instruments may be strong by intuition, exclusion restrictions may still be violated if adoption is also enhanced by knowledge of the use of irrigation facilities, availability of modern produce/product storage facilities, or managers of irrigation infrastructure and food storage. We check for instrument relevance using an informal test where alternative versions of the outcome equations are estimated with the instruments. If the coefficients of the instruments in the outcome models are not significant, then the instruments are valid and can be excluded from the outcome equations for SAPs[34]. Alternatively, the instruments are said to be valid if they jointly affect the different infrastructures but the level of adoption of SAPs.

Results and discussion

Effect of infrastructure on adoption of interrelated SAPs

As mentioned previously, the adoption of interrelated SAPs may be influenced by time-invariant unobserved heterogeneity and thus lead to inconsistent estimates. Thus, we estimated two different specifications of the MVP models for comparison, namely, the MVP model with CRE (CRE-MVP) in Table 4 and the MVP model without CRE in Supplementary Table S1. Since the CRE-MVP model does not control for time-varying unobserved heterogeneities, we augment it with CFA for each of the SAPs where generalized residuals from a set of first-stage CRE-probit models for use of irrigation and produce/product storage facilities (Supplementary Table S3) are introduced as additional regressors in CRE-probit models of the SAPs considered (Supplementary Table S4). Regarding the CRE-MVP models, most of the coefficient estimates of the CRE-MVP model in Table 4 are smaller than those of the MVP model without CRE in Supplementary Table S1. These suggest upward bias if time-constant unobserved heterogeneity was not controlled for. Regarding CFA models, none of the coefficients on the generalized residuals is statistically significant. However, most coefficients of the means of time-varying explanatory variables are statistically significant in the second-stage CRE-probit models of each of the SAPs. Further, a joint test that all coefficients of the means of the time-varying explanatory variables are jointly equal to zero was rejected in these models. These, perhaps, suggest that the unobserved heterogeneities correlating with infrastructure are time-invariant but not time-varying. We therefore focused on the results of the CRE-MVP model which controlled for potential interdependencies between SAPs and endogeneity due to time-invariant unobserved heterogeneities.

As previously mentioned, plot-level adoption decisions of households may be interdependent (substitutes or complements). This assertion is confirmed by the likelihood ratio test of the CRE-MVP model which rejects the null hypothesis of zero correlation between the error terms ($\chi^2(45) = 573.977$, $p < 0.01$). This also seems to suggest that plot-level adoption of SAPs by maize producers is not mutually exclusive, i.e., adoption decisions in SAPs are interrelated. We provide further insights into how the SAPs are interrelated using the correlation matrix associated with the CRE-MVP model. The

Table 4. Coefficient estimates of the CRE-MVP.

Variables	CR	AM	MT	RR	CF	PH	IS	RH
Household/farm characteristics								
Sex_HHH	0.0468***	0.0473***	0.0156*	0.0516*	0.0667*	0.0482*	0.0494***	0.0408*
	(0.0113)	(0.0115)	(0.0081)	(0.0299)	(0.0391)	(0.0254)	(0.0187)	(0.0229)
Age_HHH	0.00424	0.000376	0.000286	0.00317	0.00131	−0.00123	−0.00120	0.000258
	(0.00330)	(0.00324)	(0.00303)	(0.00361)	(0.00423)	(0.00212)	(0.00408)	(0.00336)
Education_HHH	0.0125	0.0130	−0.00896	−0.00339	0.0222	−0.000829	−0.00105	−0.0132
	(0.0120)	(0.0120)	(0.0115)	(0.0133)	(0.0157)	(0.00769)	(0.0157)	(0.0126)
Labour use	−0.0131	−0.00752	−0.	0.0188	−0.0134	0.00551	0.0110	−0.0130
	(0.0129)	(0.0126)	(0.0120)	(0.0124)	(0.0162)	(0.00795)	(0.0163)	(0.0133)
TLU	0.270**	0.236**	0.511***	0.076	0.379***	0.543***	0.332***	0.259*
	(0.119)	(0.113)	(0.136)	(0.315)	(0.074)	(0.133)	(0.089)	(0.091)
FBO membership status	0.0360	0.0846	0.0848	−0.0998	−0.0919	0.113	0.0542	0.00787
	(0.146)	(0.141)	(0.134)	(0.162)	(0.195)	(0.0913)	(0.187)	(0.156)
FBO_residual	0.113	−0.179	−0.170	−0.244	−0.227	0.130	0.0934	0.0153
	(0.162)	(0.159)	(0.145)	(0.167)	(0.214)	(0.100)	(0.189)	(0.173)
Asset_index	0.0449***	0.0424*	0. 0409**	−0.136	0.0682***	0.0275*	0.0462***	0.0447***
	(0.0136)	(0. 0233)	(0.0193)	(0.249)	(0.0238)	(0.0155)	(0.0183)	(0.0145)
Dep_ratio	−0.00383	0.0495	−0.216	−0.0290	0.0329	0.0394	0.0140	0.0451
	(0.0528)	(0.0461)	(0.144)	(0.0574)	(0.0614)	(0.0319)	(0.0586)	(0.0478)
Plot_size	0.589***	−0.679***	0.923***	0.580***	−0.616***	−0.589***	−0.332***	−1.285**
	(0.191)	(0.158)	(0.212)	(0. 226)	(0.059)	(0. 137)	(0.089)	(0.625)
Plot_title	0.166***	0.381**	0.023	0.103	0.125***	0.006	0.114	0.261***
	(0.042)	(0.189)	(0.126)	(0.124)	(0.044)	(0.125)	(0.129)	(0.062)
Plot_distance	−0.589***	−0.679***	0.114**	0.405***	−0.721***	−0. 476***	−0.353**	0.241*
	(0.191)	(0.158)	(0.045)	(0.129)	(0.247)	(0.147)	(0.154)	(0.143)
Institutional conditions								
Contract	−0.0740	0.0687	0.289	0.256	−0.00264	0.175	0.0716	−0.256
	(0.228)	(0.219)	(0.210)	(0.242)	(0.303)	(0.133)	(0.261)	(0.227)
Credit	0.005	−0.275*	−0.0170	0.0466	−0.0962*	−0.0930**	−0.155*	0.160
	(0.004)	(0.149)	(0.200)	(0.164)	(0.0522)	(0. 0431)	(0.0829)	(0.162)
Tenure_sec	−0.0133	0.117	0.116	0.0502	0.109	−0.0367	−0.0154	−0.200
	(0.140)	(0.137)	(0.127)	(0.151)	(0.178)	(0.0877)	(0.174)	(0.143)
Extension	−0.102	−0.0883	−0.155	−0.277*	0.0681	0.156*	−0.245	−0.224
	(0.133)	(0.132)	(0.122)	(0.143)	(0.172)	(0.0832)	(0.167)	(0.143)
Agroecological/location dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Infrastructure use								
Produce/product_storage_facility	0.296***	0.547*	0.580**	0.508**	0.585*	0.318*	0.330*	0.444**
	(0.091)	(0.287)	(0.287)	(0.229)	(0.345)	(0.188)	(0.183)	(0.214)
Irrigation_facility	0.253***	0.285***	0.678**	0.823*	0.546*	0.343***	0.332*	−0.384***
	(0.086)	(0.067)	(0.345)	(0.445)	(0.283)	(0.132)	(0.198)	(0.149)
Year	0.003	0.000	0.000	−0.001***	−0.000	−1.165***	−1.100*	0.270**
	(0.004)	(0.005)	(0.004)	(0.000)	(0.000)	(0.317)	(0.660)	(0.119)
Constant	−2.065***	−1.595***	−0.158	−2.523***	−2.047***	−0.624***	−0.617**	−1.152***
	(0.384)	(0.373)	(0.334)	(0.423)	(0.474)	(0.238)	(0.250)	(0.389)
χ^2(18)- Statistics for joint significance of mean of plot varying covariates	79.56	67.01	57.51	80.33	67.23	63.45	90.21	68.66
Observations	2,548	2,548	2,548	2,548	2,548	2,548	2,548	2,548

Standard errors in parentheses. *p*-values in squared brackets *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

correlation matrix is presented in Supplementary Table S2 and shows that the adoption of some SAPs is conditional on the adoption of other SAPs. Of particular interest is Rainwater harvesting (RH) which correlates positively and significantly with all the SAPs under consideration and thus, suggests complementarity between RH and all the SAPs considered in this study. This further suggests that joint modeling of adoption decisions regarding SAPs will be more efficient than separate modeling. The complementarity and substitutability between plot-level adoption of SAPs corroborate with the findings of Huss et al.[35] in Ghana where farm investment techniques were found to be interdependent.

Regarding our main variables of interest, we found that the coefficients associated with the use of irrigation are significant and positively related to all the SAPs except with the adoption of rainwater harvesting (RH) where a negative and significant relationship is observed. Thus, except RH, the adoption of all SAPs tends to be higher for households using irrigation facilities. This result is plausible given that the presence of irrigation facilities does not just facilitate the adoption of SAPs but regulates income and transaction costs for farm investment[12]. The negative relationship between the use of irrigation facilities and RH implies that adoption of RH tends to be lower on plots where irrigation facility is used. This is also plausible given that both irrigation facility and RH technique save the same purpose of making water accessible for production[12,16]. Moreover, both are resource-demanding and a household investing labor and/or money in the use of an irrigation facility may have less labor and money available for the adoption of RH (loss of labor and income effect). The use of produce/product storage facilities is also significant and positively related to the adoption of all the SAPs and thus suggests that the adoption of SAPs is higher on plots associated with the use of storage facilities. These results accord with the conceptual link between the use of produce/product storage facilities and the adoption of SAPs. Produce/product storage facilities are known for preserving seeds and other production inputs until the production period[35] and can therefore enhance the adoption of improved seeds and other inputs like chemical fertilizer, manure, pesticides/herbicides. However, the storage of improved seeds and these inputs means increased income and reduced liquidity constraints for investment in other SAPs including CR, MT, RR, and RH. The results concur with the findings of past studies[36] about the relationship between produce/product storage facilities and technology adoption.

Concerning household characteristics, we found that male-headed households are more likely to adopt the SAPs than female-headed households. This is plausible given that more opportunities exist for men than women in Africa. Similar results have been displayed in past studies on the adoption[37]. Tropical livestock unit (TLU) and asset index of household utilities are also positively related to the adoption of all the SAPs even though the effect is not significant for RR. TLU and asset index are not liquid assets for investment but can sometimes relax the resource constraints for the adoption of SAPs. Whereas camel/donkeys may be useful in the transportation of materials for the adoption of AM, CF, PH, and IS, cattle may be useful in minimum tilling of the soil. On the other hand, sheep, goats, pigs, chickens, and household utilities may be sold to invest in SAPs. The effect of plot-level variables on SAPs is mixed. For instance, plot size is significant though it is negatively related to the adoption of CF, PH, IS, AM, and RH but positively related to the adoption of CR, RR, and MT. This makes it open to different interpretations. On one hand, the results suggest that the probability of adoption of CF, PH, IS, AM, and RH is significantly low on large plots but on the other hand, the results suggest that the probability of adoption of each of CR, RR, and MT is significantly high on large plots as compared to small plots. Nonetheless, the results are plausible for a reason. Given the poor market in SSA[38], adoption of such practices is likely to be low on larger plots since the cost of adoption on such plots will be higher as compared to small plots. Plot distance is also negative for IS, CF, and PH but positive for CR, AM, MT, RR, and RH and thus suggests that plots further away from input and output market outlets are more likely to choose the adoption of CR, AM, MT, and RR, over the adoption of IS, CF, and PH. This is plausible because distant markets do not only increase transaction costs for adoption but also restrict labor mobility, credit, and information access[2], and thus, may discourage the adoption of market-dependent technologies including IS, CF, and PH. Titled plots are also positively related to the adoption of SAPs though only CR, AM, CF, and RH are significant. This suggests that the probability of adoption of these SAPs is more likely to be higher under registered plots. This is plausible given that registration of plots reduces uncertainty regarding returns on investment in land and yields improving technologies[25]. Also, FBO membership status is positive and significantly related to the adoption of all SAPs. This means that farmers who belong to an FBO have a higher likelihood of adopting SAPs relative to nonmembers. Perhaps group members help each other on the farm and share ideas or resources that help improve adoption. These results echoed the relevance of social capital in technology adoption and are also in line with past studies on adoption[25].

Among the variables representing institutional conditions, only contract farming and extension advice are positively signed and significant to the adoption of CF, PH, and IS. This is plausible given that recent agricultural interventions including contract farming and extension approaches are geared towards increased use of soil fertility and yield-enhancing SAPs. Although village-level credit availability is significant for the adoption of AM, CF, PH, and IS, the relationship is negative probably because such credit was not accessed by households for production despite its existence. Further, the effect of agroecological/location characteristics also accords well with what is common about the effect of variation in agroecological conditions/location on adoption. Agroecological/location dummies are individually significant and positively related to all SAPs except CR. In particular, the agroecological/location dummies are significantly related to CF, IS, and PH at 1%. Input subsidy programs targeting the distribution of CF, IS, and PH below market prices have been witnessed in not only seven of the countries (i.e., Ghana, Nigeria, Kenya, Tanzania, Malawi, Zambia, and Ethiopia) considered in this study but in Mali, Burkina Faso, and Senegal[39] and might have contributed to the adoption of these SAPs. Jointly, these variables are significantly different from zero ($\chi^2(70) = 128$, p-value < 0.01) and thus, indicate the significance of variation in agro-climatic conditions and location of the farmers' plots in the adoption of SAPs. This is consistent with past studies indicating the significance of agroecological conditions in the adoption of SAPs[2]. Lastly, the high degree of significance associated with the constant term in Table 4 suggests that even in the absence of the independent variables included in the model, there is a statistically significant baseline effect on the adoption of SAPs in agriculture. In simpler terms, this indicates that there are factors beyond those included in our model that influence the adoption of sustainable agriculture practices. These unobserved or omitted variables could include cultural norms, market conditions, government policies, or other contextual factors that impact farmers' decision-making.

Effect of infrastructure on level of investment in land improving techniques

Table 5 presents the CRE-OPRETRE results of the effect of infrastructure on the level of adoption of SAPs (An OPRETRE models were also conducted for the comparison with the CRE-OPRETRE models. The coefficients differ between the OPRETRE and CRE-OPRETRE models and thus, suggest the influence of time-invariant unobserved heterogeneity. The results can be obtained from the corresponding author upon request). Although CRE-OPRETRE estimates the use of infrastructure and level of adoption, as well as the effect of infrastructure on the level of adoption, we present only the results of the effect of infrastructure on levels of adoption to save space. The results on determinants of use of irrigation and storage infrastructure, and level of adoption from the CRE-OPRETRE are respectively presented in Supplementary Tables S5 and S6 but are not discussed since they are not our focus. It is, however, important to note that all the instrumental variables are significant determinants for the use of infrastructure but are not significant on the level of adoption of SAPs (Supplementary Tables S5 & S6). This suggests the instruments are valid and can be excluded from the equations for the level of adoption. We also note that the correlation coefficients between the observation-level errors from the level of adoption of SAPs and use of irrigation and storage are all significantly different from zero and range between 0.17 and 0.87, though the effect is positive for only the errors between the level of adoption and storage facility. Thus, while the likelihood of SAP adoption at higher levels is decreased by unobserved factors increasing the likelihood of using irrigation facilities, it is decreased by unobserved factors increasing the likelihood of using produce/product storage facilities. In simple terms, irrigation and produce/product storage facilities are each endogenous, and the application of the OPRETRE model is appropriate. Further, the correlation coefficients between the random effects affecting the level of adoption and random

Table 5. Average effect of infrastructure (ATET) on the level of adoption of SAPs.

ATET_ L_SAPs	Irrigation facility	Produce/product storage facilities
ATET_Pr1 (1 vs 0)	−0.50 (0.12)***	−0.11 (0.02)***
ATET_Pr2 (1 vs 0)	−0.10 (0.03)***	−0.13 (0.06)**
ATET_Pr3 (1 vs 0)	0.14 (0.04)***	0.10 (0.03)***
ATET_Pr4 (1 vs 0)	0.18 (0.04)***	0.19 (0.03)***
ATET_Pr5 (1 vs 0)	0.38 (0.03)***	0.35 (0.17)**

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. Robust standard errors are in parentheses; ATET is the average treatment effect on the treated; L_SAPs is level of adoption of SAPs, ATET_Pr1, ATET_Pr2, ATET-Pr3, ATET_Pr4, and ATET_Pr5 represent ATET on the probability of adopting 1, 2, 3, 4 and 5 or more of any SAPs in this study.

effects affecting the use of infrastructure are all significant and range between 0.32 and 0.84 although only adoption and produce/product storage facilities are positive. Thus, unobserved time-varying factors that increase the probability of using irrigation facilities also tend to decrease the probability of adoption at higher levels. In contrast, unobserved time-varying factors that increase the probability of using produce/product storage facilities also tend to increase the probability of adoption at higher levels. Further, results of the means of time-varying explanatory variable in the models for the level of adoption and use of infrastructure indicate the presence of time-invariant unobserved heterogeneity and thus, justify the application of the CRE. Regarding the effect of infrastructure on the level of adoption (i.e., the average treatment effect on treated, ATET) in Table 5, we found that the average probability of adoption of any one or two of the SAPs decreases significantly with the use of all infrastructures. Specifically, the ATET for adopting any one of the SAPs (ATET_Pr1) is −0.50 when the irrigation facility is employed on a plot and −0.11 when the storage facility is employed. Thus, the ATET for adopting any one of the SAPs is 0.50, and 0.11 lower for the use of irrigation and produce/product storage facilities versus when none of these infrastructures is used on a household's plot. Further, the ATET for adopting any two of the SAPs (ATET_Pr2) is −0.10 for the use of irrigation and −0.13 for the use of produce/product storage facilities. These imply that the ATET for adopting any two of the SAPs (ATET_Pr2) is 0.10, and 0.13 lower when using irrigation and produce/product storage facilities as compared to the use of none of these facilities. On the contrary, the ATET for adopting any three or more SAPs increases significantly with the use of all infrastructures. For instance, all infrastructures significantly increase the proportion of households adopting any three of the SAPs in the sample. Specifically, the ATET for adopting any three of the SAPs (ATET_Pr3) is 0.14 for the use of irrigation facilities and 0.10 for the use of storage facilities. These suggest that the ATET for adopting any three of the SAPs (ATET_Pr3) is 0.14, and 0.10 higher when irrigation and produce/product storage facilities are used than if they had not been used. Thus, each infrastructure is likely to increase the proportion of households adopting SAPs at higher levels than it would be if households were not using any of such infrastructures on their plots. Further, the ATET for adopting any four of the SAPs (ATET_Pr4) is 0.18 for the use of irrigation facilities and 0.19 for the use of produce/product storage facilities. Also, we note that the ATET for adopting any five or more of the SAPs (ATET_Pr5) is 0.38 and 0.35 greater when households respectively used irrigation and produce/product storage facilities versus when no household used any of these facilities. Thus, each infrastructure is likely to decrease the proportion of households adopting SAPs at lower levels but increase it at higher levels than it would be if households were not using such infrastructure on their plots. We suspect this is attributed to the higher cost of infrastructure for adoption at lower levels. Per classical economic reasoning, the cost of using each of these infrastructures for adopting at most two of the SAPs will be higher than the cost of using the same infrastructures for adopting at least three of the SAPs. Moreover, given the role of irrigation, and storage in improving income, the increase in the proportion of households adopting the SAPs at higher levels is not surprising. This is because increased income from the use of such infrastructures plays a significant contribution to the adoption of more SAPs.

Conclusions

Investment in physical infrastructures remains one of the possible ways to solve the problem of low adoption rate in sub-Saharan Africa, yet investment in such infrastructures has been very low in the region. This raises questions about whether the different infrastructures that are touted as profitable are beneficial to African farmers. To date, information answering these questions is limited in existing literature. Moreover, the existing information on the adoption effect of infrastructure over time did not focus on multiple infrastructures despite the policy relevance of such study in Africa. We combined the correlated random effects with multivariate probit, control function, and ordered probit regression with endogenous treatment and random effects[20] on panel data that document infrastructure and production information of eight countries in sub-Saharan Africa to estimate the effects of irrigation and storage facilities on households' plot-level adoption decisions and as well as the level of adoption of interrelated SAPs in sub-Saharan Africa. The methodological approaches allow for control of endogeneity due to potential selection bias, time-varying, and time-invariant unobserved heterogeneities. The results show that there is a strong complementarity and substitutability between SAPs. This is implied in the interrelationship between the SAPs and thus suggests that promoting the adoption of any one of the SAPs may influence the adoption of the other SAPs. This is a cost-effective way of promoting the adoption of interrelated SAPs that can be explored by African governments to enhance the adoption of SAPs. Promoting the adoption of rainwater harvesting may be particularly important in this regard since it is positively related to the other SAPs. Further, unobserved factors influencing the use of irrigation and produce/product storage facilities also tend to influence the adoption of SAPs. Thus, if adoption decisions had been analysed without controlling for endogeneity, the pure effect of the irrigation and storage infrastructures would have been biased. This would have had a far-reaching effect on policies aimed at addressing challenges in the adoption process and low adoption rates in sub-Saharan Africa.

Most importantly, the results showed that the use of irrigation facilities is significant and positively related to all the SAPs except the adoption of rainwater harvesting (RH) which is a potential substitute for irrigation facilities. Further, the use of storage is significant and positively related to the adoption of all the SAPs considered and thus reveals the importance of investing in the development of production infrastructures to enhance the adoption of sustainable agricultural practices. This further reveals the importance of developing post-production infrastructure by the African government to facilitate the uptake of SAPs. Other important policy variables including FBO membership status, contract farming, and extension advice also influenced the adoption of SAPs and thus, suggest the need for establishing and strengthening local and government institutions to facilitate the uptake of SAPs in Africa. Resources implied in TLU, and asset index also influence the adoption of SAPs and thus suggest the need for the empowerment of farmers to ease liquidity constraints in adoption. Regarding levels of adoption, the results revealed that each infrastructure is also likely to decrease the proportion of households adopting SAPs at lower levels but increase it at higher levels. Thus, the role of infrastructure extends beyond just influencing the adoption decision of farmers but facilitates the uptake of multiple SAPs in Africa. This reinforces the development of production and post-production infrastructure for the uptake of SAPs in Africa. Despite the findings, the study is not without limitations. For instance, while we have incorporated various factors such as gender of head of household, plot size, tropical livestock unit, assets, education, and age, we acknowledge that we have not delved deeply into how these factors influence the capability of individual farms to make decisions, particularly regarding the adoption of sustainable practices. Integrating Sen's capability approach into our analysis would have indeed enriched our understanding by considering not only the presence of these factors but also the agency and decision-making environment within households. This would not have only aligned our work with broader discussions on development and poverty reduction but would have also highlighted the importance of addressing disparities in decision-making capabilities to promote more equitable and sustainable agricultural development. To address this gap, we propose future studies to expand findings to explore how the relative capability of households to make decisions affects their choices regarding sustainable agricultural practices. This can include factors such as access to information, resources, social networks, and institutional support, which are also crucial determinants of decision-making agency within households. Indeed, the importance of considering additional factors beyond those explicitly examined in our analysis is even highlighted by the significance of the constant terms which reminds less mathematically oriented audiences that while our model provides valuable insights, it may not have captured all determinants of SAP adoption.

In summary, this study highlights the critical role of infrastructure investments, such as irrigation and storage facilities, in shaping the adoption of interrelated SAPs in sub-Saharan Africa. By addressing endogeneity and accounting for the interconnectedness of SAPs, the findings offer valuable insights for designing cost-effective and integrated policy interventions. These insights underscore the need for targeted investments and coordinated promotion strategies to enhance sustainable agricultural practices, improve food security, and foster resilience among African farming households.

Data availability

The data that support the findings of this study are available and can be downloaded at https://www2.statsghana.gov.gh/nada/index.php/catalog/65/get_microdata.

Conflict of interest

The author declares that there is no conflict of interest.

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