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Renewable energy, agriculture, and carbon dioxide emissions nexus: implications for sustainable development in sub-Saharan African countries

Jingyi Wang[1], Chenglin Jiang[2], Mingquan Li[3], Shuai Zhang[4] and Xuebiao Zhang[1*]

Abstract

Sub-Saharan Africa (SSA) has experienced a high economic growth rate over the last two decades, which has been accompanied by concerns about increasing carbon dioxide (CO_2) emissions. This study aims to find out whether renewable energy and agriculture can help reduce CO_2 emissions for selected SSA countries. A balanced dataset incorporating CO_2 emissions, renewable energy consumption, agricultural land per capita, GDP per capita, urbanization level and energy intensity of 38 SSA countries covering the period 2000–2019 is utilized. The differentiated-generalized method of moments (GMM) is employed as a benchmark estimation method to estimate the effects of renewable energy and agriculture on CO_2. The regional heterogeneity analysis of countries at different income levels is then carried out. The moderating role of government governance in the energy-agriculture-environment nexus is also investigated. The following conclusions are highlighted: (1) the consumption of renewable energy can reduce CO_2 emissions, while agriculture increases them; (2) the mitigating effect of renewable energy on CO_2 emissions is relatively larger in countries at a low income level countries than in high-income countries, while agriculture aggravates CO_2 emissions in lower middle-income and low-income regions, but mitigates emissions in upper middle-income regions; and (3) governance quality turns the mitigating role of renewable energy use on CO_2 emissions into an increasing one, and exaggerates the polluting effect of agriculture. Finally, the study proposes policy implications for improving renewable energy use and green agricultural growth to achieve sustainable development in SSA.

Keywords Renewable energy consumption, Agriculture, CO_2 emissions, Government governance

1 Introduction

Sub-Saharan Africa (SSA) has experienced tremendous improvements in economic growth over the past two decades. Although SSA's gross domestic product (GDP) only accounts for 2.2% of the world GDP in 2021, the annual growth rate is remarkable, 4% from 2000 to 2021, which is higher than the world average. However, natural resources and agriculture are still known to be the main drivers of the economy. The two main sectors, namely resource and agriculture, are significant carbon emitters. Carbon dioxide (CO_2) emissions from SSA have long been ignored as it only occupies approximately 2.4% of

*Correspondence:
Xuebiao Zhang
zhangxuebiao@caas.cn
[1] Agricultural Information Institute, Chinese Academy of Agricultural Sciences, Beijing 100081, China
[2] Jilin Agro-Tech Extension Station, Jilin 130033, China
[3] Dehui Agro-Tech Extension Center, Jilin 130300, China
[4] Division of Graduate Studies Administration, China Foreign Affairs University, Beijing 100091, China

the global emissions [1]. However, it has been increasing rapidly by 65.5% from 2000 to 2019 [2]. Increasing CO_2 emissions are leading to climate change which threatens the region considering its high levels of poverty and inadequate adaptive capacity. The negative impacts of climate change will worsen if no intervention measures are implemented, and the poor will be the first to bear the brunt. Climate change has secondary impacts, causing crop yield reduction and failures and are likely to increase the risk of civil unrest. Hence, it is high time to seek a way to mitigate the growth trends of CO_2 emissions.

The fast growing economies in SSA are heavily dependent on energy consumption, which is increasing spectacularly in most SSA countries. Africa is home to all kinds of fossil fuels that still dominate energy use, far outweighing the renewable energy and degrading the environment. What's more, as a major supplier of raw materials such as oil to the rest of the world, the extraction of natural resources in SSA is accelerating, causing great damage to the environment and the climate. SSA is also rich in renewable energy, the use of which can contribute to mitigating CO_2 emissions and minimizing negative environmental impacts. The potential for renewable energy use in SSA is enormous. Sunlight in SSA is about to be around 320 days per year, while its use for energy production is negligible and limited to lightning. There is about 1300 GW of wind potential in SSA, but the installed capacity is only 190 MW. The region also has sufficient geothermal potential in the range of 10 to 15 GW [3]. Investment, viable policies and political will are required for the reliable development of renewable energy sectors. SSA is actively developing solar energy, geothermal energy and wind power generation. Increased use of renewable energy is expected to help reduce carbon emissions and promote environmental protection.

In addition to natural resources, agriculture is also the backbone of most SSA countries. The agricultural sector is the main source of livelihood for many people, employing nearly half of the labor force. Agricultural sector emits the second largest CO_2 in the world. This is due to the fact that each process in agriculture, such as sowing, field management, irrigation and harvesting consumes large amounts of energy. The inefficient use of energy during these processes further increases carbon emissions. However, there exist two opposing views on the impact of agriculture on the environment. Borlaug [4] argues that the development of agriculture leads to rising incomes, which creates demand for a better environment and drives the government to enforce environmental regulations. Moreover, efficient agriculture limits the expansion of arable land into wasteland, thereby reducing pollution. On the contrary, the Jevons Paradox states that agricultural development tends to increase the profitability, which may encourage the expansion of farmland, increasing CO_2 emissions and degrading the environment [5]. Agricultural performance in many SSA countries lags far behind other regions such as Europe and Asia. Almost 80% of the agricultural land and production is rain-fed, so the productivity is very low to meet human demand, and 31% of the population is in severely food insecure [6]. How does agricultural development affect the environment? Research on the environmental impacts of agriculture is essential for sustainable development, especially in SSA, where agriculture is linked to the well-being of millions of people.

The literature is replete with studies that focus on the energy-economy-environment nexus in Africa. However, agriculture is often ignored in the SSA nexus. Another fact that has been ignored in most studies is the government governance. The institutional arrangements of most SSA countries are weak, and can influence the extent of the environmental impact of new energy consumption and agriculture. The study fills a cavity in the literature by contributing to these three aspects. First, this study considers the consumption of renewable energy and agriculture as the key economic indicators that affect the environment. This can contribute to a more comprehensive analysis and extend the existing literature for SSA countries. The renewable energy in this study includes solar, wind, geothermal, biomass, biofuels and hydroelectricity. The carbon emission includes both direct and indirect ones. Second, as illustrated in the literature, the environmental impacts of energy use and agriculture varies in countries of different income levels [7, 8], this study further subdivides SSA based on different income levels to check the heterogeneity. Third, this study attempts to explore the moderating effects of government governance in the agriculture-energy-environment nexus. A stable political environment and appropriate legislative measures are conducive to the adoption of innovations in both energy and agricultural sectors, which is likely to reduce greenhouse gas emissions. The study uses three indexes to proxy different dimensions of government governance and tries to identify the moderating effects of government governance in the way in which the explanatory variables influence the environment.

1.1 Literature review

1.1.1 Renewable energy consumption and CO_2 emissions

Scholars have long been interested in the nexus of energy-environment. For example, Destek and Sinha [9] employ the panel data of 24 countries from the Organization for Economic Co-operation and Development, covering the period 1980–2014, to explore the environmental impact of energy use. They conclude that the ecological footprint can be reduced by using more renewable energy. Sebri and Ben-Salha [10] use the vector error correction model to check the interaction between the CO_2 emissions and clean energy consumption in BRICS members (i.e., Brazil, Russia, India, China, and South Africa) and find a bidirectional one. Hanif et al. [11] investigate the nexus of renewable energy and CO_2 emissions for 25 countries at upper-middle income level and lower-middle income level, respectively, from 1990 to 2015, and reveal a mitigating role of renewable energy on CO_2 emissions. Taking 9 Mediterranean countries as a sample, Belaid and Zrelli [12] uncover that renewable electricity reduces CO_2 emissions. Acheampong [13] discovers that energy consumption boosts the carbon emissions in Middle East and North Africa, however, the case is different in SSA. Numerous studies have proved that renewable energy consumption is environmentally friendly and plays a vital role in lowering CO_2 emissions towards a green environment [14, 15].

1.1.2 Agriculture and CO_2 emissions

Agriculture is an important source for CO_2 emissions, with a proportion of more than one third of the greenhouse gas emissions in the world [16]. Researchers find the relationship between agriculture and CO_2 emissions either conflicting or synergistic. When agriculture damages the environment, a contradictory situation arises. Such a situation is demonstrated by Gokmenoglu and Taspinar [17], who identify the positive correlation between agricultural value added and CO_2 emissions in Pakistan. Wang et al. [18] conclude that CO_2 emissions respond to agricultural output with positive elasticities. Using data for Brazil from 1980 to 2011 and employing autoregressive distributed lag and vector error correction model, Jebli and Youssef [19] detect unidirectional causality from agricultural value added to CO_2 emissions. Liu et al. [20] discover that agriculture is conducive to emitting CO_2 in the BRICS countries. Sah and Devakumar [21] show that chemical inputs and machinery in the agricultural production process result in higher CO_2 emissions in India. Also, rural dwellers tend to be in energy poverty and rely on the use of primary fuels, thus causing more carbon emissions [22–24]. The problem is more common and serious especially in developing countries [25], so there is a need to investigate the situation in SSA. The synergistic situation which means agricultural development could be sustainable, is verified by Jiang et al. [26], who discover that agricultural value added tends to mitigate CO_2 emissions in China.

1.1.3 The existing nexus analysis in SSA

How to manage the relationship between economic development and environment, and how to achieve a benign interaction between the two, is a realistic issue facing many countries today. The objectives of economic development and environmental protection are the same, both aiming to meet people's needs for a better life, and the two can be transformed into each other [27]. On the one hand, high-quality economic development must be environmentally friendly and sustainable. For example, through the transformation and upgrading of traditional industries, the continuous development and expansion of new industries, and the promotion of industrial restructuring, we can effectively reduce pollutant emissions. On the other hand, strengthening environmental management, accelerating ecological construction, forming green production methods and lifestyles, and promoting continuous improvement of environmental quality can also create more room for economic development. Therefore, it is important to investigate the nexus between economic indicators and environment. There is a growing literature on the analysis of the economic indicator-environment nexus analysis in SSA. Djellouli et al. [28] investigate dynamic links between energy consumption, economic growth, foreign direct investment (FDI) and CO_2 emissions in Africa and discover that besides renewable energy, all the other variables, i.e., economic growth and FDI, lead to more CO_2 emissions. Renewable energy consumption is beneficial to the environment, while the rise of gold price contributes to more environmental pollution. Salahuddin et al. [6] illustrate that fossil fuels are conducive to CO_2 emissions. They also find that FDI has a detrimental effect on the environment in SSA.

As agriculture develops, more surplus labor will be transferred to urban areas, and land for urban development will increase. However, the impact of urbanization on CO_2 emissions is not yet clear. Some scholars have argued that the use of agricultural land and permanent plantation by urban development will weaken the ecological function of agriculture, which in turn will increase carbon emissions [29]. However, other scholars have argued that urbanization increases the agglomeration of production and livelihoods and improves the efficiency of energy use, thereby reducing carbon emissions [30]. Although the majority of people live in rural areas, SSA is experiencing an accelerating urbanization process, growing from 31.4% in 2000 to 41.8% in 2021 [2]. Rapid urban expansion in SSA is closely associated with the excessive use of agricultural land and energy. Unplanned urbanization has also made it difficult for authorities to manage in a sustainable way. Furthermore, the transformation of the natural environment into cities has resulted in indiscriminate damage to the ecological balance [31].

Energy intensity measures the proportion of energy consumption in total economic output and indicates whether the energy utilization is rational. Higher energy intensity means that one country achieves economic development by applying more energy rather than improving productivity of energy use. Thus, improving energy intensity can save more natural resources and is conducive to a more sustainable environment [32]. Some studies have investigated the nexus of energy intensity and CO_2 emissions in Africa and find that energy intensity promotes emissions [1, 33], however, there is also a view that energy intensity helps to mitigate CO_2 emissions [34].

A country's government governance determines many economic issues, such as environmental governance, climate change mitigation and sustainable development. The government is the main driving force for environmental protection and sustainable development, seeking a balance between the two. The government addresses the relationship between environmental protection and economic development through environmental legislation, law enforcement and supervision, policy formulation and market regulation. Countries with higher level of governance tend to reduce CO_2 emissions more effectively [35], as better governance leads to the formulation of polices which are environmentally friendly and support energy transition [36]. Political instability leads to lower trust in politicians and uncertainty in governance structures especially in developing countries [37]. The relatively weak governance capacity of governments can lead to misallocation of funding and public goods in the socio-economic sectors. As access to renewable energy and agricultural products is a type of public goods, stronger government governance capacity stimulates development of renewable energy and agriculture. Considering the weak governance capacity of governments in most SSA countries, such an analysis is vital to enlighten the policymakers on how to deal with the increasing CO_2 emissions.

Overall, despite the significant progress and fruitful conclusions of the current literature, there are still areas of interest that have been ignored. This study will help to expand the research by contributing to three aspects. First, this study creatively includes agriculture into the energy-environment nexus analysis for SSA. Also, different from the literature that uses agricultural value added or agricultural output as an indicator of agriculture, the study uses agricultural land per capita, which is more representative of the characteristics of agricultural development in SSA. Second, the heterogeneity analysis is carried out as the impact may across countries at different income levels. The study further subdivides SSA based on different income levels to check the heterogeneous influences. Third, the study checks the moderating effects of governance quality on the environmental impacts of renewable energy consumption and agriculture in SSA. In this way, this study provides fresh evidence on the environmental effects of both renewable energy and agriculture systematically. In addition, the heterogeneous and moderating effect analysis can provide more information for the policymakers to adjust relevant policies.

1.2 Empirical model and data

Apart from the main determinants on CO_2 emissions, i.e. renewable energy and agriculture, which are the focus of this paper, economic growth, urbanization and energy intensity are often identified as key factors influencing CO_2 emissions based on previous literature reviews [1, 30, 32, 33]. The literature has used various indicators to represent the development of agriculture, such as agricultural value added [20], crop yield [38] and total agricultural output [18], etc. However, the expansion of cultivated land has been an important driver of agricultural growth in SSA in the past few decades but is rarely used in the literature. Therefore, the study uses agricultural land per capita as a proxy for agriculture. The multivariate framework is constructed as follows:

$$CO_{2it} = f(RE_{it}, AGRI_{it}, PGDP_{it}, UR_{it}, EI_{it}) \tag{1}$$

where CO_{2it} represents CO_2 emissions per capita; RE_{it} represents the percentage of renewable energy consumption in total energy use; $AGRI_{it}$ denotes agricultural land per capita; $PGDP_{it}$ denotes GDP per capita; UR_{it} denotes the urbanization level; EI_{it} denotes energy intensity; i represents the 38 SSA countries; and t denotes year from 2000 to 2019.

To mitigate data instability and remove potential heteroskedasticity, each variable is transformed into a logarithmic specification. In addition, to account for the possible lag in CO_2 emissions, the first-order lagged term of CO_2 is introduced into the equation. Equation (1) is then rewritten as follows:

$$lnCO_{2it} = \beta_0 + \beta_1 lnCO_{2it,-1} + \beta_2 lnRE_{it} + \beta_3 lnAGRI_{it} + \beta_4 lnPGDP_{it} + \beta_5 lnUR_{it} + \beta_6 lnEI_{it} + \varepsilon_{it} \tag{2}$$

where $\beta_1 - \beta_6$ are the coefficients of $CO_{2it,-1}$, RE, $AGRI$, $PGDP$, UR and EI; β_0 and ε_{it} represents the intercept and random disturbance terms, respectively.

As can be seen in Eq. (2), the introduction of the lagged dependent variable $lnCO_{2it,-1}$ may lead to the problem of endogeneity. Therefore, the study uses the method of Generalized Method of Moments (GMM) to deal with the endogeneity problems since the static models such as ordinary least squares, fixed effects and random effects may result in biased estimators. The GMM can deal with the endogeneity problem by using instrumental variables.

The common instrumental variables include predetermined variables and lagged terms of exogenous variables. One of the GMM method, the differential GMM (DIFF-GMM), uses instrumental variables to derive the corresponding moment conditions. When the N is small, the differential GMM is more appropriate to satisfy the asymptotic properties. Another type of GMM method, the system GMM (SYS-GMM), allows for a richer set of instruments, so that the regression result is more consistent and efficient, but only when the cross-section unit is sufficiently large. Considering the sample characteristics, the DIFF-GMM is utilized as the benchmark regression. The study also uses the SYS-GMM and feasible generalized least squares (FGLS) as a comparison. In general, the Arellano-Bond (A-B) test and the Sargan test are conducted to examine the validity. The p-value of the AR(1) and AR(2) is less than 0.1 and greater than 0.1, respectively, indicating that there is no evidence of second-order serial correlation. The p-value of the Sargan test is greater than 0.1, meaning that the instrumental variables are effective.

A balanced panel data from 2000–2019 of 38 SSA countries are applied based on data availability. The definition of variables and data sources are shown in Table 1. Data for the variables are all derived from the dataset of World Development Indicators. The descriptive statistics of the variables are presented in Table 2. From Table 2, it can be seen that among all the variables, the distribution of $lnCO_2$ has the largest degree of dispersion, with the standard deviation being 1.33, and the mean value is more skewed towards the Minimum. The degree of dispersion of *lnPGDP* is also relatively large, but the distribution is more symmetrical. *lnRE*, *lnAGRI* and *lnUR* all show right-skewed distributions, with their mean values more skewed towards the Maximum, and *lnEI* is more skewed towards the left.

The correlation test is conducted to verify the relationships between the selected variables. Table S1 of Supplemental Materials shows the correlation values between CO_2 emissions and their determinants in SSA. The direction and the strength of the variables are illustrated by the sign and value of the correlation coefficients. All the dependent variables are correlated significantly at 1% level with the independent variables. This preliminary result shows that renewable energy consumption, agricultural land, economic growth, urbanization and energy intensity are all conducive to CO_2 emissions. The correlation among the explanatory variables is also investigated to examine the presence of multicollinearity. The result matrix shows that the correlation coefficients of the explanatory variables are less than 0.8, so there is no serious collinearity exists.

Table 2 Descriptive statistics of the variables

Variable	Obs	Mean	Std. Dev	Min	Max
$lnCO_2$	760	-1.130	1.331	-3.894	2.149
lnRE	760	4.047	0.821	-0.342	4.588
lnAGRI	760	3.705	0.608	1.182	4.393
lnPGDP	760	7.045	0.950	5.555	9.740
lnUR	760	3.566	0.463	2.110	4.497
lnEI	760	1.796	0.553	0.756	3.292

2 Results analysis

2.1 Benchmark regression

The estimation results of Eq. (2) are listed in Table 3. As can be seen, the lagged term of CO_2 emissions is significantly positive, indicating that the rising trend will continue in the absence of relative intervention policies in SSA. The coefficients of the renewable energy consumption are obviously negative in both the static models, i.e., FGLS, and dynamic models i.e., the DIFF-GMM and SYS-GMM; in other words, CO_2 emissions can be reduced by using more renewable energy. This finding confirms the carbon-mitigating effect of renewable energy consumption and strongly corroborates the empirical results of Namahoroet al. [1] and Samour et al. [39]. Compared to traditional energy sources, renewable energy can provide affordable, more reliable, stable, and sustainable support

Table 1 Description of the variables in the study

Variable	Definition	Units	Data source
CO_2	CO_2 emissions per capita	Mt	World Bank, 2022
RE	Ratio of renewable energy consumption in total energy consumption	%	World Bank, 2022
AGRI	Agricultural land that is arable, under permanent crops, and under permanent pastures per capita	km^2	World Bank, 2022
PGDP	GDP per capita	2017 dollars at constant prices	World Bank, 2022
UR	Urban population ratio of the total population	%	World Bank, 2022
EI	Energy use per unit of gross domestic product	PPP USD kg^{-1} oil equivalent	World Bank, 2022

Notes: PPP means purchasing power parity

Table 3 Benchmark regression results

	FGLS	DIFF-GMM	SYS-GMM
$\ln CO_{2,t-1}$		0.695***	0.879***
		(25.73)	(21.84)
lnRE	-0.161***	-0.197***	-0.052**
	(-6.32)	(-6.66)	(-1.99)
lnAGRI	0.029***	0.050***	0.031**
	(5.19)	(3.91)	(1.98)
lnPGDP	1.045***	0.241***	0.102**
	(73.59)	(7.89)	(2.10)
lnUR	0.554***	0.331***	0.135***
	(25.91)	(7.20)	(2.67)
lnEI	0.161***	0.103***	0.022***
	(9.66)	(4.50)	(2.82)
constant	-9.753***		-0.899**
	(-55.93)		(-1.96)
Wald test	0.000		
AR(1)		0.000	0.000
AR(2)		0.367	0.339
Sargan test		0.989	0.970

Notes: ** and *** indicate significance at the 5% and 1% level, respectively. The value in the parenthesis are the t values

for economic and social development. As coal, oil and gas resources are concentrated in a few countries such as South Africa, Nigeria, Libya, Algeria, Angola, etc., most countries depend on imported fossil fuels heavily. The structure of energy consumption in SSA is quite worrying as non-renewable energy dominates the total consumption. Moreover, the most prominent challenges to reduce CO_2 emissions in SSA are the rising consumption of non-renewable energy, and the weak substitution of renewable energy [13]. This has left most African countries with huge traditional energy costs. Today, SSA governments have recognized the importance of a new energy transition, and almost all SSA countries are parties of the Paris Agreement on climate change, and most have adopted strategic plans, targets, and specific actions to reduce carbon emissions to keep up with the pace of global development transformation. The results could be a positive sign for the policymakers to issue polices aiming for green and sustainable growth by unlocking the renewable energy potential in SSA. Some countries have begun to invest in large-scale new energy projects and have received support from European and American countries and international multilateral financial institutions.

Another key finding of the study is that agriculture exerts a significant positive effect on CO_2 emissions in SSA, as a 1% increase in the agricultural land per capita can contribute to 0.05% CO_2 emissions. While most SSA countries have achieved uninterrupted agricultural growth since independence, rapid population growth has made the net surplus of agricultural growth in SSA very limited, with much of the agricultural growth being offset. Climate change is also having an increasing impact on agricultural development in SSA. Over the past two decades, SSA has experienced an increase in extreme weather events and increasingly erratic rainfall patterns in rain-fed agricultural areas. At the same time, institutional resources to support agriculture in SSA are scarce, and smallholder farmers do not have access to strong external support to adapt to climate change. On the other hand, raw agricultural production in SSA has relied on expanding cultivated areas to increase crop yields, which is unfavorable to improve land and labor productivity. Rain-fed farming and poor agricultural infrastructure in SSA have led to low agricultural productivity. As a result, the increasing food production to meet the demand by the growing population mainly comes from the expansion of agricultural land other than yield increase [31]. Deforestation has been identified as the second largest human-induced source of CO_2 emissions, second only to the global energy sector. However, agriculture is considered to be a driver of deforestation in SSA, with about 15.6 Mha of forest lost between 2010 and 2015. Besides, the agricultural sector is a major consumer of non-renewable energy, as most of the agricultural equipment is powered by fossil-fuel, and the fertilizers and other agrochemicals are rich in nitrogen, which has potential for carbon emissions. The findings in this study highlight the urgent need of introducing eco-friendly technologies in the agricultural sector and to promote agricultural productivity. The results correspond to Jebli and Youssef [19], Rosenzweiget al. [16] and Wang et al. [18] but contradict Rudel et al. [5].

As for the control variables, economic growth is positively related to on CO_2 emissions at 1% significant level. This means that the economic development of SSA is currently at the expense of the environment at present. Urbanization significantly promotes environmental degradation as the coefficient is obviously positive. An augmentation in 1% urbanization causes a 0.33% increase of CO_2 emissions in SSA. This result suggests that the urbanization process in SSA is relatively crude and far from achieving the emission mitigating effects. Energy intensity is also an important driver of CO_2 emissions in SSA, with a coefficient of 0.103 at the 1% significant level. The carbon-emitting effect of energy intensity further demonstrates that the economic development of SSA is highly dependent on energy and its use is inefficient, leading to environmental degradation. The findings mirrored the results of Namahoro et al. [1], who affirm the possible positive link between energy intensity and CO_2 emissions.

2.2 Asymmetry analysis

According to the descriptive statistical analysis in Table 2, the distribution of $lnCO_2$ is asymmetric and has the characteristics of a left-skewed distribution In order to obtain a more accurate estimation of the results, a symmetry analysis is carried out in this section to test the effects of the variables at different levels of $lnCO_2$. The quantile regression model is applied and we select five quantiles of CO_2 emissions and Table 4 and Fig. 1 illustrate the results.

Table 4 Results of the asymmetry analysis

	Quantiles				
	10th	**25th**	**50th**	**75th**	**90th**
lnRE	0.024	-0.016	-0.193*	-0.500***	-0.297***
	(0.58)	(-0.38)	(-1.87)	(-14.36)	(-7.81)
lnAGRI	0.078**	0.057***	0.018	-0.042***	0.017
	(2.59)	(2.86)	(0.87)	(-4.05)	(0.74)
lnPGDP	1.160***	1.046***	1.019***	0.902***	1.005***
	(17.01)	(19.00)	(35.39)	(24.92)	(17.8)
lnUR	0.514***	0.639***	0.604***	0.778***	0.737***
	(7.07)	(7.85)	(13.39)	(15.58)	(8.40)
lnEI	-0.036	-0.005	0.136***	0.208***	0.490***
	(-0.47)	(-0.10)	(3.53)	(5.66)	(9.2)
constant	-10.699***	-10.254***	-9.717***	-8.870***	-9.790***
	(-23.81)	(-34.65)	(-27.47)	(-22.95)	(-23.01)

Notes: *,** and *** indicate significance at the 10%, 5%, and 1% level, respectively. The value in the parenthesis are the t values

The CO_2 emission-mitigating effect of renewable energy consumption in SSA is only significant at the 50th, 75th and 90th quantiles, indicating that when CO_2 emissions are low, the mitigating effect of renewable energy consumption is not obvious. As the quantile of CO_2 emissions increases, renewable energy will exert greater impact on eliminating carbon emissions in SSA. Regarding the coefficient of agriculture, it is only at the 10th and 25th quantile that agriculture can be detrimental to the environment by emitting more carbon, while at the 75th quantile the impact on the environment becomes positive, as the coefficient turns negative. The reason for this may be that with the growing CO_2 concentration, the photosynthetic efficiency and organic matter accumulation increase, and the yields of some crops such as rice, beans, maize and sorghum will improve, enhancing carbon storage in soils and biomass and making the carbon sequestration effect to a certain extent.

In addition, the effects of economic growth and urbanization are significantly positive across the entire CO_2 distribution. The coefficients of energy intensity are significant at the 50th, 75th and 90th quantiles, meaning that in regions with high levels of CO_2 emissions, increasing energy intensity may be more conducive to environmental degradation.

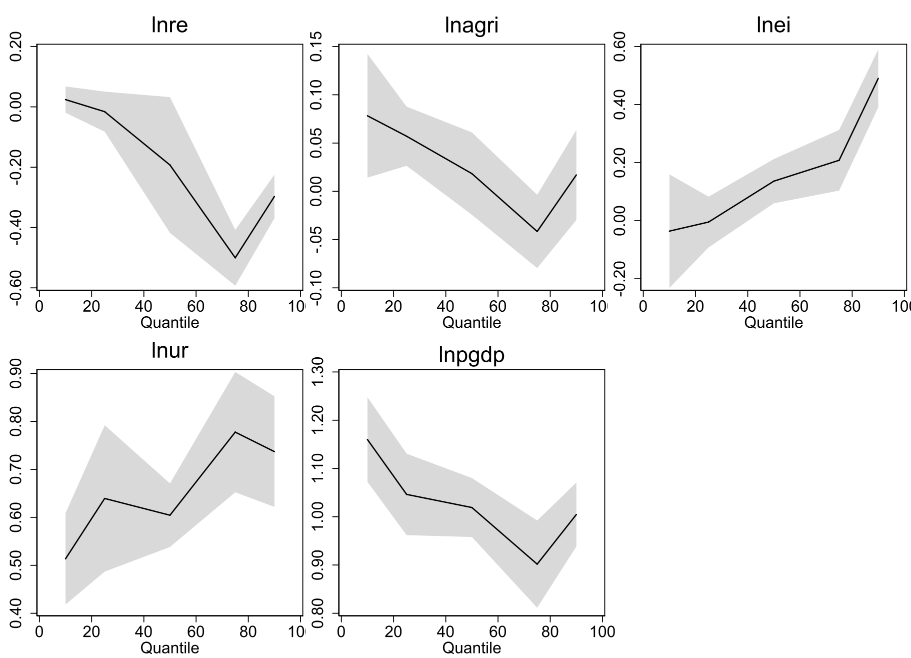

Fig. 1 Changes in panel quantile regression coefficients. *Notes:* The x-axis represents the conditional quantiles and y-axis denotes the coefficients

2.3 Regional heterogeneity discussion

Given the income inequality across the SSA region, the impact of renewable energy consumption and agriculture on CO_2 emissions may be heterogeneous across different countries. Therefore, the study further examines the heterogeneous relationships between the selected variables. According to the World Bank, countries in the world can be classified into four groups: high-income, upper middle-income, lower middle-income and low-income economies. As there is only one country in the sample that falls into the high-income economy category, i.e., Seychelles, the study removes it from the sample and classifies the remaining countries into three income-based subsamples: upper middle-income, lower middle-income and low-income economies. The classification of countries is listed in Table 5 and the regressions of the subsamples are presented in Table 6.

It is obvious that renewable energy consumption mitigates CO_2 emissions for all the subsamples. This result confirms the robustness and stability of the benchmark regression. However, the coefficients of renewable energy consumption vary at different income levels, thus verifying the heterogeneity.

According to the results of DIFF-GMM, the lower income level, the larger carbon-mitigating effect of renewable energy, as the coefficients are -0.087, -0.501 and -1.490 for upper-middle income region, lower middle-income region and low-income regions, respectively. This may because that the economies of upper-middle income countries are mainly based on resource exports, such as uranium exports in Namibia, diamond exports in Botswana, and tourism in Mauritius. The potential for renewable energy is under-utilized, so the carbon-mitigating effect of renewable energy consumption may be lower than in other regions. For countries with lower income levels, renewable energy consumption reduces more CO_2 emissions. The possible reason may be that these countries are experiencing an extensive mode of development, so the marginal emission reduction effect of renewable energy consumption is relatively large.

As for agriculture, the coefficient is negative for upper-middle income regions, but positive for lower middle-income region and low-income regions. The coefficient in lower middle-income region is not statistically significant. Upper-middle income countries tend to have relatively higher agricultural value added per worker, implying that agriculture in these countries is more efficient. Higher productivity tends to discourage land expansion and thus mitigate carbon emissions to a certain extent. As discussed above, the extensive economic development and lower agricultural productivity in lower middle-income and low-income countries encourage more forest to be converted to cropland, contributing to more CO_2 emissions.

After the symmetry and heterogeneity tests, it can be seen that although the coefficients of lnRE and lnEI are not significant at the 10th and 25th quantiles, and the coefficient lnAGRI is not significant at the 50th quantile, the estimated coefficients of other variables are significant and in the same direction as those of the benchmark model, and thus verifies the robustness of the benchmark model.

The constraints of global warming on the economic development in the world are becoming more and more severe. The world economy has to some extent entered

Table 6 Estimated results of heterogeneous analysis

	Upper middle-income	Lower middle-income	Low-income
ln $CO_{2,t-1}$	0.737***	0.584***	0.433***
	(12.62)	(10.21)	(7.91)
lnRE	-0.087***	-0.501***	-1.490***
	(11.30)	(-4.55)	(-8.14)
lnAGRI	-0.129***	-0.105	0.368***
	(8.00)	(-1.19)	(2.94)
lnPGDP	0.434***	0.808***	0.799***
	(2.66)	(-3.09)	(7.67)
lnUR	-0.072	0.348**	0.558***
	(-0.62)	(2.39)	(3.52)
lnEI	0.037	0.027	0.486***
	(0.59)	(0.52)	(6.33)
AR(1)	0.000	0.000	0.001
AR(2)	0.114	0.244	0.212
Sargan test	0.380	0.952	0.987

Notes: ** and *** indicate significance at the 5% and 1% level, respectively. The value in the parenthesis are the t values

Table 5 The classification of countries by income level

Income level	Countries
Subsample 1: upper middle-income	Botswana, Gabon, Mauritius, Namibia, South Africa
Subsample 2: lower middle-income	Angola, Benin, Cameroon, Comoros, Congo, Côte d'Ivoire, Ghana, Kenya, Lesotho, Mauritania, Nigeria, Senegal, Tanzania, Zimbabwe
Subsample 3: low-income	Burundi, Burkina Faso, Democratic Republic of the Congo, Ethiopia, Gambia, Guinea, Guinea Bissau, Liberia, Madagascar, Malawi, Mali, Mozambique, Niger, Rwanda, Sierra Leone, Togo, Uganda, Zambia,

an era of low-carbon competition, and the low-carbon economic development model has become an important focus of economic development for all countries. In this context, agricultural production also faces the challenge of how to achieve low-carbon production. Compared to developed countries in Europe and the United States, which already have a relatively stable population structure, SSA countries generally face the constraints of rapid population growth and relatively outdated agricultural production technologies. The current rapid urbanization of SSA and the increasing demand for agricultural products will inevitably increase the demand for domestic agricultural production, which in turn will inevitably rebalance the ecosystem. This explains the simultaneous expansion of arable land, urbanization and increase in CO_2 emissions over the sample period in this study.

Achieving coordination between renewable energy development, green agricultural production and economic development is important for SSA to realize sustainable development and enhance its participation in global climate governance. The paper shows that CO_2 emissions can be reduced by promoting the use of renewable energy. It gives a hint that promoting the use of renewable energy in agricultural production can offset the increase in CO_2 emissions resulting from the expansion of agricultural land, especially in lower middle-income and low-income countries. Lower income countries cannot afford to develop the economy through sacrificing the environment as ecological restoration is more difficult to achieve. However, they could use rational management and technological innovation instead of compromising environmental sustainability [40]. Promoting renewable energy is usually more economically and technically cost effective than organic farming or low-carbon agricultural production techniques in SSA. Hence, the government should use policies and incentives to encourage the agricultural sectors to support environmental-friendly projects [41]. Therefore, the promotion of renewable energy in economic development, particularly in agricultural production, could be enhanced in SSA.

2.4 The moderating role of government governance

This section examines the moderating role of governance quality in efforts to prevent environmental degradation. As there is no generally unified definition and measurement of governance quality, this study chooses three governance indicators, namely government effectiveness (GE), regulatory quality (REG) and rule of law (ROL), to proxy the quality of government governance. The data are derived from the World Governance Indicators. These three indices directly reflect the effectiveness of the policy making and implementation. As illustrated by Kaufmann et al. [42], GE and REG represent the capacity of the government to effectively formulate and implement sound policies, the quality of the public and civil service and the ability to promote private sector development; ROL shows the respect of citizens by capturing perceptions of the extent to which agents have confidence in and abide by the rules of society. In other words, the selected indices represent the quality of governance from both the governmental and citizen perspectives.

Table 7 shows the estimates of the interactive terms. The DIFF-GMM method still serves as the benchmark regression. Although the coefficient of renewable energy consumption is found to be significantly negative, the interaction of renewable energy consumption with each governance indicator produces a significantly positive result. Specifically, GE, REG and ROL turn the negative effect of renewable energy consumption on CO_2 emissions into a positive one, as the coefficients of the interaction terms are 0.081, 0.072 and 0.069, respectively. This suggests that governance quality interacts with renewable energy consumption to increase CO_2 emissions. As for agriculture, the coefficient is positive and consistent with above discussions. In addition, the interaction of agriculture with each governance indicator generates outcomes with no change in sign and significance. The interaction of agriculture with governance quality still increases CO_2 emissions although the impact is now somewhat reduced (0.029, 0.021 and 0.022% compared to 0.091, 0.075 and 0.045%, respectively, when there is no interaction). The plausible explanation is that the quality of governance in SSA is lagging behind and that the renewable energy and agriculture sectors are poorly regulated. Relevant supportive policies may be insufficient to play an active role in guiding the investment, construction and promotion of renewable energy, resulting in the least consumption and little management. Governments also do a poor job of effectively transferring new agricultural knowledge to farm households to improve agricultural productivity, leading to higher CO_2 emissions.

In summary, the study evaluates the effects of renewable energy consumption and agriculture on CO_2 emissions in SSA and this may help come to more comprehensive analysis and extend the existing literature for SSA countries. The paper may provide a new sight to explore the ways to reverse the rising trend of CO_2 emissions which is threatening SSA. However, there are some limitations in this study which provide guidance for future research. First, this study only conducts research at the country level from the macro perspective and lacks micro level analysis. Therefore, the use of a microscopic perspective at the farm household level will be considered in future studies. Second, industrial development has a direct impact on CO_2 emissions, but we did not include it in our variables to avoid multicollinearity with

Table 7 The moderating role of government governance

	FGLS			DIFF-GMM			SYS-GMM		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$lnCO_{2,t-1}$				0.631***	0.678***	0.682***	0.809***	0.811***	0.836***
				(11.42)	(22.26)	(14.70)	(16.13)	(16.38)	(17.64)
lnRE	-0.220***	-0.158***	-0.199***	-0.248***	-0.195***	-0.167***	-0.021***	-0.036***	-0.151**
	(-7.64)	(-5.78)	(-7.23)	(-4.73)	(-3.95)	(-4.54)	(2.79)	(2.89)	(-2.35)
lnAGRI	0.041***	0.040***	0.048***	0.091***	0.075***	0.045*	0.068***	0.048**	-0.019
	(5.57)	(4.42)	(6.95)	(2.83)	(2.69)	(1.89)	(2.74)	(2.33)	(-1.18)
RE_GE	0.203***			0.081***			0.199***		
	(6.47)			(4.37)			(2.72)		
AGRI_GE	0.069***			0.029***			0.068***		
	(6.17)			(4.29)			(2.81)		
RE_REG		0.122***			0.072***			0.122*	
		(3.29)			(7.54)			(1.87)	
AGRI_REG		0.040***			0.021***			0.038*	
		(3.46)			(7.22)			(1.86)	
RE_ROL			0.203***			0.069***			-0.043
			(7.94)			(4.03)			(-1.28)
AGRI_ROL			0.070***			0.022***			-0.013
			(7.66)			(3.70)			(-1.16)
lnPGDP	1.018***	1.042***	1.027***	0.400***	0.227***	0.237***	0.276***	0.231***	0.088
	(59.77)	(65.51)	(66.67)	(7.92)	(6.16)	(7.15)	(3.59)	(3.18)	(1.60)
lnUR	0.551***	0.559***	0.545***	0.191***	0.363***	0.347***	0.049	0.090**	0.133***
	(20.34)	(23.08)	(23.99)	(2.38)	(6.19)	(4.44)	(0.67)	(2.38)	(3.19)
lnEI	0.157***	0.160***	0.138***	0.159***	0.125***	0.113***	0.098***	0.073**	0.017
	(8.27)	(7.75)	(8.05)	(4.91)	(4.48)	(6.13)	(3.14)	(2.52)	(1.16)
constant	-9.138***	-9.604***	-9.162***				-1.721**	-1.802***	-0.937*
	(-44.83)	(-48.92)	(-46.38)				(-2.29)	(-3.18)	(-1.82)
Wald test	0.0000	0.0000	0.0000						
AR(1)				0.000	0.000	0.000	0.000	0.000	0.000
AR(2)				0.436	0.373	0.362	0.329	0.334	0.324
Sargan test				0.990	0.976	0.943	0.945	0.961	0.965

Notes: *, ** and *** indicate significance at the 10%, 5% and 1% level, respectively. The value in the parenthesis are the t values. RE_GE, RE_REG, and RE_ROL represent the interactive terms between renewable energy and government effectiveness, regulatory quality and rule of law, respectively. AGRI_GE, AGRI _REG, and AGRI _ROL represent the interactive terms between agriculture and government effectiveness, regulatory quality and rule of law, respectively

agriculture. In the future studies, such impacts will be considered more thoroughly.

3 Conclusion and policy implications

This study explores the role of renewable energy consumption and agriculture on CO_2 emissions in 38 SSA countries covering 2000–2019. The DIFF-GMM is employed as the benchmark method. Furthermore, the study carries out regional heterogeneity analysis to check the heterogeneous effects across countries at different income levels. The moderating effects of government governance in the nexus of renewable energy-agriculture-environment is also investigated. The overall results highlight the following findings:

(1) Renewable energy consumption exerts a significant negative effect on CO_2 emissions while agriculture exerts a positive effect. Specifically, a 1% increase in the renewable energy consumption leads to a 0.2% reduction in the CO_2 emissions, while a 1% increase in the agricultural land per capita can contribute to a 0.05% decrease in CO_2 emissions.

(2) The mitigating effect of renewable energy consumption on CO_2 emissions is relatively greater in countries of lower income. Agriculture exacerbates carbon emissions in regions of lower income, but mitigates them in upper-middle income regions.

(3) Governance quality turns the negative impact of renewable energy consumption on CO_2 emissions into

a positive one, as the interaction of renewable energy consumption with governance quality increases CO_2 emissions. The interaction effects between agriculture and governance quality increase CO_2 emissions although the impact is somewhat reduced.

Policy implications are therefore presented based on these findings. First, given that renewable energy consumption is conducive to mitigating CO_2 emissions, SSA countries can give priority to shifting from the over-reliance on nonrenewable energy to renewable energy. SSA has a large untapped potential of renewable energy and it is high time to incorporate it into its energy portfolio. Policies that encourage the use of renewable energy, such as green taxes, feed-in tariffs, and renewable energy certificates will be favorable. Also, the share of renewable energy sources in the energy consumption structure should be increased. Meanwhile, the heterogeneous effect of renewable energy consumption on CO_2 emissions should be taken into consideration for each country. Since the carbon mitigating effect of renewable energy consumption is relatively greater in low-income countries, more deliberate efforts should be taken to promote renewable energy.

Second, policymakers should be aware of not only the importance of agriculture to the economies of SSA, but also its impact on environmental degradation, given the negative relationship that exists between agriculture and carbon emissions. On the one hand, there is a need to shift towards sustainable agricultural systems that improve food production without depleting natural resources. The adoption of climate-smart and eco-friendly technologies should be promoted in the agricultural sector to diminish carbon emissions. It is also important to invest in clean agriculture and while replacing polluting forms of fossil fuel consumption with renewable energy. On the other hand, a comprehensive agricultural R&D and technology extension system should be established, to promote high-yield cultivation technologies to smallholder farmers, thereby improving agricultural productivity and decreasing agricultural land occupation.

Third, better governance is essential for SSA to boost the use of renewable energy and promote environmentally friendly agricultural technologies. Since there is evidence that the quality of governance can interact with renewable energy consumption and agriculture to exacerbate their carbon emissions effects, it is important for SSA governments to take responsibility in this area. Improved government effectiveness and regulatory frameworks are conducive to promoting the agricultural systems and investments in renewable energy to mitigate environmental degradation. In this way, appropriate and workable policies should be formulated and properly monitored.

Supplementary Information

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Additional file 1. Table S1. Correlation coefficients of the variables.

Authors' contributions

Jingyi Wang: Data curation, Software, and Writing – original draft; Chenglin Jiang: Data curation; Mingquan Li: Methodology; Shuai Zhang: Conceptualization, Validation, and Supervision; Xuebiao Zhang: Project administration, Visualization.

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Availability of data and materials

Data and materials will be made available on request.

Declarations

Competing interests

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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