A G D I Working Paper

WP/22/007

ICT and agriculture in Sub-Saharan Africa: effects and transmission channels

Edmond Noubissi Domguia
Centre d'Etudes et de Recherches en Management et Economie,
Laboratoire de Recherche en Economie Fondamentale et Appliquée,
Dschang, Cameroon
E-mail : enoubissidomguia@yahoo.fr

Simplice Asongu
African Governance and Development Institute,
P.O. Box 8413,Yaoundé, Cameroon
E-mails: asongusimplice@yahoo.com, asongus@afridev.org

2022 African Governance and Development Institute WP/22/007

Research Department

ICT and agriculture in Sub-Saharan Africa: effects and transmission channels

Edmond Noubissi Domguia & Simplice A. Asongu

January 2022

Abstract

This study contributes to the extant literature on the nexus between information and communication technologies (ICTs) and agriculture. Despite increasing attention on the subject, existing studies are sparse on the channels through which ICTs affect the agricultural sector. We use a stochastic impact model extended to the population, affluence and technology regression model to assess both the impact and transmission of ICTs on agriculture in 18 sub-Saharan African countries. The empirical results show that ICT use measured by Internet, mobile and fixed-line telephone penetration boosts the agricultural sector enormously. In addition, the mediation analysis reveals that ICTs not only have a direct positive effect on agriculture but also a positive indirect effect through its impact on financial development and trade openness and a negative indirect effect through energy consumption. However, the total effect is positive and shows that ICTs are supporting the development of the agricultural sector in sub-Saharan Africa. To enhance the positive effects of ICTs on agriculture, governments should design policies to improve access to credit for the private sector, promote liberalization, and provide financial incentives for the development of green and less expensive agricultural technologies.

Keywords: ICT, agriculture, Sub-Saharan Africa, transmission channels, mediation.

1. Introduction

The holistic application of ICTs to agricultural development is receiving increasing attention. Indeed, the agricultural sector has always been characterized by a strong demand for information and communication (Cash, 2001; McNamara et al., 2011). Three facts justify this growing demand. Firstly, the adoption of ICTs can improve the productivity and efficiency of agriculture. Indeed, the rapid diffusion of ICTs has led to a powerful interest in developing applications that allow farmers to access markets, services and inputs, as well as support decision-making processes and the management of farms (Daum et al., 2019). Secondly, ICTs have the potential to enable farmers to overtake the challenges of agricultural production (Binswanger and Rosenzweig 1986). These challenges consisted mainly of risks that are exacerbated by climate change. These risks include: seasonality and spatial dispersion of agriculture, high transaction costs, asymmetric information and the need for very specific management knowledge. Thus, the triptych of information, communication and knowledge are key factors that can enable the acceleration of agricultural development by means of production planning, marketing management, effective post-harvest and adoption of farming practices (Bertolini, 2004; Kizilaslan, 2006; Kalusopa, 2005; Lio and Liu, 2006; Sarahelen and Sonka, 1997; Palaskas et al. 1997; Poole and Kenny, 2003; Streeter et al. 1991). Thirdly, information asymmetry in the agricultural sector generates inefficiencies throughout the production chain (Eggleston et al., 2001; Ravallion, 1986). Such information asymmetry is the major problem facing farmers in developing countries (Gollakota, 2008; Adhiguru and Mruthyunjaya, 2004; Rao, 2006).

Moreover, there seems to be unanimity both in theory and practice on the effects of ICTs on agriculture. Overall, the authors highlighted in the previous paragraph found only beneficial effects of ICTs on agriculture. The estimation technique can partially explain this unanimity in the literature used, the variables used to capture agriculture and ICT, the periodicity and the sample of countries chosen for the study. However, existing work has ignored the role and importance of the mechanisms by which ICTs can affect agriculture. This could however be useful in identifying the key factors on which policies could operate to lead to food security and sustainability. To fill this gap, we analyze the effects of ICT adoption on the agricultural sector in Sub-Saharan Africa (SSA) with a focus on transmission mechanisms. Specifically, the purpose of the study is to provide answers to the following questions: Does ICT adoption impact the agricultural sector in SSA? If so, what are the transmission channels for the impact of ICTs on agriculture? By extension, what are the corresponding implications for food security and sustainability?

This study is important for at least four reasons. First, agriculture in SSA is a vector for growth. Indeed, agriculture is the engine of overall growth for most countries in the region and is indispensable for poverty reduction and food security. The share of the agricultural sector in the SSA economy is about 17.1% of real GDP and accounts for 40% of the foreign exchange earnings by these countries (WDI, 2016). Second, inadequate extension services and inadequate infrastructure are the key causes of low agricultural output in SSA compared to other regions. This results in low use of irrigation, fertilizers, improved seeds and pesticides (Bilali and Allahyari, 2018). Third, agricultural development and poverty reduction in SSA are closely linked to the evolution of small-scale agriculture (FAO, 2009). Indeed, the development of ICTs has turned food systems into globally integrated and capital-intensive chains. Thus, the differential related to the adoption of unknown technologies and the diffusion of knowledge can cause the crowding out of smallholders by large farmers. Fourth, SSA is on the verge of a digital revolution (ITU, 2019). Indeed, most SSA countries are increasingly relying on ICTs to ensure the market competitiveness of their economies through technical innovation and global entrepreneurship.

After this introductory part, we structure the rest of the paper as follows. Section 2 presents the literature review. Section 3 describes the data and the econometric approach. Section 4 presents and discusses the main empirical results gotten. Section 5 concludes with implications and future research directions.

2. Literature review.

2.1. ICT and agriculture: evaluating the direct effect

The sublimation capacity of virtually all sectors of activity offered by ICTs is the subject of a plethora of studies (Dao et al., 2011; Caputo et al., 2018). However, in this synthesis of the literature, we focus on work related to the influence of ICTs on agriculture. Indeed, several authors have shown that ICTs can improve the resource efficiency of the agricultural sector and the productivity of food systems (Svenfelt and Zapico, 2016; Berti and Mulligan, 2015; Thöni and Tjoa, 2017). In this way, ICTs can be applied throughout the agricultural chain. We can use them to better manage basic production factors (soil, capital, labour and land), to access services and inputs, including services that are extended, and to facilitate marketing and processing. In other words, ICTs are more conducive to the development of precision agriculture. For Balafoutis and al. (2017), precision agriculture technologies (PAT) include variable rate irrigation, variable rate nutrient application, variable rate pesticide application, precision physical weeding technology, variable rate plantation/seeding, machine guidance (driver help or self-steering), traffic-controlled agriculture (a system that confines all machine loads to permanent traffic lanes).

According to Lehmann and al. (2012), ICTs can help reduce the use of agricultural inputs (fertilizers, energy, pesticides and water) and environmental externalities. This justifies the growing interest that many farms around the world may have in using ICTs. These farms are using extensive data and data analysis to improve the productivity of their farming practices (Bilali and Allahyari, 2018). For example, ICTs make it possible to adapt the quantities of inputs to the genuine needs of crops and according to land area, and to reduce energy consumption and the ecological footprint of the agricultural sector. This reduction in using inputs has positive effects on the environment (Balafoutis et al., 2017; Schrijver et al., 2016; Bora et al., 2012; Mutchek and Williams, 2010; Saidi, 2013) and on the economy (Balafoutis et al., 2017; Tekin, 2010; Batte and Ehsani, 2006). In a similar vein, Hedley (2015) argues that ICT-based decision support systems enable farmers to minimize production costs and the ecological footprint of their activities while maximizing production efficiency. However, the adoption of ICTs by farmers depends on the margin they can make on the sales of their products (Berti and Mulligan, 2015). This idea is further supported by Mintert et al. (2016), who show that widespread adoption of ICTs in agriculture is a function of the additional profitability gain that farmers can derive from such adoption.

The influence of ICTs on agriculture is useful for ensuring food security. Indeed, this has led to a burgeoning literature on the relationship between ICTs and food security (Bello and Aandderbigbe, 2014; Kolshus et al., 2015).

Conway (2016) attests that the first Green Revolution in Africa was a failure because of low ICT adoption rates. Similarly, infoDev (2009) assumes that the current mobile revolution on the continent offers genuine hope for different outcomes. In addition, ICT can improve rural livelihoods as well as empower small scale farmers in developing countries by improving connectivity (McLaren et al., 2009; Sylvester, 2015) and increasing the access and usage of agricultural and market information (infoDev, 2009). As a result, ICTs contribute to empowering farmers as innovators, enabling them to respond to opportunities and threats. Such empowerment can be achieved by improving their access to information leading to innovation (UNCTAD, 2008). In addition, ICTs, especially mobile phones, enable farmers, even in developing countries, to access needed financial services at low cost (Kolshus et al., 2015; World Bank, 2017).

Finally, ICTs are also needed for food processing, distribution and consumption. ICTs are involved in the transport and storage of agricultural products (Kolshus et al., 2015; Harris et al., 2015; Thöni and Tjoa, 2017). They reduce the number of middlemen and therefore contribute to reducing transaction costs in the food chain (Berti and Mulligan, 2015; Sylvester, 2015; FAO, 2013; Conway, 2016; FAO, 2017). We also need ICTs to reduce information asymmetry along the production chain and ensure food traceability (Wognum and Bremmers, 2009; Wognum et al., 2011; Kaloxylos al., 2013; Caputo et al., 2018; Del Giudice et al., 2017).

In the light of these findings, it is relevant to engage new research on the incidence of ICT penetration on agriculture. Considering that countries from SSA are still at the primary stages of adopting ICT, the following hypothesis is tested:

Hypothesis 1: ICT penetration ameliorate agricultural sector in SSA countries.

2.2. The role of transmission channels

Although there has been a growing strand of empirical works on the effect of ICT on agriculture, the extant studies have failed to empirically identify the mechanisms via which ICT impedes or improves the agricultural activities. From the attendant literature, which is engaged in the subsequent paragraphs of this section, energy consumption, financial development and trade openness are potential channels.

The first is the energy consumption mechanism. Accordingly, there is a large bulk of literature on the impact of energy consumption on agriculture (Stanhill, 2012; Jones, 1989; Leach, 1975), and most of these studies conclude to a favourable contribution of energy consumption to increasing agricultural activities. In this context, ICT could increase the agricultural sector if it contributes to improve energy efficiency. Conversely, ICTs can contribute to a reduction in agricultural activities if their adoption is accompanied by a high demand for energy. The empirical literature on the effects of ICT on energy consumption is far from unanimous. For example, Yu et al. (2020) have demonstrated the usefulness of ICTs in reducing energy demand. Conversely, employing ICT users; the imports percentage of ICT goods in total imports and mobile phone subscribers as proxies for ICT, Afzal and Gow

(2016) establish that energy consumption is positively linked to the penetration of ICT in 11 emerging economies. This finding is consistent with the results obtained by Dabbous (2018) over the 1995–2014 period in MENA countries.

Trade openness denotes the second mechanism from ICT to agricultural sector. The corresponding indirect impact of ICT on the agriculture sector can be elicited by the fact that ICT mitigates the constraints and the costs linked to agricultural trading activities. Moreover, information is made available by the internet on the location of factors of production and such information can be leveraged upon to improve international trade in goods. For example, Choi (2010) assessed the impact of internet usage on trade services in 151 countries during the period 1990-2006 and the corresponding result indicates that a 1% positive change in internet usage leads to an increase in trade services between 0.023% and 0.042%. Yushkova (2014) examines the incidence of ICT on trade in nations which have various technology categories (Low, High, High-medium and Medium-low technology industries, including Manufactures). The findings show that the use of ICT stimulates exports both in importing and exporting countries contingent on the technology category. Ozcan (2018) has examined the impact of ICT on international trade involving Turkey and its partners in trade. Using an extended gravity model, the author found that ICT penetration substantially boosts the volumes of Turkish trade in terms of imports and exports.

The third mechanism considered is financial development. In essence, access to finance has been well established as a major obstacle to the prosperity of many sectors of the economy, including the agricultural sector (Ssozi et al., 2019; Asongu, 2020). From a theoretical angle, Asongu et al. (2016) have argued that ICT (i) improves financial sector development via improvements in the availability of credit to both households and firms; (ii) reduces asymmetric information between lenders and borrowers and (iii) boosts competition between financial sectors (i.e. the formal and informal sectors). In the process of enhancing financial intermediation and consolidating financial transactions, ICT can improve long term economic growth (Tchamyou et al., 2019) by means of better allocation of productive investments, and hence, increases agricultural sector development. Edo et al. (2019) establish that internet adoption has both a positive and a significant effect on financial development during the period 2000-2016 in Kenya and Nigeria. In the light of the preceding arguments and corresponding findings, we propose the following testable hypothesis:

Hypothesis 2: The effect of ICT on agricultural sector operates through energy consumption, trade openness and financial development.

3. Model, variables and data.

3.1. Empirical model

Given the very close link between agriculture and the environment, we propose to use one of the models employed to capture the effects of anthropogenic activities on the environment. Shahbaz et al. (2017) and Yu et al. (2020) also made this adaptation for the estimation of the ICT-energy demand link. In the present study, a STIRPAT (Stochastic Impact by Regression on Population, Affluence and Technology) model proposed by Dietz and Rosa (1994) is thus used. The basic STIRPAT model for our study is Equation (1):

$$I_{it} = aP_{it}^{b}\, A_{it}^{c} T_{it}^{d} \varepsilon_{it} \qquad (1)$$

Where agriculture (I) is a function of population size (P), wealth (A) and technology (T); a is a constant term while superscripts b, c and d are parameters linked to P, A and T respectively and Ɛ is the error term. The indices i and t represent country and time, respectively.

To take into account other variables, we extend the basic STIRPAT model as follows in Equation (2):

$$I_{it} = aP_{it}^{b}\, A_{it}^{c} T_{it}^{d} Z_{it}^{e} \varepsilon_{it} \qquad (2)$$

Where Z represents other exogenous variables that can influence the agricultural sector and e, the parameter associated with Z. Z is a vector of transmission channels. The linear model is obtained by introducing the log into Equation (2). This results in Equation (3):

$$lnI_{it} = a + blnP_{it} + clnA_{it} + dlnT_{it} + elnZ_{it} + \varepsilon_{it} \qquad (3)$$

Where In (...) is the Nerian logarithm.

To analyse the effects of ICTs on agriculture in SSA, Equation (3) has been reworded to Equation (4) as follows:

$$lnAgri_{it} = \alpha_0 + \alpha_1 \ln(ICT)_{it} + \alpha_2 \ln(GDP)_{it} + \alpha_3 \ln(Z)_{it} + \mu_i + \theta_t + \varepsilon_{it} \quad (4)$$

Where Agri is the agricultural sector, ICT is information and communication technology which can also be used as a proxy for population because of its unit of measurement, GDP is per capita income. Z is the matrix of control variables and also the transmission channels which includes financial development (fidev), energy consumption (Energy), foreign direct investment (FDI) and trade openness (Trade).

In order to verify whether some of our control variables have a mediating effect the agricultural sector, causal mediation analysis is employed (Baron and Kenny, 1986; Zhao et al., 2010). The attendant procedure is useful for understanding if and to what extent the incidence on agriculture by ICTs is mediated by modulating variables. However, it is worthwhile to note that the mediation analysis supposes that ICT adoption predates the transmission mechanisms.

Relaxing the underlying assumption could either underestimate or overestimate the indirect impact. Therefore, the results will provide insights into simple policy-making guidelines. The attendant analysis comes after the method of Papyrakis and Gerlagh (2004), who have studied the transmission channels surrounding the resource curse hypothesis. A mediation analysis has also been used by Yogo and Mallaye (2015) to study the transmission mechanisms of health aid. To our knowledge, no previous attempts have focused on channels ranging from ICTs to agriculture.

The analysis of mediation is established by estimating the following model in Equation (5):

$$lnZ_{it}^{j} = \beta_0 + \beta_1 \ln ICT_{it} + \varphi_{it} \qquad (5)$$

Where Z^j is the j^{th}channel. β_1 is the effect of ICT on the transmission channel, β_0 is the constant and φ_{it} is the error term. In the first step of the algorithm, Equation (5) is estimated to determine the impact of ICT on each transmission channel. If β_1 is statistically significant (i.e. if ICT penetration explains part of the variation in the transmission channel), then we calculate the indirect effects of ICT on agriculture. By replacing Equation (5) in Equation (4), we obtain Equation (6):

$$lnEn_{it} = \alpha_0 + \alpha_3\beta_0 + (\alpha_1 + \alpha_3\beta_1) \ln ICT_{it} + \alpha_2 \ln(GDP)_{it} + \alpha_3 \varphi_{it} + \mu_i + \theta_t + \varepsilon_{it} \qquad (6)$$

α_1 is the direct effect of ICTs on agriculture; $\alpha_3\beta_1$ is the indirect effect of ICTs on agriculture; and ($\alpha_1 + \alpha_3\beta_1$) is the total effect of ICTs on agriculture. We estimate these effects using the structural equation modelling approach, which allows these effects to be tested in a single analysis as opposed to testing different regressions. Consistent with Zhao et al. (2010), for mediation to be empirically valid, the indirect effect (i.e. $\alpha_3\beta_1$) should be statistically significant.

3.2. Variable specification

i. Dependent variable.

The dependent variable for our empirical model is agriculture. We use three different indicators of the agricultural sector in this study. The first-two proxies represent output while the last one measures an agricultural input. (i) Total value of crop and livestock production (output), (ii) total agricultural factor productivity (TFP) growth, (iii) total agricultural land in hectares equivalent of rainfed cropland (LandUse). These variables have been used in the empirical literature to capture agriculture (Plant et al., 2000; Balafoutis et al., 2017; Adelaja and George, 2019).

ii. Independent variable of interest

For this study, we selected information and communication technologies (ICT) as an independent variable of interest. We use three proxy variables to capture it, namely: Internet use, fixed and mobile phone subscription rates. We measure Internet use as the proportion of the population with access. The number of fixed telephone subscriptions is understood as the sum of the number of fixed wireless local loop, active analogue fixed telephone lines and Voice over IP (VoIP) subscriptions. Cellular mobile telephone subscriptions represent subscriptions to a public mobile telephone service which provides PSTN using cellular technology access. This indicator encompasses the number of postpaid subscriptions as well as the number of prepaid accounts that are active (i.e., used within a period of three months).

iii. Control variables.

To avoid data omission bias and in accordance with the extant agriculture literature (Zakaria et al., 2019; Musayev, 2016; Shahbaz et al., 2013b; Lio and Liu, 2008; Wallin and Segerström, 1994), we include five control variables in this paper. The first is income per capita (GDP). This variable is used to capture national development. Income per capita could have an important positive impact on the agricultural sector through scale effects (Sadorsky, 2013). Second, we monitor the role of foreign direct investment (FDI) on agriculture. The fact justifying the choice of this variable is that foreign investment in SSA mostly focuses on the agricultural sector (Claassen et al., 2012; Dupasquier and Osakwe, 2006; Cotton and Ramachandran, 2001). We use the share of FDI in GDP as an indicator of FDI. Third, the impact of financial development (fidev) is controlled through domestic credit to the private sector as a % of GDP (Kolshus et al., 2015; World Bank, 2017). Fourth, energy consumption is per GDP purchasing power parity (Energy). It is useful for operating tractors and other agricultural machinery (Lehmann et al., 2012). It articulates the use of primary energy prior to transformation into alternative fuels for end-use, which is equivalent to domestic production plus stock changes and imports, minus exports and fuels supplied to aircraft and ships involved in international transport. Fifth, trade openness, enables farmers to sell their products and increase market share (Börjesson et al., 2014). Trade openness represents the sum of exports and imports of goods and services measured as a share of GDP.

3.3. Data

Our sample is a panel of 18 countries in Sub-Saharan Africa over the period 1990-2014. Benin; Botswana; Cameroon; Congo, Dem, Republic; Congo; Ivory Coast; Gabon; Ghana; Kenya; Mauritius; Mozambique; Niger; Nigeria; Senegal; South Africa; Sudan; Tanzania; Zimbabwe. Other countries (Burkina Faso; Burundi; Cape Verde; Central African Republic; Chad; Equatorial Guinea; Ethiopia; Gambia; Guinea; Guinea-Bissau; Lesotho; Liberia; Madagascar; Malawi; Mali; Mauritania; Namibia; Rwanda; Sao Tome & Principe; Seychelles ; Sierra Leone ; Swaziland ; Uganda ; Zambia) are excluded because of data availability (Land Use; Production; Mobile; Internet) constraints at the time of study. Data are from the World Bank database (WDI, 2020). The descriptive statistics and the correlation matrix between the variables are presented in Tables 1 and 2, respectively. Looking at all the correlation coefficients, we can see that they all have values below 0.7. Accordingly, this threshold has been identified in the literature as the information criterion (Kennedy, 2008; Asongu et al., 2020, 2021). Hence, we can say that there is no multicollinearity problem. The difference in the number of observations is because of missing data.

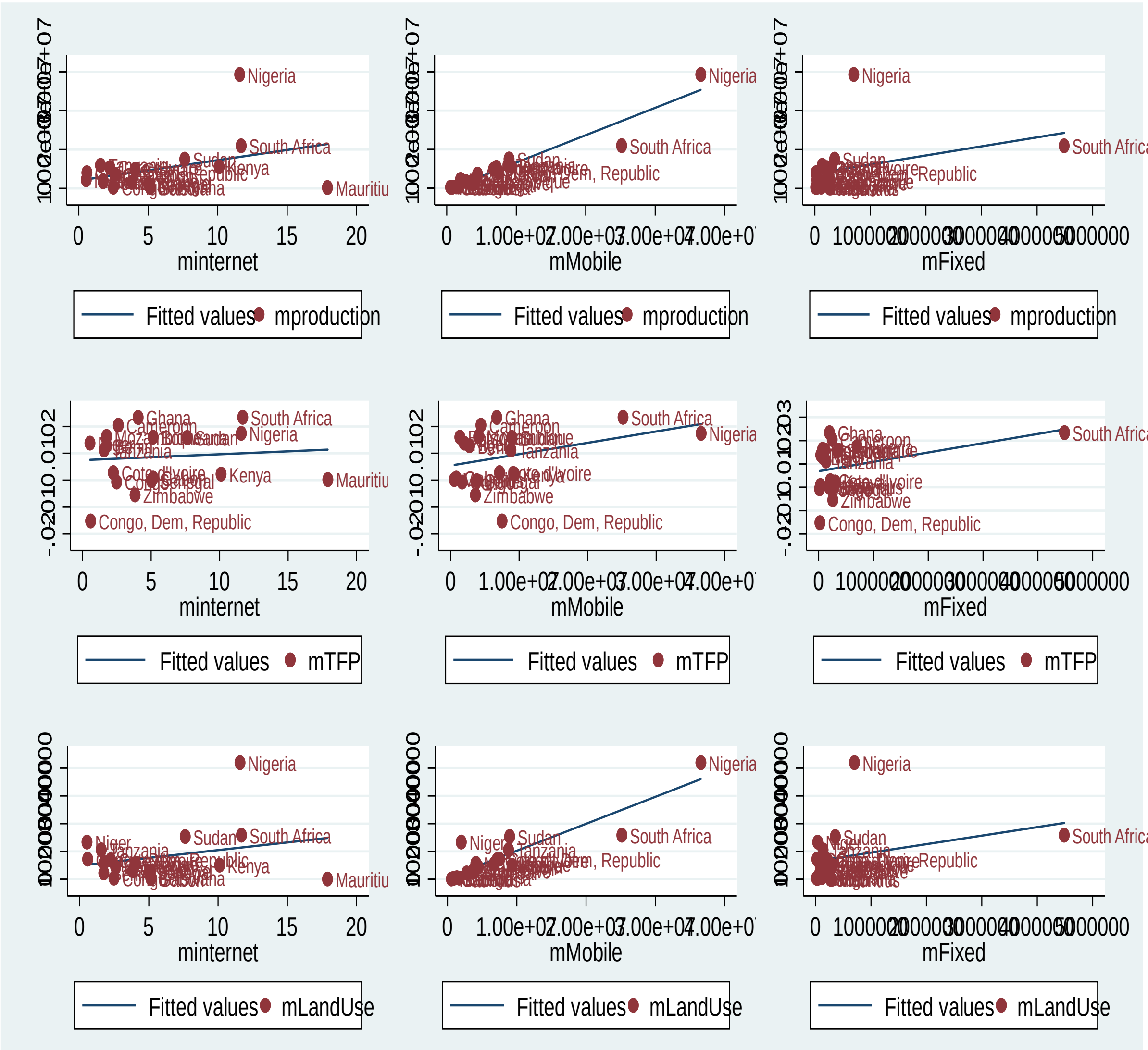
Table 1: Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
Production	450	4842485	6839994	198989.1	4.08e+07
TFP	450	.0086234	.0808552	-.3854856	.5419649
LandUse	450	7864.857	9796.8	74.27788	51256.22
Internet	347	5.382793	9.027345	0	49
Mobile	373	7897434	1.75e+07	0	1.39e+08
Fixed	450	430294.9	1020104	0	5492838
Fidev	441	21.90556	30.1652	.4913875	160.1248
FDI	449	2.473059	4.230841	-8.70307	39.4562
Energy	439	685.0842	628.8355	113.0905	3129.079
Trade	445	66.55411	29.68432	11.08746	156.8618
GDP	449	377094.7	812580.7	.0000138	5440686

Both Figure 1 and Table 2 suggest a similar trend between the agricultural sector indicators and the ICT indicators selected for this study.

Table 2: Correlation matrix.

	production	TFP	LandUse	Internet	Mobile	Fixed	Fidev	FDI	Energy	Trade	GDP
production	1.0000										
TFP	0.0561	1.0000									
LandUse	0.9539	0.0410	1.0000								
Internet	0.2804	-0.0044	0.1716	1.0000							
Mobile	0.6674	0.0245	0.5735	0.6629	1.0000						
Fixed	0.3439	0.0592	0.3156	0.2340	0.3384	1.0000					
Fidev	0.1083	0.0292	0.0572	0.4428	0.2650	0.8590	1.0000				
FDI	-0.0904	-0.0633	-0.0411	-0.0022	0.0048	-0.1241	-0.1021	1.0000			
Energy	0.1250	0.0188	0.0710	0.2994	0.2155	0.7213	0.7247	-0.0940	1.0000		
Trade	-0.4174	-0.0714	-0.5028	0.0734	-0.1976	-0.1845	0.0802	0.2334	0.0897	1.0000	
GDP	-0.1823	-0.0203	-0.2080	0.0083	-0.0659	-0.1717	-0.1704	0.0640	0.4005	0.2407	1.0000



Data source: World Bank, 2020

Figure 1: *Agriculture and ICTs*

4. Results and discussions

4.1. Preliminary analyses

i. Cross-sectional dependency test results

An enormous part of the literature on panel data has shown that models using panel data are likely to be subject to cross-sectional dependence in error terms. This cross-sectional dependency may be because of, *inter alia*, common shocks, common unobserved factors and spatial dependence (De Hoyos and Sarafidis, 2006). Failure to account for cross-sectional dependence in a panel study has many consequences, including the problem of endogenous and serial correlation.

Table 3: Result of the cross-sectional dependency test

Variables	Cross-sections included	Total panel observations	Test	Stattistics	p-value
Lnproduction	18	450	Pesaran's test	36.95981***	0.0000
TFP	18	450	Pesaran's test	2.923301***	0.0035
lnLandUse	18	450	Pesaran's test	18.46002***	0.0000
LnInternet	18	347	Pesaran's test	50.91184***	0.0000
LnMobile	18	371	Pesaran's test	52.45312***	0.0000
LnFixed	18	448	Pesaran's test	28.80043***	0.0000
LnEnergy	18	422	Pesaran's test	5.275667***	0.0000
LnGDP	18	449	Pesaran's test	52.26347***	0.0000
LnTrade	18	445	Pesaran's test	8.218542***	0.0000
LnFDI	18	449	Pesaran's test	15.41199***	0.0000
Lnfidev	25	441	Pesaran's test	19.25259***	0.0000

Notes: **** indicates a significance level of 1%.*

Table 3 presents the results of the cross sectional dependence test. The coefficient shows that the null hypothesis of the non-existence of cross sectional dependence is rejected at 1%, confirming the existence of a spatial effect between the countries in our panel. The results of the dependency test further imply that second generation stationarity tests are the most appropriate.

ii. Unit Root Test Results

The results in Table 3 showed us the existence of cross sectional dependence. Thus, the first generation unit root tests (Levin, Lin and Chin, Im, Pesaran and Shin, the panel unit root tests of Augmented Dickey Fuller and Phillips-Perron) are no longer appropriate. We therefore use the second-generation panel unit root tests developed by Pesaran (2007). These are the

Pesaran cross-sectionally augmented Dickey-Fuller (CADF) and the Pesaran cross-sectionally augmented Im, Pesaran and Shin (CIPS) tests. Both tests are compatible with the existence of cross-sectional dependence. The results are reported in Table 4. From this table it can be seen that all variables are integrated of order 1 or 0 with the CADF Pesaran test. It then becomes necessary to carry out a cointegration test to analyse the existence of a long-term relationship between the variables.

Table 4: Unit Root Test Results

Variables	LevelIntercept and Trend	1st difference Intercept and trend	Order of integration
Lnproduction	-3.438***		I(0)
TFP	-11.599***		I(0)
lnLandUse	-0.390	-6.903***	I(1)
LnInternet	-6.780***		I(0)
LnMobile	-5.461 ***		I(0)
LnFixed	2.622	-4.023***	I(1)
LnEnergy	2.070	-7.362***	I(1)
LnGDP	0.665	-8.271***	I(1)
LnTrade	-1.129	-6.648***	I(1)
LnFDI	-3.468***		I(0)
Lnfidev	-2.898 ***		I(0)

Notes: *Selection of the number of delays is based on the AIC criterion. *** indicates a significance level of 1%.*

iii. Westerlund Co-integration Test Results

The cointegration test performed is Westerlund's cointegration test which takes into account the existence of cross sectional dependence, unlike Pedroni and Kao's cointegration tests. The coefficients obtained lead us to reject the null hypothesis of non-cointegration between the variables. Thus, the estimation of our model will be carried out by the cointegration relation estimation methods.

Table 5: Westerlund Co-integration Test Results Models

Modèles	Variance ratio	p-value
lnProductionlnInternetlnenergylnGDPlnTradelnfidevlnFDI	-2.6059***	0.0046
lnProductionlnMobilelnenergylnGDPlnTradelnfidevlnFDI	-2.4070***	0.0080
lnProductionlnFixedlnenergylnGDPlnTradelnfidevlnFDI	-1.6780**	0.0467
TFP lninternetlnenergylnGDPlnTradelnfidevlnFDI	-3.7301***	0.0001
TFP lnMobilelnenergylnGDPlnTradelnfidevlnFDI	-3.8591***	0.0001
TFP lnFixedlnenergylnGDPlnTradelnfidevlnFDI	-3.6645***	0.0001
lnLandUselninternetlnenergylnGDPlnTradelnfidevlnFDI	-2.3025**	0.0107
lnLandUselnMobilelnenergylnGDPlnTradelnfidevlnFDI	-2.5166***	0.0059
lnLandUselnFixedlnenergylnGDPlnTradelnfidevlnFDI	-2.1415**	0.0161

Notes:***, *** indicates a threshold of 5% and 1% respectively.*

The existence of a cointegrating relationship between the variables makes it necessary to use an appropriate estimation technique to calculate the model parameters. In our study, we use Fully Modified Ordinary Least Squares (FMOLS).

4.2. Baseline estimate

The results of the estimates using FMOLS cointegration methods are reported in Tables 6, 7 and 8. It is shown that this analytical technique developed by Pedroni (2001, 2004) is more powerful than the Ordinary Least Squares (OLS) method because it corrects the problems of endogeneity and serial correlation.

Table 6: Agricultural production and ICTs

	Dependent Variable: LnPRODUCTION		
Variables	Method: Panel Fully Modified Least Squares (FMOLS)		
Lninternet	0.039534*** (0.0000)		
LnMobile		0.039329*** (0.0000)	
LnFixed			0.144353*** (0.0000)
Lnfidev	0.034836*** (0.0006)	0.029672*** (0.0023)	0.019837** (0.0233)
LnFDI	0.003349*** (0.0001)	0.004100*** (0.0000)	0.007968*** (0.0000)
LnEnergy	0.107180*** (0.0003)	-0.029380 (0.2683)	0.236019*** (0.0000)
LnGDP	0.086196*** (0.0000)	0.062868*** (0.0000)	0.096902*** (0.0000)
LnTrade	0.044313** (0.0298)	0.037401** (0.0360)	0.096534*** (0.0000)
Periodsincluded	21	23	23
Cross-sections included	18	18	18
Total panel observations	295	320	387
Adjusted R-squared	0.994446	0.994634	0.990023

Note: *in brackets the p-values; **, *** indicate a threshold of 5% and 1% respectively.*

The results presented in Table 6 show that ICTs are boosting agricultural production in Sub-Saharan Africa. This can be justified by the fact that ICTs in SSA play a key role in reversing the decline of the rural agricultural population and also in facilitating access to market information, which gives farmers the opportunity to acquire quality agricultural inputs at competitive prices, promote their products in different markets and negotiate prices. In this way, ICTs enable farmers to sell their products at decent prices and thus increase production. They also enable farmers to better respond to market demands. Indeed, by mapping markets for different products, ICTs could help farmers to decide where it is best for them to market their products and to have information on barriers to entry in some foreign markets. This result confirms those of Verdouw et al. (2015) and Conway (2016).

Finally, it is useful for increasing the productive power of workers in this sector. This result is consistent with the work of Smith (1776) who stated: *"Whatever the soil, climate, or size of a nation's territory, the abundance or poverty of its resources depends on the productive power of its labour"*.

By connecting farmers to the resources and services they need, ICTs enable farmers to improve their productivity. This is the meaning of the positive signs of all the parameters associated with the different ICT indicators in Table 7. Indeed, smallholder farmers in SSA countries regularly use mobile and internet applications to obtain accurate information about the next agricultural season and to access market information without depending on intermediaries. This is useful for reducing their transaction costs and enabling them to access inputs at lower costs, thus improving their productivity. Thus, greater application of ICTs in agriculture will eliminate inefficiencies, save money and improve farmers' earnings (Hasan and Isaac 2008).

Table 7: Total agricultural factor productivity and ICTs

Variable	Dependent Variable: TFP		
	Method: Panel Fully Modified Least Squares (FMOLS)		
Lninternet	0.236874*** (0.0000)		
LnMobile		0.143467*** (0.0000)	
LnFixed			0.169564*** (0.0000)
Lnfidev	0.129884** (0.0255)	0.208144*** (0.0000)	0.089305*** (0.0035)
LnFDI	0.123354* (0.0728)	0.530138*** (0.0000)	0.266307*** (0.0000)
LnEnergy	0.649942*** (0.0000)	0.243861*** (0.0000)	0.042441* (0.0810)
LnGDP	0.247380*** (0.0000)	0.079761*** (0.0000)	0.035794*** (0.0000)
LnTrade	0.314352*** (0.0000)	0.038961*** (0.0056)	0.022333** (0.0296)
Periodsincluded	21	23	23
Cross-sections included	18	18	18
Total panel observations	295	320	387

Note: *in brackets the p-values; *, **, *** indicate a threshold of 10%, 5% and 1% respectively.*

ICTs also have a beneficial effect on land use in SSA (Table 8). Certainly, ICTs can provide information on the agricultural potential of a piece of land and whether it is suitable for the production of a specific crop and livestock. ICT applications can also help to facilitate farmers' access to land through its actions on land market activities and land reforms and increase transparency (Kummu et al., 2012; McLaren and Stanley, 2017). This result is also similar to that of Bertot et al. (2010), who estimate that the computerization of land registers in India has saved farmers 1.32 million labour days through improved processing and 806 million rand in bribes due to lower levels of corruption.

Table 8: Land use and ICTs

	Dependent Variable: LNLANDUSE		
Variable	Method: Panel Fully Modified Least Squares (FMOLS)		
Lninternet	0.022791*** (0.0000)		
LnMobile		0.020807*** (0.0000)	
LnFixed			0.083290*** (0.0000)
Lnfidev	0.030212*** (0.0029)	0.031551*** (0.0016)	-0.012741 (0.1129)
LnFDI	0.000115 (0.8943)	0.000867 (0.3047)	0.004460*** (0.0000)
LnEnergy	0.006087 (0.8359)	0.083678*** (0.0023)	0.060927** (0.0205)
LnGDP	0.036320*** (0.0001)	0.032904*** (0.0000)	0.052565*** (0.0000)
LnTrade	0.154290*** (0.0000)	0.093950*** (0.0000)	0.054931*** (0.0004)
Periodsincluded	21	23	23
Cross-sections included	18	18	18
Total panel observations	295	320	387
Adjusted R-squared	0.995113	0.995215	0.993445

***Note:** in brackets the p-values; **, *** indicate a threshold of 5% and 1% respectively.*

In general, the transformation of agriculture in Sub-Saharan Africa relies on a greater appropriation of digital platforms by smallholders that will enable them to improve access to information on agronomic practices and markets.

Our control variables all have a positive and for the most part, significant effect on the agricultural indicators used in this study. There is a positive effect of access to credit on agriculture. Thus, the development of the financial system enhances the development of the agricultural sector in SSA countries. However, the rural population in SSA remains largely underserved or even excluded from the formal financial sector. The provision of financial services needs special attention from governments to ensure that farmers have easy access to them. Similarly, foreign direct investment is improving agriculture in SSA. Stimulating FDI is therefore of strategic importance for the agricultural sector in SSA. SSA countries therefore need to formulate integrated strategic policies and a regulatory framework for FDI in the agricultural sector, including infrastructure development, competition, trade and research and development. Second, energy consumption is beneficial for agriculture. Indeed, the agricultural act mobilises energy for animal feed, the operation of machinery and farm buildings. Nevertheless, reducing energy consumption is an important issue for farms because of its economic and environmental stakes. Indeed, in view of the depletion of fossil fuels and their supply at increasingly high prices, energy savings offer real opportunities for reducing the burden on farms (Chebbi and Boujelbere, 2008; Cascailh et al., 2012; Akinwale et al., 2013).

Trade openness creates incentives that are likely to make agriculture an economically viable sector in SSA. Indeed, trade openness allows for better remuneration of agricultural labour through increased market shares. This result reflects the usefulness of trade liberalization for improving the efficiency of agricultural resource allocation. These results are similar to those of Tokarick (2003); Cline (2004) and World Bank (2004). Our results also confirm that the economic well-being of individuals and agriculture are closely linked. Certainly, improving people's purchasing power leads to an increase in global food demand, which is a fundamental stimulus to agricultural growth and progress.

Figure 1 suggests that the results in Tables 6, 7 and 8 are driven by Nigeria and South Africa. For this reason, we decide to exclude them from the analysis to reassure ourselves that the positive effect of ICTs on agriculture in SSA is only driven by them. The results in Table 9 show that the influence of ICT on production, factor productivity and land use remained similar in sign to the results found previously. However, we can see the reduction in the amplitude and significance of the parameters associated with ICT. Thus, while these results do not invalidate the previous results, they do confirm the importance of Nigeria and South Africa in explaining the dynamics of the ICT-agriculture relationship in SSA.

Table 9: Analysis of ICT effects on agriculture excluding some countries

Variable	Dependent Variable: LNPRODUCTION			Dependent Variable: TFP			Dependent Variable: LNLANDUSE		
	Method: Panel Fully Modified Least Squares (FMOLS)								
	1	2	3	4	5	6	7	8	9
LNINTERNET	0.061036**			0.046079*			0.014305		
	(0.0273)			(0.0949)			(0.6031)		
LNMOBILE		0.040665***			0.106676***			0.009111	
		(0.0000)			(0.0000)			(0.7189)	
LNFIXED			0.154543***			0.038464**			0.095820***
			(0.0000)			(0.0248)			(0.0000)
LNFIDEV	0.142692***	0.024152**	0.025112	0.011079	0.215494***	0.075219**	0.032062	0.028870	0.003098
	(0.0000)	(0.0231)	(0.4380)	(0.7313)	(0.0000)	(0.0206)	(0.3209)	(0.3605)	(0.9237)
FDI	0.072607*	0.003648***	0.134412***	0.003131	0.029990	0.064568	0.098784**	0.127590***	0.128908***
	(0.0831)	(0.0000)	(0.0043)	(0.9402)	(0.2360)	(0.1685)	(0.0187)	(0.0000)	(0.0062)
LNENERGY	0.127830***	0.032443	0.222654***	0.087608***	0.115335***	0.064032**	0.048358*	0.012587	0.071179***
	(0.0000)	(0.2355)	(0.0000)	(0.0030)	(0.0002)	(0.0126)	(0.0992)	(0.6814)	(0.0056)
LNGDP	0.067293***	0.073521***	0.097085***	0.030472***	0.047194***	0.004320	0.069914***	0.066662***	0.058195***
	(0.0000)	(0.0000)	(0.0000)	(0.0016)	(0.0006)	(0.6264)	(0.0000)	(0.0000)	(0.0000)
LNTRADE	0.024302	0.031280	0.076736***	0.086441***	0.018327	0.003660	0.169891***	0.092322***	0.084146***
	(0.3153)	(0.1179)	(0.0000)	(0.0004)	(0.2705)	(0.8389)	(0.0000)	(0.0000)	(0.0000)
Adjusted R-squared	0.922855	0.992687	0.759318	-0.959305	-21.943801	-8.311247	0.909566	0.868121	0.857022
Periodsincluded	19	23	23	19		23	19	23	23
Cross-sections included	16	16	16	16		16	16	16	16
Total panel observations	257	279	343	257	279	343	257	279	343

Note: *in brackets the p-values; **, *** indicate a threshold of 5% and 1% respectively*.

4.3. Evaluating the importance and significance of the transmission channels

The above estimates are quite interesting as they provide insights into useful information on how ICT development is affecting the agricultural sector in SSA. However, the estimates do not indicate the relevance and significance of the channels from ICTs to agriculture. For this study, we look at the channels through which ICTs affect agricultural production. For this purpose, we use causal mediation analysis. The effect of ICTs on each transmission channel is shown in Table 10.

Table 10: Results of the structural model

variables	LnInternet	lnMobile	LnFixed	Constant	Observations
lnfidev	0.1882***			2.6417***	317
	(0.02305)			(0.05430)	
lnTrade	0.03639***			4.1512***	317
	(0.010660)			(0.022924)	
lnEnergy	0.091795***			6.25942***	317
	(0.012588)			(0.037362)	
lnfidev		0.10644***		1.1599***	307
		(0.017929)		(0.23921)	
lnTrade		0.003383		4.0930***	307
		(0.009152)		(0.133976)	
lnEnergy		0.04891***		5.57373***	307
		(0.01389)		(0.1882407)	
Lnfidev			0.51802***	-3.6144***	316
			(0.03202)	(0.378933)	
lnTrade			0.0684***	4.9688***	316
			(0.017332)	(0.2146797)	
lnEnergy			0.26616***	3.0459***	316
			(0.0283428)	(0.34167)	

Note: *Bootstrap standard errors in parentheses; *** is statistical significance at 1% level.*

The results show that the adoption of internet, fixed and mobile telephony have a positive and significant effect on the chosen channels. All other things being equal, an increase in the adoption of ICTs significantly stimulates financial development, trade openness and energy consumption. In fact, a 1% increase in the rate of Internet use leads to a significant increase in credit to the private sector, trade openness and energy consumption of 18.2%, 3.639% and 9.1795%, respectively. Similarly, a 1% increase in the mobile phone penetration rate significantly increases credit to the private sector, trade openness and energy consumption by 10.644%, 0.3383% and 4.891%, respectively. Finally, an additional 1% increase in the fixed telephone adoption rate leads to an increase in financial development, trade openness and energy consumption of 51.802%, 6.84% and 26.616%, respectively. The positive effect of ICTs (internet, fixed and mobile telephony) on financial development is consistent with the study of Edo et al. (2019) who have concluded that an improvement in ICT adoption significantly increases financial development in Nigeria and Kenya. On the other hand, Choi (2010) and Yushkova (2014) establish that ICT penetration boosts trade flows in many countries, hence its positive effect on trade openness. The positive effect of ICT on energy consumption has also been highlighted by Sadorsky (2012) and Yu et al. (2020) who conclude that ICT development is accompanied by an increase in energy consumption.

Since variation in the transmission mechanism is partially traceable to ICT penetration, we calculate the direct and indirect effects of ICT on agricultural production. The estimated coefficients in Equation (7) are provided in Table 6 and the ICT coefficient includes both the direct and indirect impacts. In addition to the total effect of ICT, we calculated its indirect effects using the product-of-the-Sobel coefficients approach. Standard errors are corrected by means of the bootstrap procedure. The results are presented in Table 11.

Table 11: Indirect effects of ICT on agricultural production

	Transmission channel	Indirect effect ($\beta_1\varphi$)	% of the mediatedeffect
ICT= Internet	Lnfidev	0.0505321*** (0.015029)	66 %
	lnTrade	0.0818642*** (0.024046)	147%
	lnEnergy	-0.0297689* (0.016814)	35%
ICT= Mobile	Lnfidev	0.0149359** (0.0060515)	10 %
	lnTrade		
	lnEnergy	-0.0058453* (0.0032004)	4 %
ICT=Fixed phone	Lnfidev	0.2407538*** (0.0366176)	40 %
	lnTrade	0.0574034*** (0.0145985)	6%
	lnEnergy	-0.0970111*** (0.0167612)	13 %

Note: *Bootstrap standard errors in parentheses; *, **, *** is statistical significance at 10%, 5%, and 1% level.*

The first observation that can be made from Table 10 is that all three mechanisms have mediated the impacts of ICTs on agricultural production. Over the study period, ICTs have indirectly increased agricultural production through financial development and trade openness. On the other hand, it has indirectly reduced production through energy consumption. We also try to calculate the contribution of each mechanism to the total impact of ICTs on agricultural production using the formula $(\frac{\beta\gamma}{\alpha+\beta\gamma})$. We find that about 35%, 4% and 13% of the total negative effects of the internet, mobile and fixed telephone respectively on agricultural production is due to energy consumption. Conversely, we find that 66% of the indirect positive effect of internet take-up on agricultural production comes from financial development and 147% from trade openness. Similarly, 40% and 6% of the indirect positive effect of the use of fixed telephones on agricultural production comes from credit to the private sector and trade openness, respectively.

The indirect positive effect of ICTs on agricultural production can be explained by the fact that ICTs contribute to improving the financial system by mitigating transaction costs and information asymmetry, in particular by improving the information flow on investment opportunities, engender more financial integration. In addition, ICTs allow farmers to access a larger share of markets, which leads to increased demand and therefore increased production. The indirect negative effect of ICTs on agricultural production could be explained by the fact that farmers still predominantly use energy-intensive hardware. Indeed, many farmers still use, for example, the desktop at the expense of the laptop or netbook for cost reasons and especially because they are difficult to steal. Thus, the green revolution in SSA needs to be driven largely by ICT innovations to ensure that smallholder farmers have access to adequate information on weather, agricultural inputs and markets. It is difficult to directly compare our results with existing research because previous studies have not highlighted the role and importance of transmission channels.

5. Conclusion and policy implications

Sub-Saharan African countries have experienced a rapid growth in ICTs, in terms of Internet penetration rates, number of fixed and mobile phone users in recent years. This increase in ICT penetration offers real advantages for the development of other sectors of activity. One of the central challenges of ICTs is their contribution to achieving a true green revolution.

This study estimates the impact of ICT adoption on agriculture in Sub-Saharan Africa. Specifically, we study the direct and indirect aspects of the effects of internet, fixed and mobile phone penetration on production, factor productivity and agricultural land in a sample of 18 sub-Saharan African countries over the period 1990-2014. The results of the static panel show that increasing ICT penetration has a positive and significant effect on the agriculture indicators selected for this study.

As a complement to the previous analysis, we use causal mediation analysis to articulate the role and relevance of mechanisms from ICTs to agriculture. Overall, the results show that financial development, trade openness and energy consumption are the mechanisms through which ICT penetration affects agriculture in sub-Saharan Africa. More specifically, ICTs have an indirect impact on the agricultural sector in sub-Saharan Africa. A beneficial indirect impact on agricultural production through its impact on financial development and trade openness and an inhibiting indirect impact on agricultural production through its effects on energy consumption.

Overall, this study showed that there are agricultural benefits associated with increased ICT penetration in the sub-region. From a policy standpoint, the following measures could be adopted to achieve a true agricultural revolution in SSA. Indeed, technologies to boost the agricultural sector are eagerly awaited. Thus, because of the food insecurity and low financial resources of rural populations associated with low production, policies aimed at improving agricultural efficiency through the use of ICTs could contribute to this. Firstly, governments should create facilities for the provision of economically viable agricultural financial services as this will empower farmers to acquire ICTs and modernize their farms. In addition, these measures could increase the indirect effect of ICTs on increasing agricultural production.

Secondly, governments need to open up their economies more and more, while at the same time strengthening legislation on the protection of small farmers and on energy-intensive agricultural equipment. This includes developing green solutions, reducing constraints on financing cost environment respectful technologies and projects. These incentives should be provided in terms of green subsidies for the adoption and/or development of technologies. Moreover, the standard could improve with respect to the transfer of ICT equipment. Finally, campaigns that are designed to improve public awareness in terms of agricultural benefits linked to the increasing penetration of ICTs in the sub-region could be encouraged. One of the drawbacks of this study is that the conclusions and corresponding policy recommendations do not take into account the specificities of each country. Accordingly, there are some disparities in the growth patterns of ICT in African countries. Hence, it is relevant to extend this study to country-specific cases in order to obtain additional insights of the impact of these policies. It is therefore worthwhile for future research to extend this study by identifying additional transmission channels.

References

Adelaja, A. & George, J., (2019). Effets du conflit sur l'agriculture : Preuves de l'insurrection de Boko Haram. World Development, 117, 184-195.

Adhiguru, P. & Mruthyunjaya, (2004). Institutional innovations for using information and communication technology in agriculture. Policy Brief 18. New Delhi: National Centre for Agricultural Economics and Policy Research.

Afzal, M.N.I., & Gow, J., (2016). Electricity consumption and information and communication technology in the next eleven emerging economies. International Journal of Energy Economics and Policy, 6 (3), 381–388.

Akinwale, Y., Jesuleye, O., & Siyanbola, W. (2013). Empirical analysis of the causal relationship between electricity consumption and economic growth in Nigeria. British journal of economics, Management and trade, 3(3), pp.227-295.

Asongu, S. A., (2020). Financial Access and Productivity Dynamics in Sub-Saharan Africa. International Journal of Public Administration, 43(12), 1029-1041.

Asongu, S. A., Biekpe, N., & Cassimon, D., (2020). Understanding the greater diffusion of mobile money innovations in Africa, Telecommunications Policy, 44(8), September 2020, 102000.

Asongu, S. A., Biekpe, N., & Cassimon, D., (2021). On the diffusion of mobile phone innovations for financial inclusion, Technology in Society, 65 (May), 101542.

Asongu, S.A., Nwachukwu, J.C., & Tchamyou, V.S., (2016). Information asymmetry and financial development dynamics in Africa. Review of Development Finance, 6 (2), 126–138.

Balafoutis, A., Beck B., Fountas S., Vangeyte J., Van Der Wal T. & Soto, I., (2017). Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. Sustainability 2017. doi:10.3390/su9081339.

Baron, R.M. & Kenny, D.A., (1986). The moderator-mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. Journal of Personality and Social Psychology, 51(6), 1173–1182.

Batte, M.T. &Ehsani, M.R., (2006). The economics of precision guidance with auto-boom control for farmer-owned agricultural sprayers. Computers and Electronics in Agriculture, 53(1), 28-44.

Bello, O. & Aderbigbe, F., (2014). ICT in Agricultural Sustainability and Food Security. International Journal of Emerging Technology and Advanced Engineering, 4(3), 508-514.

Berti, G. & Mulligan, C., (2015). ICT & the future of food and Agriculture. Stockholm: 2015.

Bertolini, R., (2004). Making information and communication technologies work for food security in Africa. 2020 Africa Conference Brief 11. International Food Policy Research Institute: Washington DC.

Bertot, J.C., Jaeger, P.T. & Grimes, J.M., (2010). Using ICTs to create a culture of transparency: E-government and social media as openness and anti-corruption tools for societies. Government Information Quartely, 27 (3), 264–271.

Bilali, H.E. & Allahyari, M.S., (2018à. Transition towards sustainability in agriculture and food systems: role of information and communication technologies. Information Processing in Agriculture (2018), doi: https://doi.org/10.1016/j.inpa.2018.06.006

Binswanger, H.P. & Rosenzweig, M.R., (1986). Behavioural and material determinants of production relations in agriculture. The Journal of Development Studie, 22 (3), 503–539.

Bora, G.C., Nowatzki, J.F., & Roberts, D.C., (2012). Energy savings by adopting precision agriculture in rural USA. Energy, Sustainability and Society, 2012. doi:10.1186/2192-0567-2-22.

Börjesson, R.M., Håkansson, C., Svenfelt, Å. & Finnveden, G., (2014). Including second order effects in environmental assessments of ICT. Environmental Modelling & Software, 56(June), 105-115.

Caputo, F., Buhnova, B. & Walletzký, L., (2018). Investigating the role of smartness for sustainability: insights from the Smart Grid domain. Sustainability Science, 2018:1–11. doi:10.1007/s11625-018-0555-4.

Cascailh, A., Belveze, J., Bochu, J.L. & Bordet, C., (2012). Consommations d'énergie dans les exploitations agricoles de Midi-Pyrénées et création d'un réseau de conseil aux agriculteurs. Innovations Agronomiques 25 (2012), 15-25.

Cash, D. W., (2001). In order to aid in diffusing useful and practical information: Agricultural extension and boundary organizations. Science Technology Human Values, 26, 431–453.

Chebbi, H.E. & Boujelbere, Y., (2008). Agricultural and non-agricultural outputs and energy consumption in Tunisia: empirical evidences from cointegration and causality. 12th congress of the European association of agricultural economists-EAAE 2008.

Choi, C., (2010). The effect of the Internet on service trade. Economic Letter, 109, 102–104.

Claassen, C., Loots, E., &Bezuidenhout, H., (2012). Chinese foreign direct investment in Africa. African journal of Business Management, 6 (47), 11583-11597.

Cline, W. R., (2004). *Trade policy and global poverty*. Peterson Institute.

Conway, G., (2016). Recipe for a new revolution. Africa's twenty-first century agricultural transformation. Foreign Aff [Special Issue Overcoming Isol Speeding up Chang Tak Success to Scale] 2016.

Cotton, L., & Ramachandran, V. (2001). Foreign direct investment in emerging economies: lessons from Subsaharan (N° 200/82). WIDER Discussion paper.

Dabbous, A., (2018). The impact of information and communication technology and financial development on energy consumption: a dynamic heterogeneous panel analysis for MENA countries. International Journal of Energy Economics and Policy, 8 (4), 70–76.

Dao, V., Langella, I. & Carbo, J., (2011). From green to sustainability: Information Technology and an integrated sustainability framework. The Journal of Strategic Information Systems, 20(1), 63-79. doi:10.1016/j.jsis.2011.01.002.

Daum, T., Buchwald, H., Gerlicher, A. & Birner, R., (2018). Times have changed. Using a pictorial smartphone app to collect time use data in rural Zambia. Field Methods, 31(1), 3-22.

De Hoyos, R. E., & Sarafidis, V., (2006). Testing for cross-sectional dependence in panel-data models. The Stata Journal, 6(4), 482-496.

Del Giudice, M., Khan, Z., De Silva, M., Scuotto, V., Caputo, F. & Carayannis, E., (2017). The microlevel actions undertaken by owner-managers in improving the sustainability practices of cultural and creative small and medium enterprises: A United Kingdom–Italy comparison. Journal of Organisational Behavior, 38(9), 1396-1414. doi:10.1002/job.2237.

Dietz, T., & Rosa, E.A., (1994). Rethinking the environmental impacts of population, affluence and technology. Human Ecology Review, 1 (2), 277–300.

Dupasquier, C., & Osakwe, P. N., (2006). Foreign direct investment in Africa : performance, challenges and responsibilities. Journal of Asian Economics, 17(2), 241-260.

Edo, S., Okodua, H., & Odebiyi, J., (2019). Internet adoption and financial development in Sub-Saharan Africa: evidence from Nigeria and Kenya. African Development Review, 31 (1), 144–160.

Eggleston, K., Jensen, R. & Zeckhauser, R., (2001). Information and Communication Technologies, Markets and Economic Development. Chapter 7. The Global Competitiveness Report 2001–2002 (GCR). Published by the World Economic Forum (WEF) in collaboration with the Center for International Development (CID) at Harvard University and the Institute for Strategy and Competitiveness, Harvard Business School.

FAO (2009). Comment nourrir le monde d'ici 2050 : le défi spécifique à l'Afrique Subsaharienne, Forum d'experts de hauts niveau, Rome 12-13 Octobre 2009.

FAO (2013). ICT uses for inclusive agricultural value chains. Rome: 2013.

FAO (2017). The future of food and agriculture: Trends and challenges. 2017. ISBN 97892-5-109551-5.

Gollakota, K., (2008). ICT use by businesses in rural India: The case of EID Parry's Indiagriline. International Journal of Information Management, 28, 336–341.

Harris, I., Wang, Y. & Wang, H., (2015). ICT in multimodal transport and technological trends: Unleashing potential for the future. International Journal of Production Economics, 159(January), 88-103. doi:10.1016/j.ijpe.2014.09.005.

Hasan, S.S. & Isaac, R.K., (2008). ICT for Sugar cane Farmers. Information for Development (i4d), mars 2008, pp. 27–28. Cité par Pradip Rey.

Hedley, C., (2015). The role of precision agriculture for improved nutrient management on farms. Journal of the Science of Food and Agriculture, 95(1), 12-19. doi:10.1002/jsfa.6734.

infoDev, (2009). ICTs for Sustainable Food Production and Agriculture - Technology and Information for the next Green Revolution 2009. http://www.infodev.org/en/Document.660.pdf.

International Telecommunication Union (ITU) (2019). Measuring digital development: Facts and figures 2019.

Jones, M.R., (1989). Analysis of the use of energy in agriculture-approaches and problems Agricultural Systems, 29 (4), 339-355.

Kaloxylos, A., Wolfert, J., Verwaart, T., Terol, C.M., Brewster, C. & Robbemond, R., (2013). The Use of Future Internet Technologies in the Agriculture and Food Sectors: Integrating the Supply Chain. Procedia Technology, 8, 51-60. doi:10.1016/j.protcy.2013.11.009.

Kalusopa, T., (2005). The challenges of utilizing information communication technologies (ICTs) for the small-scale farmers in Zambia. Library Hi Tech, 23(3), 414–424.

Kennedy, P. (2008). A Guide to Econometrics. Oxford: Blackwell Publishing

Kizilaslan, N., (2006). Agricultural information systems: A national case study. Library Review, 55, 497–507.

Kolshus, K., Pastore, A., Treinen, S. & Van der Elstraeten, A., (2015). E-agriculture 10 year Review Report: Implementation of the World Summit on the Information Society (WSIS) Action Line C7. ICT Applications: e-agriculture. Rome: 2015. www.fao.org/3/a-i4605e.pdf

Kummu, M., De Moel, H., Porkka, M., Siebert, S., Varis, O. & Ward P.J., (2012). Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Science of the Total Environment, 438: 477-89. doi:10.1016/J.SCITOTENV.2012.08.092.

Leach, G., (1975). Energy and food production, Food Policy, 1(1), 62-73

Lehmann, R.J., Reiche, R. & Schiefer, G., (2012). Future internet and the agri-food sector: State of-the-art in literature and research. Computers and Electronics in Agriculture, 89(November), 158-174. doi:10.1016/j.compag.2012.09.005.

Lio, M. & Liu, M. C. (2008). Governance and agricultural productivity: A cross-national analysis. Food Policy, 33(6), 504-512.

Lio, M. & Liu, M., (2006). ICT and agricultural productivity: Evidence from cross country data. Agricultural Economics, 34, 221–228.

McLaren, C.G., Metz,T., van den Berg, M., Bruskiewich, R.M., Magor, N.P. & Shires, D., (2009). Informatics in Agricultural Research for Development. Advances in Agronomy, 102, 135–157.

McLaren, R. & Stanley, V., (2017). ICT for Land Administration and Management. ICT in Agriculture (Updated Edition): Connecting Smallholders to Knowledge, Networks, and Institutions. World Bank, Washington, DC.

McNamara, K., Belden, C., Kelly, T., Pehu, E. & Donovan, K., (2011). Introduction ICT in Agricultural Development. ICT in Agriculture (Updated Edition): Connecting Smallholders to Knowledge, Networks, and Institutions. World Bank, Washington, DC.

Mintert, J., Widmar, D., Langemeier, M., Boehlje, M., & Erickson, B., (2016). The Challenges of Precision Agriculture: Is Big Data the Answer? Paper presented at the Southern Agricultural Economics Association (SAEA) Annual Meeting; San Antonio, Texas; February 6-9, 2016.

Musayev, V., (2016). Externalities in Military Spending and Growth: The Role of Natural Resources as a Channel through Conflict. Defence and Peace Economics, 27(3), pp. 378–391, doi: 10.1080/10242694.2014.994833.

Mutchek, M.A. & Williams, E.D., (2010). Design Space Characterization for Meeting Cost and Carbon Reduction Goals. Journal of Industrial Ecology, 14(5), 727-739. doi:10.1111/j.1530-9290.2010.00282.x.

Ozcan, B., (2018). Information and communications technology (ICT) and international trade: evidence from Turkey. *Eurasian Economic Review*, 8, 93–113. https://doi.org/10. 1007/s40822-017-0077-x.

Palaskas, T. B., Harriss-White, B. & Crowe, T., (1997). The evolution of local market commodity price behaviour in south India, 1972–92. Journal of International Development, 9, 101–115.

Papyrakis, E., & Gerlagh, R., (2004). The resource curse hypothesis and its transmission channels. Journal of Comparative Economics. 32(1), 181–193.

Pedroni, P., (2001). Purchasing power parity tests in cointegrated panels. The Review of Economics and Statistics, 83(4), 727–731.

Pedroni, P., (2004). Panel cointegration: asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. Econometric Theory, 20, 597–625.

Pesaran, M. H., (2007). A simple panel unit root test in the presence of cross-section dependence. *Journal of applied econometrics*, *22*(2), 265-312.

Plant, R.E., Pettygrove, G.S. & Reinert, W.R., (2000). Precision agriculture can increase profits and limit environmental impacts. California Agriculture, 54, 66–71.

Poole, N. D. & Kenny, L., (2003). Agricultural market knowledge: Systems for delivery of a private and public good. Journal of Agricultural Education and Extension, 9, 117–126.

Rao, N. H., (2006). A framework for implementing information and communication technologies in agricultural development in India. Technological Forecasting and Social Change, 74, 491–518.

Ravallion, M., (1986). Testing market integration. American Journal of Agricultural Economics, 68, 102–109.

Sadorsky, P., (2013). Do urbanization and industrialization affect energy intensity in developing countries? Energy Economics, 37, 52–59.

Saidi, A., (2013). An Introduction to Precision Agriculture and its Role in Sustainable Development of Agriculture. Journal of Basic and Applied Scientific Research, 3:417–21.

Sarahelen, T. & Sonka, S. T., (1997). Potential effects of information technologies on the economic performance of agricultural and food markets. American Journal of Agricultural Economics, 79, 657–662.

Schrijver, R., Poppe, K & Daheim, C. (2016). Precision agriculture and the future of farming in Europe. Brussels: 2016.

Shahbaz, M., Chaudhary, A.R., & Ozturk, I., (2017). Does urbanization cause increasing energy demand in Pakistan? Empirical evidence from STIRPAT model. Energy 122, 83–93.

Shahbaz, M., Shabbir, M. S. & Butt, M. S., (2013). Effect of financial development on agricultural growth in Pakistan: New extensions from bounds test to level relationships and Granger causality tests. International Journal of Social Economics, 40(8), 707-728.

Ssozi, J., Asongu, S. A., & Amavilah, V. H. (2019). The Effectiveness of Development Aid for Agriculture in Sub-Saharan Africa. Journal of Economic Studies, 46(2), 284-305.

Stanhill, G. (Ed.), (2012). Energy and agriculture. Springer Science &Business Media.

Streeter, D. H., Sonka, S. T. & Hudson, M. A., (1991). Information technology, coordination, and competitiveness in the food and agribusiness sector. American Journal of Agricultural Economics, 73, 1465–1471.

Svenfelt, Å. & Zapico, J.L., (2016). Sustainable food systems with ICT? Proceedings of the 4th International Conference on ICT for Sustainability (ICT4S 2016); Amsterdam, 2016, p. 194–201.

Sylvester, G., (2015). Success Stories on Information and Communication Technologies for Agriculture and Rural Development. Bangkok: 2015. www.fao.org/3/a-i4622e.pdf

Tchamyou, V.S., Erreygers, G., & Cassimon, D., (2019). Inequality, ICT and financial access in Africa. Technological Forecasting and Social Change. 139, 169-184 https://doi.org/10.1016/j.techfore.2018.11. 004.

Tekin, A. B., (2010). Variable rate fertilizer application in Turkish wheat agriculture: Economic assessment. African Journal of Agricultural Research, 5(8), 647-652. doi:10.5897/AJAR09.562.

Thöni, A. & Tjoa, A.M., (2015). Information technology for sustainable supply chain management: a literature survey. Enterprise Information Systems, 11(6), 828–858. doi:10.1080/17517575.2015.1091950.

Tokarick, M. S., (2003). Measuring the impact of distortions in agricultural trade in partial and general equilibrium (No. 3-110). International Monetary Fund.

UNCTAD, (2008). The Information Economy Report 2007-2008 – Science and Technology for Development: the new paradigm of ICT. Geneva: 2008.

Verdouw, C.N., Wolfert, J., Beulens, A.J.M. & Rialland, A., (2016). Virtualization of food supply chains with the internet of things. Journal of Food Engineering, 176:128–36. doi:10.1016/j.jfoodeng.2015.11.009.

Wallin, J. E., & Segerström, U., (1994). Natural resources and agriculture during the Iron Age in Ostrobothnia, western Finland, investigated by pollen analysis. Vegetation History and Archaeobotany, 3(2), 89-105.

Wognum, N. & Bremmers, H., (2009). Environmental transparency of food supply chains - Current status and challenges. Global Perspective for Competitive Enterprise, Economy and Ecology - Proceedings of the 16th ISPE International Conference on Concurrent Engineering, 2009, p. 645–652.

Wognum, P.M., Bremmers, H., Trienekens J.H., Van Der Vorst J.G.A.J. & Bloemhof J.M., (2011). Systems for sustainability and transparency of food supply chains - Current status and challenges. Advanced Engineering Informatics, 25(1), 65-76. doi:10.1016/j.aei.2010.06.001.

World Bank (2004). Global Economic Prospects 2004: Realizing the Development Promise of the Doha Agenda.

World Bank, (2017). ICT in Agriculture: Connecting Smallholders to Knowledge, Networks, and Institutions. Washington DC: 2017.

World Bank, (2020). World Development Indicators, http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators

Yogo, U.T., & Mallaye, D., (2015). Health aid and health improvement in Sub-Saharan Africa: accounting for the heterogeneity between stable states and post-conflict states. Journal of International Development, 27 (7), 1178–1196.

Yu, Y., Zhang, N., & Kim, J.D., (2020). Impact of urbanization on energy demand: An empirical study of the Yangtze River Economic Belt in China. Energy Policy 139 (2020) 111354.

Yu, Y., Zhang, N., & Kim, J.D., (2020). Impact of urbanization on energy demand: An empirical study of the Yangtze River Economic Belt in China. Energy Policy 139 (2020) 111354.

Yushkova, E., (2014). Impact of ICT on trade in different technology groups: analysis and implications. International Economics and Economic Policy, 11 (2014), 165–177.

Zakaria, M., Jun, W., & Khan, M. F., (2019). Impact of financial development on agricultural productivity in South Asia. Agricultural Economics, 65(5), 232-239.

Zhao JR., X.L., & Chen Q., J.G., (2010). Reconsidering Baron and Kenny: Myths and Truths about Mediation Analysis. Journal of Consumer Research, 37(2), 197–206.