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Review article

Impact of investments in agricultural innovation on food security in sub-Saharan Africa☆

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ABSTRACT

Empirical evidence proves that agricultural research and development expenditure, and researchers attract high returns though the investments have long gestation periods. Nonetheless, Sub-Saharan Africa invests meagerly in agricultural research and development, and researchers. This study explores the impacts of agricultural research and development expenditures, and researchers on food security in the region and across the sub-regions. The study applies Bootstrapped linear squared dummy variable due to its capacity to handle heterogeneity and missing observations and two-step system generalized method of moments techniques to analyze the data on 24 sub-Saharan African countries over the period 2000–2016. Data on measures of food security, food production per capita, and food price index are obtained from Food and Agriculture Organization stat, data on population growth is sourced from World Development Indicators, and data on investments in agricultural innovations are extracted from International Food Policy Research Institute. Our findings show that investments in agricultural innovation substantially increase food security through food productivity growth. The full-time equivalent of agricultural researchers' hours is more impactful on food security than agricultural research and development spending. The findings also reveal that the investments are more effective in enhancing food security in Eastern, Southern, and Western African sub-regions while they instead exacerbate the problem of food insecurity in Central Africa. The policy implications are that adequate resources should be channeled into proper agricultural research and development to introduce new crop varieties or significantly improved crops, etc. Moreover, there should be coordination between large and small countries in investments in order for the countries to benefit from the economies of scale.

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1. Introduction

Food security is the same as achieving the sustainable development goal 2 (SDG2) of zero hunger by 2030. Food security considerably improves educational outcomes in terms of increased academic performance [1], promoting school attendance [2], high school enrolment, and low school dropout rate [3]. Food security also lowers the prevalence of diseases such as asthma (Gundersen & Ziliak, 2015), depression [4], and abnormal body weight [5]. Again, food security is fundamental in boosting labor productivity, raising workers' earnings [6], and mitigating conflict and violence [7]. Thus, food security is critical to poverty reduction and overall national development.

Even with the global pledge to attain high food security; hunger and malnutrition remain highly prevalent as about 770 million people are at the risk of food deprivation across the world. This development does not only make the pathway to achieving SDG2 unrealistic; it also returns the world to 2005 hunger levels [8]. The problem is most pronounced in Africa, particularly sub-Saharan Africa, where about 63.2 percent of the region's population were food-insecure in 2021 [8].

In Sub-Saharan Africa (SSA), the agricultural sector generates at least 20 % of GDP and employs 70 % of the labor force. Despite these agricultural contributions; the region draws global attention in view of its perennial challenges of food insecurity. The SSA population grows at 2.4 percent annually; the region population stood at 1.18 billion in 2021 [9] and it is projected to increase to 2 billion by 2050. Africa misses a step to be food self-sufficient given that the existing methods of food production in the continent are crude and unsustainable. The continent is also being inexplicably affected by climate change, thus heightening the urgency of the need for change in the agricultural sector.

Raising agricultural productivity remains the most important pillar to reaching food security. Agricultural innovation, in turn, is an effective factor for enhancing agricultural productivity especially in the long run. Agricultural technological advancements pave the way for high-yield crops, curtailing crop losses, more efficient utilization of limited resources [10], and the final transition from low-productivity subsistence farming to high productivity [11]. Indeed, Evenson [12] points out that the extraordinary Asian agricultural productivity growth emanated mainly from crop genetic upgrading and new crop varieties. Notwithstanding, agricultural technological advancements cannot be achieved without corresponding investments in agricultural Research and Development (R&D) and researchers to create new knowledge and ideas. Although agricultural R&D investment and researchers have high positive returns; the investment has very long gestation periods, thus requiring continuous and steady funding. Otherwise, any underinvestment in this regard may strangulate long-term agricultural productivity, poverty reduction, and the ability to develop strong food and non-food value chains [10]. Technology advancements such as Artificial Intelligence (AI), blockchain technologies, the Internet of Things (IoT), big data, and drones are typical agricultural innovations [13].

Drawing from endogenous growth theories, agricultural productivity growth remains one of the important pathways through which investments in agricultural innovation influence national food security. Agricultural R&D investment and researchers produce knowledge, ideas, and innovations, which afterward modernize the cultivation and processes of agricultural production or bring about agricultural technological progress [14]. Agricultural technological progress is about producing better seeds and varieties, improving soil fertility, and raising crop and livestock yields, thereby accelerating the *availability* aspect of food security [15,16]. In other words, agricultural R&D investments and research are catalysts for the development, adoption, and diffusion of new and advanced agricultural knowledge or innovation that ultimately boost crop production [17].

Technological advancement also lowers food prices as occasioned by excessive food supply and lower cost of food production through more efficient utilization of agricultural inputs, reducing food losses, modern transport and storage systems, etc. [16]. This suggests that the investments foster the *accessibility* aspect of food security [18,19]. Agricultural productivity growth, enabled by Agricultural R&D investment and research, leads to higher income gains on the part of the farmers thereby translating into enhanced nutrition, and improvements in dietary variety (AU, 2022; [15]). It is inferred that food *utilization* and *use* come about due to technologically-supplied high-nutrient staple foods that are rich in many elements (vitamins, iron, zinc, protein, etc.). Finally, agricultural technological advancements introduce strategies to resolve acute and chronic food shortages such as weather-forecasting technologies, technologies to detect crop stress, climate-compatible agricultural practices, etc. [16].

From the empirical ground, there are many studies that empirically test the relationships between investments in agricultural innovation and various dimensions of food security. For instance, Mutenje et al [20] use the farming-household dataset to explore the correlation between the adoption of agricultural innovation and food security in Malawi, wherein they find that improved maize and storage facilities significantly raise average maize output. This is an evidence that agricultural innovation leads to *food availability*, a dimension of food security. This finding is supported indirectly by Adetutu and Ajayi [21] in their stochastic frontier analysis of the impact of domestic and foreign R&D on agricultural productivity for some sub-Saharan African (SSA) countries, implying that the investments boost food availability. Sinyolo's [22] findings in South Africa are in line with those of Adetutu and Ajayi [21] and Mutenje et al [20] in terms of food availability. Also, Gouvea et al. [23] establish that agricultural technology expands food availability among OECD countries but the technology magnifies food affordability or accessibility across a sample of non-OECD countries.

However, Lee, Koh, and Jeong [24] employ cross-country data to explore the connection between agricultural R&D investment cereal self-sufficiency ratio (food availability), whereby their findings show U-shaped relationships between them. In terms of food access, while utilizing Computable Generable Equilibrium (CGE) to analyze the Global Trade Analysis Project dataset, Kristkova et al. [15] observe that agricultural R&D investments enhance *food access* by lowering food prices. Lachaud and Bravo-Ureta [25] apply Bayesian dynamic stochastic frontier models on Latin American countries over the period 1981–2012 to distinguish the short and long-run effects of agric. R&D investments. Their results indicate that the investments have more positive impacts on food security in the long run than in the short run. Based on *food stability*, Mdemu et al. (2022) observe that agricultural innovation using soil water and nutrient monitoring tools improves food security in Tanzania.

Agricultural Science and Technology Indicators (ASTI) depict that Africa has been investing meagerly in agricultural R&D. Worse still, the investment relative to agricultural GDP (AgGDP) has been persistently dwindling between 2000 and 2016. For instance, agricultural R&D as a percentage of AgGDP has declined to 0.39 percent in 2016 from 0.42 to 0.54 percent in 2010 and 2000 respectively (AU, 2022). AU further observes that the limited investments were mostly allocated to increasing the number of researchers, salary increments, and rehabilitation of dilapidated machines and equipment while leaving the funding for actual research projects to donors. Additionally, African countries have recorded successes in producing a modest number of agricultural researchers, courtesy of donor support for training. Beintema and Sads [26] reveal that there are about 16,000 Full-Time Equivalents (FTEs) in SSA as of 2016. But then, there are few qualified principal researchers as a Doctor of Philosophy (PhD) is the minimum qualification for an agricultural researcher to conceive, execute, manage high-quality research, and effectively communicate with policymakers, donors, and other stakeholders [26].

Apparent from the review, there is a conclusive finding that investments in or adoption of agricultural innovations significantly leapfrog food security through the channel of agricultural productivity growth established in the theoretical framework. This means the investments improve food security by ensuring food accessibility, availability, and stability. Understanding the impacts of investments in agricultural innovations on food security in SSA and its sub-regional heterogeneity have several merits. First, there are extant studies that have explored the effects of the investments on many dimensions of food security such as food availability [20,23], food accessibility [15,19], and food stability (Mdemu et al., 2022). Nonetheless, these studies have mostly failed to directly examine the problem in SSA as the available ones have largely focused on how the adoption of agricultural innovations, instead of the investment, boosts food security in the region.

Second, this current study uses relatively recent data on investments in agricultural innovations and food security in SSA as well as two proxies of food security: average dietary energy supply adequacy and prevalence of undernourishment. These measures are good enough to reflect most of the dimensions of food security, and at once, they serve as an avenue for sensitivity analysis. Therefore, this study provides fresh insights into the body of knowledge. Third, this study also provides fresh evidence to the body of knowledge in two significant ways: utilization of two effective econometric techniques, and sub-regional heterogeneity in SSA.

The remaining parts of this study are structured as follows: data and methodology are presented in Section 2. Section 3 provides results and discussions, and section 4 advances the conclusion and policy implications.

2. Data and methodology

This study focuses on 24 Sub-Saharan African countries[1] over the period 2000–2016. The scope is restricted to 2000–2016 as the International Food Policy Research Institute (IFPRI) collected data on agricultural researchers as well as R&D expenditure in ASTI database only for that period and for those countries. Again, in exploring the effect of innovation on food security, it is important to decompose this effect based on sub-regions: Central Africa, East Africa, Southern Africa, and West Africa. Data on population growth is obtained from World Development Indicators while data on average dietary energy supply, prevalence of undernourishment, food consumer price index, and food production per-capita index are extracted from Food and Agricultural Organization Stat.

3. Variables and their measurements

Following relevant extant literature, we utilize two (2) indicators of food security: *Average dietary energy supply adequacy (ADEA)* and prevalence of *undernourishment (UNDR)* as a proportion of the population. As a proxy of food availability, ADEA is the Dietary Energy Supply (DES) as a proportion of the Average Dietary Energy Requirement (ADER). ADEA is an index of adequacy of food supply in terms of calories as it normalizes each country's or region's average supply of calories for food consumption. UNDR is the probability that a randomly selected individual from the population eats an amount of calories that is deficient in her/his energy requirement for an active and healthy life. UNDR is calculated by making a comparison of the probability of distribution of actual daily dietary energy consumption to a threshold level or minimum dietary requirement. In the literature of innovation economics, researchers and R&D expenditure are among the most widely used measures of innovation [27]. The measures are particularly indicators of innovation inputs for they can be deplored to generate innovative outputs or useful knowledge for innovation. In this regard, we employ the number of agricultural researchers (ARSR) in terms of (FTEs) based on work hours and agricultural R&D spending (ARDS) (in million USD) to represent a country's agricultural innovation inputs or investment in agricultural innovation.

We control for food price represented by the *food consumer price index* (FCPI) to indicate food affordability; *food production* per capita (FPPI) to serve as the mechanism through which agricultural innovation impacts national food [in]security; and we also control annual population growth (APGR). Variation in FCPI can influence the affordability of food, which in turn can affect food security; increasing food production per capita could bring about improved food availability, which is a key component of food security. Thus, controlling for FPPI enriches our understanding of the additional contribution of innovation to food security, beyond changes in production levels [28]. Population growth could raise demand for food, and high food demand pressurizes food systems to produce more food depending on the availability of resources [29].

The study hypothesizes that agricultural researchers and investment in agricultural R&D, as proxies of agricultural innovation, are

[1] Benin, Botswana, Burkina Faso, Congo Republic, Côte d'Ivoire, Ethiopia, Gabon, the Gambia, Ghana, Kenya, Lesotho, Madagascar, Malawi, Mali, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, Sierra Leone, South Africa, Tanzania, Togo and Zambia. Mozambique has no data on ADEA while Niger and Zambia have no data on UNDR.

expected to significantly contribute to national food security in the region. Specifically, investments in agricultural innovation are anticipated to raise Average dietary energy supply adequacy and lower the prevalence of undernourishment.

4. The model specification

To realize the objective of the study of whether national investment in agricultural innovation spurs food security, we adopt Warr's [30] model wherein food security is determined by food price and food per capita production. This means food security is chiefly determined by food availability (represented by food per-capita production) and food accessibility (represented by food price). Equation (1) specifies the original form of Warr's [30] model:

$$FOSE_{it} = \rho_0 + \rho_1 FCPI_{it} + \rho_2 FPPI_{it} + \mu_{it} \tag{1}$$

Where $FOSE_{it}$ stands for food security as measured by average dietary energy supply or prevalence of undernourishment; $FCPI_{it}$ represents the food consumer price index indicating changes in food prices; $FPPI_{it}$ is the food production per-capita index suggesting average food availability. We extend the model to incorporate investment in agricultural innovation as well as control for population growth as in Mughal and Sers [31]. Sub-Saharan Africa has the highest rate of population growth at 2.5 percent, which is far higher than the global average of 0.8 percent in 2022 ([32]). This means increased demand for food in the region and many studies established that population growth is a key driver of food insecurity in SSA (see Ref. [33–35]). The extended model is robust as it reflects some important dimensions of food insecurity: food availability, affordability, and utilization. The extended model is specified in equations (2) and (3) as follows:

$$FOSE_{it} = \rho_0 + \rho_1 FCPI_{it} + \rho_2 FPPI_{it} + \rho_3 POPG_{it} + \rho_4 ARCR_{it} + \eta_t + \zeta_t + \mu_{it} \tag{2}$$

$$FOSE_{it} = \rho_0 + \rho_1 FCPI_{it} + \rho_2 FPPI_{it} + \rho_3 POPG_{it} + \rho_4 ARDS_{it} + \vartheta_t + \tau_t + \varepsilon_{it} \tag{3}$$

$POPG_{it}$ is the annual population growth rate; $ARCR_{it}$ is the agricultural researchers in terms of number of full-time equivalents based on work hours; and $ARDS_{it}$ serves as the agricultural R&D spending. Note that ARCR and ARDS are the proxies of national investment in agricultural innovation. Where η and ϑ represent country dummies; ζ and τ represent time dummies; μ and ε are the overall error terms for the equations; and $\rho's$ are the parameters to be estimated.

We estimate the equations using both static and dynamic panel regression models of bootstrapped least squares dummy variable (LSDV) and two-step system generalized method of moments (sys-GMM) correspondingly. Bootstrapped LSDV technique is a sort of fixed-effect estimator that considers heterogeneity across cross-sectional units and over time as well as seeks to replicate the results multiple times by resampling the observations (with replacements) [36]. Bootstrapping can efficiently handle the problem of missing data by employing resampling techniques to generate estimates. This can guarantee the reliability of the dataset and avoid spurious results [37]. Bootstrapping method is effective in dealing with a problem of heterogeneity [38] and, SSA countries can vary significantly in their agricultural policies, practices, and levels of innovation leading to heterogeneity.

Sys-GMM estimator was developed by Arellano and Bond [39] for short panel data analysis based on data-generating assumptions that the procedure could be dynamic in which current values for the explained variable are determined by its past values. This is in addition to the assumption that the explanatory are weakly exogenous and could be correlated with the past and even present values of the error term. The strengths of the estimator lie in its ability to tackle potential endogeneity and autocorrelation as well as being consistent when T is small. As proposed by Arellano and Bond [39], Hansen statistics and second-order autocorrelation, *AR(2)*, are the key specifications validating the instruments or otherwise.

5. Results and discussions

In Table 1, the descriptive statistics reveal that the mean values of the average dietary energy supply adequacy and rate of undernourishment for the SSA are 111.29 and 18.98 percent respectively. This means there was an oversupply of calories by about 11.29

Table 1
Summary statistics of variables for sub-Saharan.

Summary	ADER	UNDR	Population Growth	Food CPI	Food per capita	Agric. Researchers	Agric. R&D Spending
Mean	111.29	18.98	2.48	70.76	97.71	366.52	6.66e+07
Std. Dev.	12.52	10.53	0.89	27.70	17.56	537.90	1.06e+08
Minimum	82	3.10	−0.40	9.69	42.49	26.98	850038.5
Maximum	142	50.70	5.79	216.40	168.56	3024.64	5.41e+08
Pair-wise Correlation Matrix							
ADER							
UNDR	**−0.91**						
Population Growth	−0.19	0.36					
Food CPI	0.33	−0.31	0.01				
Food per capita	0.14	−0.18	−0.25	0.26			
Agric. Researchers	0.10	−0.13	0.06	−0.08	−0.10		
Agric. R&D Spending	0.26	−0.34	−0.10	−0.09	−0.07	0.79	

percent over the study period. The average full-time equivalents of the agricultural researchers and agricultural R&D spending for the region hover around 366.52 h and US$ 66.6 million per annum respectively.

The table shows that the average Food CPI and Food per capita production for SSA stand at 70.76 and 7.71 respectively. The correlation matrix suggests that there are weak correlations between the variables except between average dietary energy supply adequacy and undernourishment rate, and between agricultural researchers' FTEs and agricultural R&D expenditure. Thus, there would be less problem of multicollinearity as those variables with strong correlation coefficients are not included in the same model at once.

Table 2 presents summary statistics for the sub-regions with West Africa having the highest mean values of average dietary energy supply adequacy and agricultural R&D spending of 117.16, which is an oversupply of calories (17.16 percent), and US$ 81.6 million per annum respectively. The table suggests that East Africa has the least mean value of average dietary energy supply adequacy of 100.25 but the highest mean rate of undernourishment of about 27.89 percent. This means the sub-region has the highest incidence of food insecurity based on the two indicators. The sub-region shows also the largest number of FTEs of 1135.68 h per annum. This implies that the incidence of food insecurity in a sub-region can persist despite having a large number of agricultural researchers due to insufficient funding as agricultural research requires adequate funding to finance research activities, infrastructure, and human resources (FAO, 1996). Other possible reasons include limited access to technology and lack of policy support [40,41]. Table 2 signifies that Central Africa has the smallest agricultural R&D spending of US$ 4.1 million per annum.

The table also indicates that Southern Africa has the largest food per capita production index of 103.06 followed by Central Africa. The highest food prices are in Central Africa at about 84.66.

A preliminary analysis between proxies of food security and investments in agricultural innovation depicts that both full-time equivalents of agricultural researchers and agricultural R&D expenditures are positively correlated with average dietary supply adequacy (Fig. 1a and b). However, agricultural R&D expenditure is more fitted with the average dietary supply adequacy in the region. Conversely, Fig. 2a and b shows that full-time equivalents of agricultural researchers and agricultural R&D expenditure are all negatively correlated with the prevalence of undernourishment in the region. This suggests that full-time equivalents of agricultural researchers and agricultural R&D expenditure could boost food security by increasing dietary energy supply while at once reducing undernourishment.

Bootstrapping LSDV results in Table 3 depict that investments in agricultural innovation enhance food security by significantly raising average dietary energy supply adequacy (ADER) in Sub-Saharan Africa and across the sub regions. In particular, the percentage rises in full-time equivalents of agricultural researchers' hours and R&D spending lead to increments in average dietary energy supply adequacy by 3.32 and 3.06 percentage points respectively (see Full-sample results in Table 3).

The table above shows that population growth, food availability, and sub-regional dummies are also statistically significant and the signs have met the theoretical expectations as well. Only West Africa, compared with Central Africa, has a positive and significant effect on average dietary energy supply adequacy in the region. Unexpectedly, the table also shows that investments in agricultural innovation cut down the dietary energy supply in the Central African region, which could be due to inefficient utilization of the resources to boost food production in the sub-region. The negative effect may be due to the small size of the sub region. Only in Southern and West African sub-regions that the investments are significant in boosting food security as the resources are efficiently deplored in introducing food supplements with sufficient energy contents. The investments have larger impacts in Southern Africa than they have in West Africa.

Table 4 shows that full-time equivalents of agricultural researchers' hours and R&D spending reduce the prevalence of undernourishment by about 32.0 and 22.4 percentage points respectively. They are statistically significant at 1 percent level. Among the control variables in Table 4, only Food per capita that significantly and negatively affects the prevalence of undernourishment.

Compared with Central Africa, Southern and eastern Africa have positive and significant effects on prevalence of undernourishment in the regions (see Table 4). Surprisingly, the table suggests that investments in agricultural innovation, instead, raise undernourishment in the Central African region, perhaps due to the inefficient application of the resources to boost food production and the small size of the countries in the region. In East, Southern, and West African sub-regions, however, the investments are significant in lowering undernourishment. It is likely that the resources are efficiently employed in introducing new and highly nutritious food supplements in the sub-regions. Similarly, the investments have the largest effects in Southern Africa, and that may be a result of the presence of more innovative and wealthier countries (like South Africa, Botswana, Mauritius, and Namibia) with large-scale spillover

Table 2
Summary statistics of variables for the sub-regions.

	Central Africa		East Africa		Southern Africa		West Africa	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Average Dietary	107.56	11.80	100.25	6.91	107.96	12.59	117.16	9.77
Undernourishment	22.38	9.35	27.88	7.87	18.94	10.47	15.12	7.60
Population Growth	3.12	0.52	2.81	0.24	1.83	1.03	2.79	0.43
Food CPI	84.66	11.77	54.22	30.75	68.90	28.29	73.58	27.42
Food per capita	101.71	8.33	88.91	13.50	103.06	18.84	91.36	10.85
Agric. Researchers	75.12	29.20	1135.68	586.10	210.16	199.34	436.54	610.21
Agric. R&D Spending	4091045	2612527	1.40e+08	7.44e+07	5.39e+07	9.88e+07	8.16e+07	1.19e+08

Source: Authors' Computation Using Stata 17.0

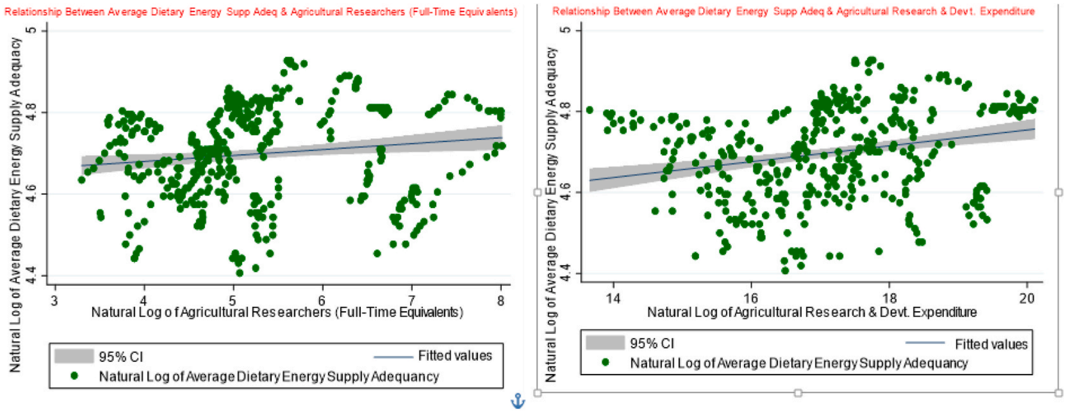

Fig. 1. a: Dietary-researchers relationship Fig. 1b: Dietary-R&D relationship.

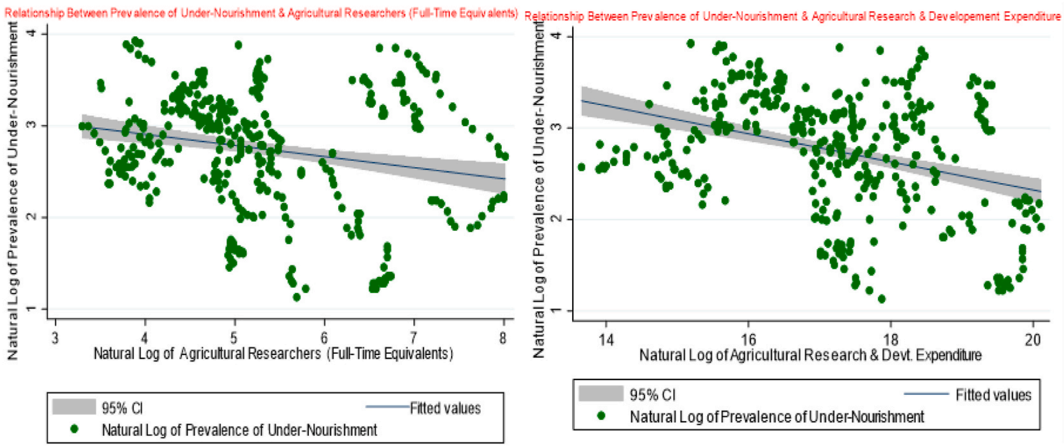

Fig. 2. a: Undernourish-researchers rel. Fig. 2b: Undernourish-R&D relationship.

effects in the regions.

Sys-GMM results in Table 5 also confirm some of the findings in Table 3 as the investments in agricultural innovation are found to significantly spur food security in the SSA countries. For instance, each of the full-time equivalents of agricultural researchers' hours and R&D spending raise average dietary energy supply adequacy by about 5.0 percentage points. The table also indicates that food CPI negatively and significantly affects average dietary energy supply adequacy while food per capita positively and significantly impacts the dietary energy supply. Full-time equivalents of agricultural researchers' hours and R&D spending reduce the rate of undernourishment in the region by 50.7 and 7.5 percentage points respectively, though weakly significant at 10 percent. System-GMM depends on instrumental variable(s) to address endogeneity and measurement errors and incorporates time dimensions in its estimation, which could be the reasons why the coefficients of full-time equivalents of agricultural researchers' hours and R&D spending are much bigger here than under Bootstrapped LSDV.

Among the control variables, only food per capita and population are statistically significant in researchers and R&D models of undernourishment in Table 4 respectively. In terms of the Sys-GMM models' goodness-of-fit, no evidence proving the existence of second-order autocorrelation in view of high p-values greater than all levels of significance. Similarly, the p-value of Hansen statistics is also higher than all levels of significance suggesting the validity of the instruments while the F-statistics are also significant. This means the estimated results are robust for inferences.

These findings align with those of previous studies [15,25] though they were conducted in different regions with different time periods and using different estimation techniques.

Evident from most of the estimated models is that full-time equivalents of agricultural researchers' hours have a bigger impact (based on the size of coefficients) on food security than agricultural R&D spending has. The possible reasons are not farfetched. The agricultural researchers' hours can be easily tailored toward priority areas in agricultural innovation. Once priority areas are identified, the researchers can produce more germane and impactful solutions for food security by engaging with relevant stakeholders to address specific food security challenges in a given region or province [42,43]. Full-Time Equivalent of agricultural researchers' hours can be more malleable and approachable to emerging challenges and opportunities compared to long-term research projects based on

Table 3
Bootstrapping LSDV results on the effects of investments in agric. Innovation on average dietary energy supply adequacy.

Average Dietary Energy Supply Adeq.	Full Sample			Central Africa		East Africa		Southern Africa		Western Africa	
	Baseline Model	Agric. Res.	Agric. R&D	Agric. Res.	Agric. R&D	Agric. Res.	Agric. R&D	Agric. Res.	Agric. R&D	Agric. Res.	Agric. R&D
Population Growth		−0.052***	−0.046***	−0.039	−0.026	0.109***	0.076	−0.088***	−0.075***	0.027*	0.063***
		(0.006)	(0.006)	(0.031)	(0.031)	(0.034)	(0.073)	(0.010)	(0.0064)	(0.014)	(0.014)
Food CPI	−0.026*	−0.004	−0.012	0.415	−0.171	0.251***	0.195***	−0.123	−0.077	0.030	0.044*
	(0.014)	(0.021)	(0.018)	(2.853)	(0.741)	(0.037)	(0.045)	(0.085)	(0.071)	(0.031)	(0.023)
Food per capita	0.117***	0.061**	0.063**	−0.990	0.244	−0.322***	−0.165	0.001	−0.031	0.136***	0.136***
	(0.0281)	(0.030)	(0.027)	(1.594)	(0.664)	(0.058)	(0.197)	(0.059)	(0.052)	(0.051)	(0.038)
Agric. Researchers		0.033***		−0.418***		0.031		0.064***		0.029***	
		(0.004)		(0.054)		(0.022)		(0.008)		(0.011)	
Agric. R&D Spending			0.021***		−0.124***		−0.021		0.064***		0.040***
			(0.003)						(0.008)		(0.005)
East Africa		−0.168***	−0.146***								
		(0.016)	(0.013)								
South Africa		−0.067***	−0.070***								
		(0.019)	(0.016)								
West Africa		0.075***	0.072***								
		(0.010)	(0.013)								
Time Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	504	409	409	34	34	51	51	137	137	170	170
R-squared	0.373	0.547	0.537	0.936	0.972	0.921	0.905	0.596	0.634	0.350	0.450
Boostrap Replication	50	35	35	48	48	35	31	20	22	50	50

Standard errors in parentheses ***p < 0.01, **p < 0.05, *p < 0.1. **Note:** Baseline model is the original Warren's [30] model, Agric. Res. Stands for the Full-time equivalents of agricultural researchers, Agric. R&D stands for the total annual expenditures on agricultural research and development.

Table 4
Bootstrapped LSDV results on the effects of investments in agric. Innovation on prevalence of under-nourishment.

Prevalence of Under-Nourishment	Full Sample			Central Africa		East Africa		Southern Africa		Western Africa	
	Baseline	Agric. Res.	Agric. R&D	Agric. Res.	Agric. R&D	Agric. Res.	Agric. R&D	Agric. Res.	Agric. R&D	Agric. Res.	Agric. R&D
Population Growth		0.423***	0.352***	0.122	0.055	0.012	−0.007	0.598***	0.456***	−0.213	−0.397***
		(0.031)	(0.028)	(0.136)	(0.174)	(0.077)	(0.222)	(0.035)	(0.028)	(0.144)	(0.128)
Food CPI	0.216***	−0.124	−0.059	−0.466	1.514	−0.659***	−0.484***	−0.699*	−1.076***	−0.035	−0.212
	(0.073)	(0.077)	(0.074)	(2.147)	(1.924)	(0.128)	(0.125)	(0.358)	(0.222)	(0.170)	(0.139)
Food per capita	−0.632***	−0.117	−0.189*	2.879***	−1.625***	0.132	0.231	0.868***	1.042***	−0.657*	−0.691***
	(0.106)	(0.140)	(0.108)	(0.235)	(0.502)	(0.192)	(0.663)	(0.191)	(0.182)	(0.370)	(0.268)
Agric. Researchers		−0.320***		1.450***		−0.226**		−0.527***		−0.147***	
		(0.023)		(0.098)		(0.094)		(0.0311)		(0.045)	
Agric. R&D Spending			−0.224***		0.399***		−0.083		−0.330***		−0.257***
			(0.021)		(0.066)		(0.117)		(0.023)		(0.032)
East Africa		1.121***	0.951***								
		(0.071)	(0.065)								
South Africa		0.418***	0.453***								
		(0.103)	(0.064)								
West Africa		−0.051	0.021								
		(0.061)	(0.071)								
Time Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	462	392	392	34	34	51	51	137	137	153	153
R-squared	0.236	0.554	0.551	0.973	0.961	0.943	0.884	0.844	0.847	0.326	0.454
Boostrap Replication	50	22	21	45	48	29	28	30	27	50	49

Standard errors in parentheses ***p < 0.01, **p < 0.05, *p < 0.1. **Note:** Baseline model is the original Warren's [30] model, Agric. Res. Stands for the Full-time equivalents of agricultural researchers, Agric. R&D stands for the total annual expenditures on agricultural research and development.

Table 5
Two-system GMM results on the effects of investments in agric. Innovation on average dietary energy supply adequacy prevalence of under-nourishment.

	Average Dietary Energy Supply Adequacy			Prevalence of Under-Nourishment		
	Baseline Models	Agric. Res.	Agric. R&D	Baseline Models	Agric. Res.	Agric. R&D
Average Dietary Energy Supply Adequacy$_{t-1}$	1.412***	0.999***	0.702***			
	(0.299)	(0.246)	(0.101)			
Prevalence of Under-Nourishment$_{t-1}$				−0.244***	0.711**	1.219***
				(0.057)	(0.354)	(0.098)
Population Growth		0.014	0.046	−0.037	−0.028	−0.181**
		(0.021)	(0.035)	(0.024)	(0.160)	(0.083)
Food CPI	−0.036**	−0.042**	0.004	0.136	0.183	0.090
	(0.018)	(0.017)	(0.014)	(0.092)	(0.129)	(0.077)
Food per capita	−0.035	0.131*	0.089		−0.964**	0.161
	(0.073)	(0.076)	(0.080)		(0.394)	(0.219)
Agric. Researchers		0.050**			−0.507*	
		(0.022)			(0.304)	
Agric. R&D Spending			0.050**			−0.075*
			(0.022)			(0.042)
Observations	480	385	361	440	385	361
Instruments/Groups	22/24	19/24	18/24	22/24	19/24	18/24
Hansen *p*value	0.317	0.210	0.483	0.341	0.210	0.483
AR(2) *p*value	0.298	0.172	0.113	0.643	0.172	0.113
F-Statistics	140456.33	92043.00	178960.80	109089	92043	178960.80

Standard errors in parentheses ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. **Note:** Baseline model is the original Warren's [30] model, Agric. Res. Stands for the Full-time equivalents of agricultural researchers, Agric. R&D stands for the total annual expenditures on agricultural research and development.

R&D spending ([44]). The agricultural researchers' hours could also be more easily channeled into collaboration and sharing of knowledge among institutions, stakeholders, and disciplines. In so doing, complex and multidimensional food security challenges can be addressed by integrating different perspectives, expertise, and resources [45].

Empirical evidence and theoretical postulations have observed that economies of scale and scope, based on inception fixed costs, are critical in determining the performance of investments in agricultural innovations [46,47]. Small countries are more often than not constrained by their lack of capacity to mobilize sufficient resources for agricultural innovation and, where sufficient resources are generated, the countries lack sufficient agricultural production areas to allocate the resources into. As a consequence, small countries record far lower returns from their investments in agricultural R&D and research (AU, 2022). Our findings on Central Africa have clearly confirmed this assertion as the investments, instead, acerbate the problem of food insecurity, and the sub-region has many small countries.

6. Conclusion and policy implication

Investing adequately in agricultural R&D and research remains an important source for generating agricultural knowledge, ideas, and innovation that subsequently bring about high food security, especially at the national level. Many developed and emerging economies have recorded successes in attaining food security and poverty reduction through their heavy investments in agricultural innovations. However, sub-Saharan Africa invests stingily in agricultural R&D and research despite glaring evidence that agricultural innovation is an effective force for guaranteeing food security. To further draw the attention of policymakers and stakeholders to the importance of investments in agricultural innovation in SSA, this study explores the impacts of agricultural R&D spending and researchers' hours on food security in the region and across the sub-regions. We extract data on agricultural researchers' hours and, agricultural R&D expenditure from ASTI database for 24 SSA countries over the period 2000–2016 while other data sources include FAO Stat and WDI. The study applied Bootstrapped LSDV and two-step system GMM techniques to analyze the dataset.

Our findings show that investments in agricultural innovation substantially increase food security utilization through food productivity growth. It is likely that the resources are allocated to innovating foods with high nutrient contents, or that undernourishment is highly prevalent in the region such that any investment leads to an important outcome. The findings also reveal that the investments are effective in enhancing food security at least in Southern and Western African sub-regions while they instead exacerbate the problem of food insecurity in Central Africa. We have equally observed that the full-time equivalents of agricultural researchers' hours are more impactful on food security than R&D spending. This is a cursor to the fact that economies of scale and scope constrain small countries from deriving the full benefits of investments in agricultural innovations as Central Africa has many small countries.

The findings have some implications for policymakers, researchers, development practitioners, and other stakeholders in the campaign of zero hunger in developing countries. The findings imply that adequate resources should be channeled into proper agricultural research and development to introduce new crop varieties or significantly improved crops, climate-compatible agricultural systems, etc. Another policy implication is that there should be coordination between large and small countries in investments in order for the countries to benefit from the economies of scale.

Data availability statement

All data used in the generation of the results presented in this manuscript will be made available upon reasonable request from the corresponding author.

CRediT authorship contribution statement

Karel Malec: Visualization, Resources, Investigation, Formal analysis, Conceptualization. **Stanislav Rojík:** Methodology, Funding acquisition, Data curation. **Mansoor Maitah:** Supervision, Resources, Funding acquisition, Data curation. **Musa Abdu:** Writing – review & editing, Project administration, Formal analysis. **Kamal Tasiu Abdullahi:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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