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Economic Growth, CH_4 and N_2O Emissions in Sudan: Where Should the Policy Focus Be?

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Abstract

This study aimed to investigate the effect of economic growth, agricultural growth and energy use on methane (CH_4) and nitrous oxide (N_2O) emissions in Sudan. Within the context of the EKC, the study applies the OLS, cointegration, vector error correction modelling (VECM) and Granger causality methods. The study has established a long run equilibrium relationship for both CH_4 and N_2O in their relation to economic growth, agricultural growth and energy use in presence of trade openness (TOP) and inflows of foreign direct investments (FDI). The estimated VECM shows that emissions of CH_4 are significantly affected by economic growth, TOP, and FDI with no effect of agricultural growth in the short run while CH_4 is found to be significantly affected by economic growth, agricultural growth, TOP and FDI in the long run. The estimated VECM for N_2O shows that N_2O emissions are more significantly affected by energy use, agricultural growth and FDI with no effect of economic growth in the short run, while N_2O is found to be significantly affected by economic growth, agricultural growth, TOP and FDI in the long run. Consistently, findings from the estimated OLS and VECMs show that the EKC does not hold for either CH_4, or N_2O emissions, and that N_2O emissions are more significantly affected by economic growth, agricultural growth and energy use than emissions of CH_4. Findings from impulse response and variance decomposition analysis confirm that emissions of N_2O are more responsive to economic growth, agricultural growth and energy use than emissions of CH_4. Granger causality analysis shows existence of bidirectional relationship between CH_4 and agricultural growth, but a unidirectional relationship from CH_4 to FDI. For N_2O, the study finds a unidirectional relationship running from agricultural growth to N_2O, while N_2O emissions are found to cause GDP per capita, the squared GDP per capita, OIL consumption and FDI. In terms of causality, these results suggest that emissions of CH_4 and N_2O have been generated more by agricultural activities than by overall economic activity, and that activities generating N_2O emissions in particular have been contributing significantly to economic growth. Within the context of the country's intended nationally determined contributions, the findings of this study suggest that policies should be directed cautiously but more effectively to control N_2O than CH_4 emissions. Economic growth could be pursued without significant environmental harm from both CH_4 and N_2O emissions. However, Sudan should expand adoption of energy efficiency measures, expansion of renewable energy use, place restrictions on production and use of fuel woods and charcoal for low carbon economy and green growth.

Keywords

CH_4, N_2O, GDP per Capita, Agricultural Growth, Energy Use, Trade Openness, FDI, Cointegration, VECM, Sudan

1. Introduction

Global warming and climate changes are international environmental problems caused by emissions and concentration of greenhouse gases (GHGs) chief among them is carbon dioxide (CO_2). Globally, in 2016, about 72% of GHG emissions consist of CO_2, but non-CO_2 emissions, namely methane (CH_4) and nitrous oxides (N_2O) make up shares of 19% and 6% and that CH_4, N_2O and Chlorofluorocarbons (CFCs) are the main GHGs contributing to global warming potential (WGP) (Olivier et al., 2017). CH_4 was the largest contributor to non-CO_2 GHG emissions, from non-dairy and dairy cattle and cattle manure management, while collectively coal mining, oil and natural gas production and distribution, and rice cultivation accounted for 25% and 10% of CH_4 emissions respectively (Olivier et al., 2017). N_2O emissions both anthropogenic and natural originate from soils which account for over half of total atmospheric N_2O inputs, (Parton et al., 2001). Emissions of N_2O are directly and indirectly related to land use and land cover changes (LULCC) and thus to agricultural growth and development. Sources emitting N_2O directly include cultivated soils and fertilized and/or grazed grassland systems, while indirect emissions result from transport of nitrous from agricultural systems into ground and surface waters, or emission as ammonia or nitrogen oxides (Smith et al., 1999). N_2O emissions stem also from agricultural biomass burning, industrial activities. According to the Intergovernmental Panel on Climate Change, IPCC, Climate Change (1995), compared with CO_2 heat trapping, a kilogram of CH_4 is 21 times as effective at trapping heat in the earth's atmosphere as a kilogram (kg) of carbon dioxide within 100 years, while the per kg global warming potential (GWP) of N_2O is nearly 310 times that of CO_2 within 100 years. The same report (IPCC, Climate Change, 1995) attributes growth of CO_2, CH_4 and N_2O to fossil fuel use, land use change and agriculture. Moreover, it has been documented that one pound of N_2O warms the atmosphere almost 300 times more than one pound of CO_2 (United

States Environmental Protection Agency (EPA), 2018). Furthermore, releasing 1 kg of CH_4 into the atmosphere is about equivalent to releasing 84 kg of CO_2, while releasing 1 kg of N_2O into the atmosphere is about equivalent to releasing about 298 kg of CO_2 (Climate Change Connection, 2015). Most of CH_4 and N_2O emissions are related to LULCC, and intensive statistical analysis of these emissions can be found in Parton et al. (2001) and Houghton et al. (2012). Importantly, it has been recognized that policy targeting reduction of CH_4 and N_2O emissions result in higher social benefits compared with reductions of CO_2 emissions based on the GWP of these trace gases (Marten & Newbold, 2014).

From 1997 to 2019, a number of conferences of Parties (COPs) have been held to reach a consensus and agreement to cut GHG emissions. The most remarkable achievement was Paris Agreement adopted at COP-21 in 2015, which replaced the Kyoto Protocol (KP) signed in 1997. Analytical and empirical efforts to analyze determinants of GHG emissions have first focused on CO_2 emissions as the main cause of global warming and have preceded formal climate agreements including the United Nations Framework Convention on Climate Change (UNFCCC), entered into force on 21 March 1994. Earlier studies such as of Grossman & Krueger (1991) found that concentrations of sulfur dioxide and smoke increase with per capita gross domestic product (GDP) at low levels of national income, but decrease with GDP growth at higher levels of income in 42 countries. Then, Panayotou (1993) has invented the so-called environmental Kuznets curve (EKC). These are fundamental examples of such earlier investigations of the relationships between economic growth and trade on CO_2 emissions. Analysis of non-CO_2 GHGs, namely CH_4 and N_2O emissions is important for climate change policy that can be taken by countries, particularly in the context of the intended nationally determined contributions (INDCs) anchored in Paris 2015 Agreement. Yet, where climate change policy should be directed needs to be grounded on sound findings from rigorous empirical studies. Both mitigation and adaptation policies to climate change have costs, and thus only the most cost effective should be designed and implemented to control GHG emissions. In general, cross-sectional studies of agriculture using the Ricardian method suggest that efficient adaptation will reduce damages from climate change (Mendelsohn et al., 1994, 1996; Mendelsohn & Dinar, 1999). However, Mendelsohn (2000) upon analysis of different types of adaptations both private and public in agriculture, forestry and the energy sectors, states that adaptations against increases in climate variance are difficult to identify and are likely to have only modest net benefits.

Sudan is a low-income country; member of the UNFCCC, signed and ratified the KP and submitted its INDCs to Paris 2015 Agreement. Although mitigation is not a priority and it's not binding with specific emission cut targets for Sudan, adaptation measures are extremely important since Sudan is vulnerable to different impacts of climate change including drought, flooding and reduced agricultural products (Nimir & Ismail, 2013). Nonetheless, for effective climate change adaptation, the driving forces of CH_4 and N_2O emissions as the main GHGs in Sudan need to be identified and their relative importance needs to be well understood. Emissions of these gases in Sudan stem mainly from agriculture, deforestation, energy use and municipal wastes. Yet, commercial energy in terms of oil production and consumption has been steadily increasing since the late 1990s and contributing increasingly to GHGs in general and CO_2 emissions in particular. In Sudan, N_2O increased by 439.29% and CH_4 increased by 242.44% over the period 1970-2017 amounting to an annual rate of increase of 9.15% and 5.05% for N_2O and CH_4 respectively. Meanwhile, CO_2 emissions have increased by 301.33% at an annual rate of 6.28%. Emissions from agriculture account for an average of 84% and 91% form total emissions for CH_4 and N_2O respectively (calculated from World Bank, 2017). The second source of CH_4 and N_2O emissions in Sudan is the energy sector. Since agriculture also accounts for more than 35% of GDP over the period 1970-2017, GDP separately and its agricultural component jointly could be major determinants of CH_4 and N_2O emissions in Sudan.

Despite their importance to global warming and climate change, relatively less analytical and empirical attention has been paid to determinants of CH_4 and N_2O emissions, globally and at country level. For Sudan, no such study on determinants of CH_4 and N_2O exists, and the country's INDCs have not been grounded on findings of rigorous empirical studies. Since the early 1990s, Toth (1995) notes that although CO_2 continues to be the single most important GHG, contributions of other trace gases to the aggregated global warming potential are sufficiently significant to justify their more equitable treatment in climate policy analysis. Even more recently, Sinha & Sengupta (2019) note that there are a limited number of studies on the estimation of EKC hypothesis for N_2O emissions, though it is one of the most harmful GHGs present in ambient atmosphere.

Upon this introduction and background information, the aim of this study is to contribute to this literature and knowledge twofold. First, how differently economic growth, agricultural growth and energy use affect emissions of CH_4 and N_2O in Sudan. Secondly, the study comparatively addresses the two most important non-CO_2 emissions with the same explanatory variables, in a context of a single country. Findings from such comparative analysis guide which and where policies can be directed effectively toward control of these emissions, and thus serves as evidence-based framework to climate change policy in Sudan in the context of its INDCs.

2. Literature Review

Huge empirical literature has been developing to investigate what development factors that lead to increases in GHGs emissions at the global and national levels. Studies from the field of environmental economics in the early 1990s the focus was on determining a level of per capita income at which GHGs generally and CO_2 emissions in particular start a reversion from upward to downward slopping in the context of the EKC hypothesis (Panayotou, 1993). Empirical tests of the EKC were earlier undertaken by Selden & Song (1994) and Grossman & Krueger (1995), with focus on economic growth, trade liberalization and GHGs emissions. But, over time and across countries CO_2 emissions per capita have been found to strongly correlate with GDP per capita (Stern, 2011). The focus has shifted to investigate probable determinants of GHGs emissions but focusing mostly on CO_2 emissions, so as to design environmental and climate change policies compatible with economic development objectives.

In empirical literature, identified factors affecting GHGs emissions in general include the scale and rate of economic growth, energy use, openness to trade and flows of capital, urbanization and the contribution of the services sector to total economic output. Technological changes in the energy sector play an important role in GHGs emissions (Wheeler, 2012; Wang et al., 2012). Population density which is important factor in energy distribution and use by sectors has also been identified as important factor affecting GHGs emissions. Empirical literature on CO_2 determinants of emissions can be found in Omri (2009), with reference to the Middle East and North Africa (MENA) countries, Kerkhof et al. (2009) for Sweden, Norway, United Kingdom and the Netherlands, Musolesi et al. (2010) for a panel of countries, Iwata et al. (2010) for the Organization of Economic Cooperation and Development (OECD) countries, Sharma (2011) for 69 countries, Stolyarova (2013) for 93 countries, clustered into 7 groups, Beck & Prathibha (2015) for OECD and non-OECD countries, Heidari et al. (2015) for The Association of Southeast Asian Nations (ASEAN) countries, Lin at al. (2016) for Africa, Maryam et al. (2017) for Brazil, Russia, India, China and South Africa (BRICS) countries, Jeremiás & Attila (2017) for 164 countries, Adewuyi & Awodumi (2017) for West African countries, Bekhet et al. (2017) for the Gulf Cooperation Council (GCC) countries, and Apergis et al. (2018) for 19 developed economies. Some of these studies find support for the EKC, while many of them find no support the hypothesis that CO_2 emissions start a reversion trend with higher level of income over time.

At country level, there are numerous studies on economic growth and CO_2 emissions, including, Soytas et al. (2007) for the United States, Zhang & Cheng (2009) and Wang et al. (2012) for China, Halicioglu (2009), Kargi (2014) and Bozkurt & Yusuf (2014) for Turkey, Iwata et al. (2009) for France, Tiwari (2011) for India, Banerjee & Rahman (2012) for Bangladesh, Odhiambo (2012) for South Africa, Birgit & Getzner (2013) for Austria, Bento (2014) for Italy, Nuno (2014) for Portugal. In addition, Lau et al. (2014) who tested the EKC between economic growth and CO_2 emissions in Malaysia with incorporation of effects from foreign direct investment (FDI) and trade openness, and also Begum et al. (2015) for Malaysia, Mahmood & Shahab (2014) and Mirza & Kanwal (2017) for Pakistan, Kang et al. (2016) on EKC for China, Shahbaz et al. (2017) for Australia, Shmelev & Speck (2018) for Sweden, Mikayilov et al. (2018) for Azerbaijan, Elwasila (2018) who finds no support of EKC for Sudan, and Zheng et al. (2019)

for regional development and carbon emissions in China, among others. Systematic review of studies on CO_2 emissions was also undertaken by Mardani et al. (2019).

This study rather focuses on reviewing some of the literature investigating non-CO_2 emissions, namely CH_4 and N_2O emissions. Managi et al. (2009) find an inverse U-shaped relationship between trade openness and sulphur dioxide (SO_2) emissions in the case of OECD countries, but not for non-OECD countries. Zhang & Chen (2010) present inventories for CH_4 emissions and embodied emissions in production, consumption, and international trade for the Chinese economy in 2007, documenting that the total CH_4 emissions by Chinese economy in 2007 were 39,592.70 Greenhouse gas (Gg-CO_2 equivalent), three quarters of China's CO_2 emissions from fuel combustion and greater than CO_2 emissions from fuel combustion of many developed countries. They identified agriculture and coal mining as the dominant direct sources of emissions, and the construction sector holds the top embodied emissions in production and consumption. They state that China is a net exporter of embodied CH_4 emissions with the emission embodied in exports represented 35.42% of the total direct emissions, mostly from exports of textiles, industrial raw materials, and primary machinery and equipments. They call for agricultural carbon-reduction strategies, coal bed methane recovery, export-oriented and low value added industry adjustment, and low carbon energy policies to address methane emissions. Also, Wang et al. (2016) find evidence in favour of the EKC hypothesis between economic growth and urbanization on SO_2 emissions in China.

For the case of Turkey, Bölük & Mert (2015) examine the effect of electricity generated from renewable energy sources in reducing GHG emissions over the period 1961-2010 using the autoregressive distributed lag (ARDL) approach. Their results show that the coefficient of electricity production from renewable sources with respect to CO_2 emissions is negative and significant in the long run and found a U-shaped (EKC) relationship between per capita GHGs and income, with a peak point of GDP per capita of $9920 which according to them was outside the observed sample period. Vavrek & Chovancova (2016) evaluate the relationship between economic development and GHGs emissions based on decoupling theory in the case of the Czech Republic, Hungary, Poland and Slovakia over the period of 1991-2012. Their results suggest that observed partial variables indicate strong decoupling of economic growth and GHGs emissions. The authors state that in order to meet their 2050 objectives to reduce GHG emissions, these countries need to accelerate restructuring the ways how they meet their demand for energy, food, transport and housing.

Utilizing time series data between 1970 and 2012 and the ARDL approach, Manuel & Mario (2017) analyze the relationship between N_2O emissions, economic growth, agricultural land used and exports in Germany. Their results show a quadratic long run relationship between N_2O emissions and economic growth, confirming the existence of an EKC for Germany. They estimated a turning point at $27,880 which according to them was within the sample and implies that Germany was in the decreasing part of the curve of environmental degradation. They also find that agricultural land area affects N_2O emissions positively, whereas exports affect emissions negatively. The paper shows that, contrary to testing the EKC in less developed countries, mitigation of N_2O emissions does not negatively affect growth in Germany and as such, it is feasible to undertake any conservative policy in order to reduce emissions without major consequences on economic sectors. Using panel unit root and cointegration tests, Cho et al. (2014) analyze determinants of total GHG, CH_4 and N_2O emissions. They found a quadratic relationship in the long run for OECD countries. They also found effects of trade openness on GHG emissions. Although exports may not affect N_2O emissions according to Kearsley & Riddel (2010) the existence of an EKC for exports may be because of the pollution haven hypothesis (PHH) asserting transfer of pollution across countries instead of mitigating it which could be described as an inverse U-shaped relationship between exports and economic growth. For the European countries, Gielen & Kram (1998) find evidences that CH_4, N_2O and CFCs play a significant role in meeting Kyoto targets by EU member states, and that their emission reductions were forecast to contribute one quarter to the total emission reduction in 2010, given the emission reduction goals of individual European countries. Furthermore, Gambhir et al. (2017) find non-CO_2 mitigation measures are less costly than CO_2 mitigation measures, with the majority of their abatement potential achievable at US2005$100/tCO2e or less throughout the 21st century compared to a marginal CO_2 mitigation cost which was estimated to be already greater than this by 2030 in the most stringent mitigation scenario.

Benavides et al. (2017) use the ARDL method to investigate the relationship between emissions of CH_4, GDP, electricity production from renewable energy sources (excluding hydro) and trade openness in Austria. They find an inverted U-shaped between GDP per capita and CH_4 emissions as well as a unidirectional causality between CH_4, GDP per capita and electricity production. Applying econometric methods on annual data for 1981-2012, Maralgua (2017) investigates the EKC hypothesis for N_2O emissions, income, exports, urbanization, and growth in different sectors of the economy for Mongolia. The author finds a highly significant and robust long-run U-shaped relationship between N_2O emissions and income. Furthermore, exports, urbanization, and growth in the industrial and services sectors were found to decrease N_2O, while growth in the agricultural sector was found to increase N_2O emissions. The author found significant short- and long-run Granger causal relationships amongst the variables. However, until recently, Sinha & Sengupta (2019) argue for better understanding of the impact of energy consumption pattern on N_2O emissions and revision of energy policies. They analyzed the impact of renewable and fossil fuel energy consumption on N_2O emissions for Asia Pacific Economic Cooperation (APEC) countries over the period of 1990-2015 in the context of the EKC hypothesis. They indicate that the efficacy of the renewable energy solutions help to reduce the level of N_2O emissions, and energy policies should be designed to be compatible with objectives of sustainable development goals (SDGs) in these nations.

In conclusions, the findings of the above reviewed studies indicate that policy measures could be effective and less costly to be directed to non-CO_2 emissions that directly targeting reduction of CO_2 emissions.

3. Methodology

This study investigates the effects of economic growth, agricultural growth and energy use with separate inclusion of oil consumption (OIL) on emissions of CH_4 and N_2O in Sudan in presence of trade openness (TOP) and inflows of foreign direct investments (FDI). The study utilizes annual time series data over the period 1970-2016. Within the context of the EKC, the study applies the ordinary least squares (OLS), cointegration, vector error correction modelling (VECM) and Granger causality methods. The study departs with a graphical analysis of total GHGs, CH_4 and N_2O emissions over time. **Figure 1** shows some type of co-movements of CH_4 and N_2O emissions in Sudan, but recently emissions of N_2O started to overtake CH_4. The figure also depicts that total GHG emissions have been steadily increasing over the study period. Over this period, Sudan has also experienced positive economic growth rates with some years of slowdown, as well as agricultural expansion with increased production and consumption of modern energy sources, namely oil and electricity but also biomass energies.

3.1. OLS Modelling

General two OLS models to analyze how differently economic growth, agricultural growth and energy use affect CH_4 and N_2O emissions in presence of (TOP) and (FDI) in natural logarithms (L) are written as follows:

$$\begin{aligned} L(\mathrm{CH_4}) = \alpha + \beta_1 L(\mathrm{GDPP}) + \beta_2 L(\mathrm{GDPP})^2 + \beta_3 L(\mathrm{CPIN}) \\ + \beta_4 L(\mathrm{EUP}) + \beta_5 L(\mathrm{OIL}) + \beta_7 L(\mathrm{TOP}) + \beta_8 L(\mathrm{FDI}) + \mu \end{aligned} \quad (1)$$

$$\begin{aligned} L(\mathrm{N_2O}) = \alpha + \beta_1 L(\mathrm{GDPP}) + \beta_2 L(\mathrm{GDPP})^2 + \beta_3 L(\mathrm{CPIN}) \\ + \beta_4 (\mathrm{EUP}) + \beta_5 L(\mathrm{OIL}) + \beta_7 L(\mathrm{TOP}) + \beta_8 L(\mathrm{FDI}) + \mu \end{aligned} \quad (2)$$

The variables are defined as follows:

CH_4 is Methane emissions measured in Kiloton (Kt) of CO_2 equivalent.

N_2O is Nitrous Oxide emissions measured in thousand metric tons of CO_2 equivalent.

GDPP is GDP per capita measured in current US Dollars.

EUP is the energy use per capita measured in kg of oil equivalent per capita.

Oil is oil consumption measured in kg per capita.

CPIN is crop production index which shows agricultural production for each year relative to the base period 2004-2006. It includes all crops except fodder crops.

TOP is trade openness measured as exports plus imports as percentage of GDP.

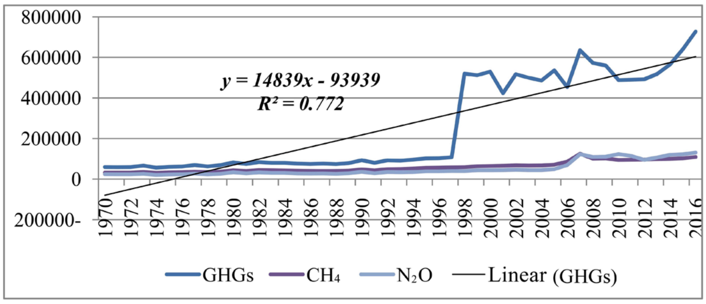

Figure 1. Trends of GHGs, CH_4 and N_2O Emissions in Sudan.

FDI is the inflow of foreign direct investments to Sudan, measured in current US Dollars.

The study departs with descriptive statistical analysis for both CH_4 and N_2O emissions together with the set of explanatory variables, as presented in **Table 1**. Based on Jarque-Bera (J-B) statistics, CH_4, N_2O and GDPP are not normally distributed.

The correlation matrix in **Table 2** shows that CH_4 is positively correlated with GDPP, CPIN and FDI. N_2O is highly positively correlated with GDPP and the squared value of GDPP, CPIN and FDI. The squared value of GDPP is highly positively correlated with GDPP and of the other independent variables only FDI and CPIN, OIL and FDI are highly positively correlated.

The correlation matrices give an initial idea that N_2O emissions are more affected by economic growth and agricultural growth than CH_4 emissions.

Equation (1) is estimated by the method of OLS to investigate the relationship between CH_4 and economic and agricultural growth. The OLS results indicate that CH_4 is positively and significantly affected by economic growth in terms of the squared value of GDPP, agricultural growth and to less extent by trade openness, while negatively and significantly affected by the actual value of GDPP and energy use. OIL consumption and FDI have no significant effects on CH_4 emissions. For N_2O, the OLS results indicate that N_2O emissions are positively and significantly affected by the squared value of GDPP, agricultural growth and trade openness, while negatively and significantly affected by the actual value of GDPP and energy use. OIL and FDI have no significant effects on N_2O emissions. For both CH_4 and N_2O emissions, the OLS results are summarized in **Table 3**.

The OLS estimates show that the coefficients of N_2O emissions with respect to economic growth are much higher than the coefficients of CH_4 with respect to economic growth. Results of the two models for both types of emissions show that low level of economic growth is also associated with low level of emissions, and emissions increase monotonically with increases in GDP per capita over time. But, both of the OLS models for CH_4 and N_2O appear unstable on the basis of the plots of cumulative sum of squares of CUSUM of the recursive residuals. Therefore the OLS estimators for both CH_4 and N_2O emissions are not reliable as shown by **Figures 2-5**.

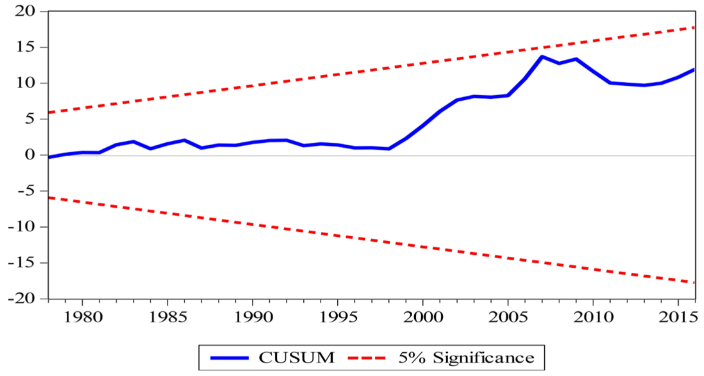

Figure 2. CH_4 stability CUSUM.

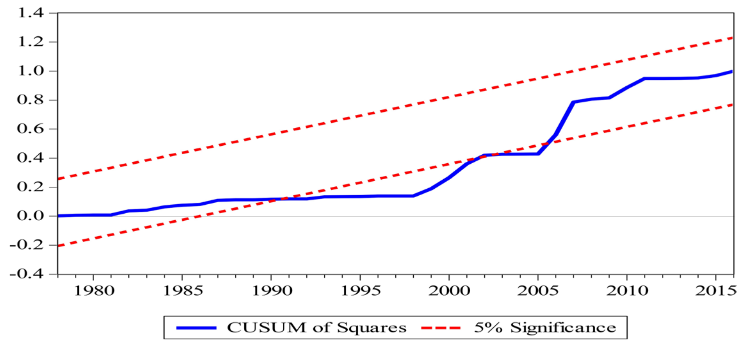

Figure 3. CH_4 stability CUSUM of squares.

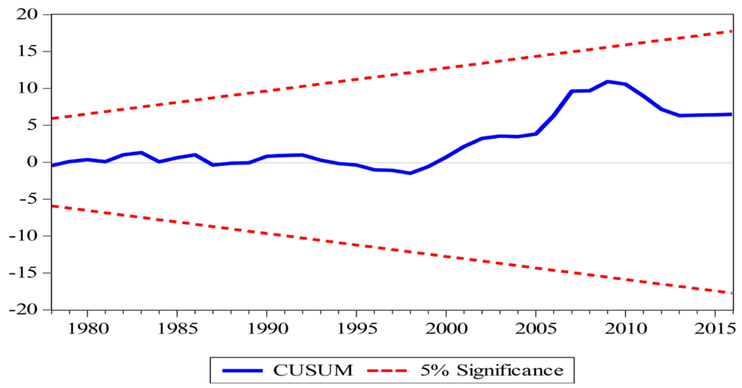

Figure 4. N_2O stability CUSUM.

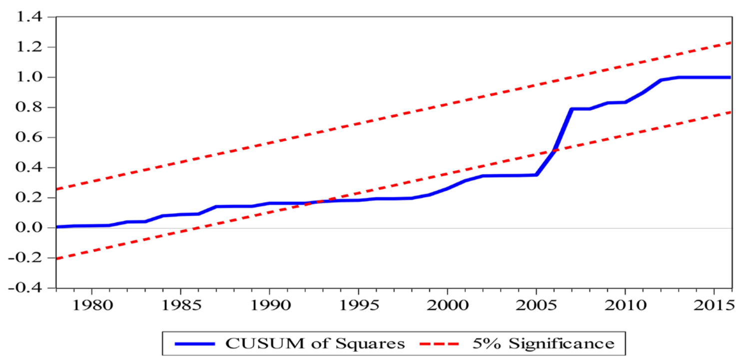

Figure 5. N_2O stability CUSUM of squares.

Table 1. CH_4 and N_2O descriptive statistics.

	Mean	Maximum	Minimum	Std. Dev.	J-B	Prob.	Obs.
CH_4	59,487.03	125,045.0	30,622.10	25,947.86	6.12	0.000	47
N_2O	50,978.73	130,632.7	20,251.59	35,263.29	12.54	0.002	47
GDPP	713.28	2684.63	175.63	606.57	34.19	0.000	47
GDP^2	868,869.2	7,207,238	30,844.57	1,556,282.0	131.82	0.000	47
CPIN	70.78	108.26	38.06	24.68	5.37	0.068	47
EUP	410.22	491.38	350.84	36.33	3.41	0.182	47
OIL	0.07	0.09	0.04	0.02	2.29	0.319	47
TOP	26.87	47.58	11.09	9.62	1.27	0.529	47
FDI	556.36	2311.46	0.000	764.57	7.90	0.019	47

Table 2. CH_4 and N_2O correlation matrix.

	CH_4						
	CH_4	GDPP	(GDPP)2	CPIN	EUP	OIL	TOP	FDI
CH_4	1.00							
GDPP	0.80	1.00						
(GDPP)2	0.72	0.97	1.00					
CPIN	0.91	0.70	0.63	1.00				
EUP	−0.68	−0.40	−0.25	−0.67	1.00			
OIL	0.67	0.65	0.57	0.66	−0.22	1.00		
TOP	0.27	−0.01	−0.07	0.32	0.03	0.59	1.00	
FDI	0.90	0.75	0.65	0.92	−0.60	0.83	0.44	1.00
	N_2O							
	N_2O	GDPP	(GDPP)2	CPIN	EUP	OIL	TOP	FDI
N_2O	1.00							
GDPP	0.89	1.00						
(GDPP)2	0.82	0.97	1.00					
CPIN	0.83	0.70	0.63	1.00				
EUP	−0.56	−0.40	−0.25	−0.67	1.00			
OIL	0.71	0.65	0.57	0.66	−0.22	1.00		
TOP	0.23	−0.01	−0.07	0.32	0.03	0.59	1.00	
FDI	0.87	0.75	0.65	0.92	−0.60	0.83	0.44	1.00

Table 3. CH_4 and N_2O OLS summary results.

	CH_4			N_2O		
Variable	Coefficient	t-Statistic	Prob.	Coefficient	t-Statistic	Prob.
L(GDPP)	−1.52	−2.937	0.006*	−4.03	−5.633	0.000*
$L(GDP)^2$	0.13	3.285	0.002*	0.34	6.205	0.000*
L(CPIN)	0.51	5.332	0.000*	0.41	3.059	0.004*
L(EUP)	−1.63	−4.687	0.000*	−2.30	−4.773	0.000*
L(OIL)	−0.17	−1.562	0.126	−0.23	−1.553	0.129
L(TOP)	0.12	1.657	0.106	0.31	3.057	0.004*
L(FDI)	0.004	0.973	0.336	−0.000	−0.030	0.976
C	22.03	6.091	0.000*	32.76	6.564	0.000*

CH_4: R-squared = 0.94; Adjusted R-squared = 0.93; SER = 0.107; SSR = 0.443; LL = 42.940; AIC= −1.487; SC = −1.172; HQC = −1.368; F-statistic = 92.24 (*P.* 0.000); DW = 1.76

N_2O: R-squared = 0.95; Adj. R-squared = 0.94; SER = 0.147; SSR = 0.843; LL = 27.80; F. Stat. = 96.06 (*P.* 0.000); AIC = −0.843; SC = −0.528; HQC = −0.724; DW = 1.73

Diagnostic Tests (CH_4)	Stat.	Prob.	DW	Diagnostic Tests (N_2O)	Stat.	Prob.	DW
Normality (J-B)	(9.04)	0.011	1.76	Normality (J-B)	(3.32)	0.190	1.73
Autocorrelation F	(0.28)	0.754	1.98	Autocorrelation F	(0.41)	0.667	2.00
Heteroskedasticity F	(0.82)	0.578	2.46	Heteroskedasticity F	(1.09)	0.390	2.61
Stability RESET F	(1.15)	0.259	1.87	Stability RESET F	(1.12)	0.276	1.68

* indicates significance at 1%level.

3.2. Dynamic Econometric Modelling

As some of the main variables of the study, i.e., CH_4, N_2O and GDPP are found to follow non-normal distribution, and the likelihood that the variables may not follow an autoregressive (AR), and a first differenced random walk I(1), which in fact were reflected by the unreliability of the above estimated OLS models, the study proceeds to dynamic econometric methods of cointegration, VECM and Granger causality analysis.

Stationarity and Cointegration

1) Stationarity Analysis

For meaningful estimation of time series econometric models and for reliable results, the stationarity of the variables must be established otherwise, estimations may be spurious (Granger, 2001). The non-stationarity and presence of a unit root in the series implies that and any shock will have a permanent effect on the system of variables. Unit root tests, namely Augmented Dickey-Fuller (ADF), Dickey & Fuller (1981), and Philips Perron (PP), Phillips & Perron (1988) tests are commonly used for establishment of stationarity. This study uses the ADF and PP unit root tests. The general ADF test equation with p lags is written as:

$$\Delta y_t = \gamma y_t + \beta_1 \Delta y_{t-1} + \cdots + \beta_p \Delta y_{t-p} + \varepsilon_t \quad (3)$$

The null hypothesis (non-stationarity) is that H_0: $\gamma = 0$, and the alterative (stationarity) AR process H_1: $\gamma < 0$. Assuming a drift (a random walk with a nonzero mean period-to-period change) against stationarity, the ADF function is written as:

$$\Delta y_t = \alpha + \gamma y_t + \beta_1 \Delta y_{t-1} + \cdots + \beta_p \Delta y_{t-p} + \varepsilon_t \quad (4)$$

With a linear trend in order to test whether the series is I(1) against the alternative that it is stationary around a fixed linear trend, a trend term component needs to be added along with the constant, i.e.,

$$\Delta y_t = \alpha + \delta t + \gamma y_t + \beta_1 \Delta y_{t-1} + \cdots + \beta_p \Delta y_{t-p} + \varepsilon_t \quad (5)$$

The lag p should be large enough to make the error term ε white noise. The estimated ADF statistics is compared with the simulated MacKinnon (2010) critical values, which employ a set of simulations to derive asymptotic results and to simulate critical values for arbitrary sample sizes. The ADF statistics must be larger than critical values in absolute value and have a minus sign. For CH_4, using the ADF and PP unit root tests, with the assumption of intercept only, and with trend and intercept, all variables included in the study are found to be nonstationary at level I(0), but they all turn to be stationary at first difference I(1) at 5 percent level of significance as presented in **Table 3**. For N_2O, using the ADF and PP unit root tests the study variables are found to be nonstationary at level but they all turn to be stationary at first difference I(1) at 5 percent level of significant as presented in **Table 4**.

2) Cointegration

Given that all variables are found to be integrated at the first order, the long run nature of the relationships between CH_4, N_2O and their explanatory variables included in the model are tested by the Johansen cointegration method. Applying this method, for CH_4 with the assumption of intercept only, the maximum Eigen value statistics indicate existence of at least three cointegrating vectors. With the assumption of intercept and trend in data, the maximum Eigen value statistics indicate existence of at least two cointegrating vectors as summarized in **Table 5**. For N_2O with the assumption of intercept only, the trace statistics indicates existence of seven cointegrating vectors while the maximum Eigen value statistics indicate existence of at least four cointegrating vectors. With the assumption of intercept and trend in data, the maximum Eigen value statistics indicate that N_2O is cointegrated with four vectors as summarized in **Table 5**.

Thus, stationarity of the study variables is established by the unit root tests and a long run equilibrium relationship is confirmed for both CH_4 and N_2O with economic growth, agricultural growth and energy use in presence of trade openness and inflows of FDI. Moreover, it appears that emissions of N_2O have more and persistent co-movements with economic growth, agricultural growth and energy use than emissions of CH_4. Upon establishment of stationarity at I(1) and the cointegration of the variables, the study proceeds to estimate an unrestricted vector autoregressive VAR model upon which an optimal lag length is selected for estimation of VECM. Results of the optimal lag length are summarized in **Table 6**.

Table 4. $CH_4$and N_2O ADF & PP stationarity test results.

Variable	Intercept	Trend & Intercept	Intercept	Trend & Intercept	Order of integration
	CH_4 Stationarity				
	ADF I(1)	ADF I(1)	PP I(1)	PP I(1)	
L(CH_4)	−8.176*	−8.110*	−8.971*	−8.971*	I(1)
L(GDPP)	−6.149*	−6.129*	−6.129*	−6.129*	I(1)
$L(GDPP)^2$	−6.006*	−6.056*	−6.056*	−6.056*	I(1)
L(EUP)	−8.887*	−9.501*	−9.510*	−9.510*	I(1)
L(OIL)	−5.496*	−5.595*	−5.578*	−5.578*	I(1)
L(CPIN)	−10.295*	−10.188*	−10.546*	−10.546*	I(1)
L(TOP)	−8.381*	−8.284*	−8.171*	−8.171*	I(1)
L(FDI)	−7.266*	−7.190*	−25.252*	−25.252*	I(1)
	N_2O Stationarity				
	Intercept	Trend & Intercept	Intercept	Trend & Intercept	Order of integration
	ADF I(1)	ADF I(1)	PP I(1)	PP I(1)	
L(N_2O)	−7.443*	−7.528*	−7.443*	−7.535*	I(1)
L(GDPP)	−6.149*	−6.129*	−6.149*	−6.129*	I(1)
L(GDPP)^2	−6.006*	−6.056*	−6.004*	−6.056*	I(1)
L(EUP)	−8.887*	−9.501*	−9.046*	−9.501*	I(1)
L(OIL)	−5.496*	−5.595*	−5.482*	−5.578*	I(1)
L(CPIN)	−10.295*	−10.188*	−10.659*	−10.546*	I(1)
L(TOP)	−8.381*	−8.284*	−8.260*	−8.171*	I(1)
L(FDI)	−7.266*	−7.190*	−22.946*	−25.252*	I(1)

* indicates stationary at 1% level; for the sake of space and ease of exposition only ADF and PP statistics for I(1) are reported.

Table 5. CH_4 and N_2O cointegration test results.

H_0	Intercept			Trend & Intercept		
	CH_4 cointegration					
	Eigen Value	Trace Statistic	Max-Eigen Statistic	Eigen Value	Trace Statistic	Max-Eigen Statistic
r = 0	0.823	269.837*	76.083*	0.823	293.710*	76.256*
r ≤ 1	0.781	193.755*	66.783*	0.781	217.454*	66.788*
r ≤ 2	0.600	126.972*	40.267*	0.621	150.667*	42.636
r ≤ 3	0.472	86.705*	28.135	0.549	108.030*	35.021
r ≤ 4	0.382	58.570*	21.200	0.392	73.009*	21.903
r ≤ 5	0.34	37.370*	18.694	0.358	51.106*	19.510
r ≤ 6	0.306	18.676*	16.055	0.315	31.596*	16.617
r ≤ 7	0.058	2.621	2.621	0.289	14.980*	14.980
	N_2O Cointegration					
	Intercept			Trend & Intercept		
	Eigen Value	Trace Statistic	Max-Eigen Statistic	Eigen Value	Trace Statistic	Max-Eigen Statistic
r = 0	0.869	284.211*	89.313*	0.869	300.806*	89.385*

Continued

r ≤ 1	0.727	194.898*	57.067*	0.727	211.421*	57.096*
r ≤ 2	0.651	137.832*	46.301*	0.658	154.325*	47.243*
r ≤ 3	0.565	91.530*	36.586*	0.591	107.082*	39.354*
r ≤ 4	0.370	54.945*	20.351	0.371	67.728*	20.394
r ≤ 5	0.338	34.594*	18.136	0.348	47.335*	18.844
r ≤ 6	0.267	16.458*	13.688	0.331	28.490*	17.706
r ≤ 7	0.061	2.770	2.770	0.217	10.785	10.785

Note: * denotes rejection of the null hypothesis at the 0.05 level.

Table 6. CH_4 and N_2O lag length selection.

CH_4						
Lag	LL	LR	FPE	AIC	SC	HQ
1	168.081	NA	1.26e-12	−4.731	−2.136*	−3.769*
2	236.975	87.684*	1.29e-12	−4.953	0.237	−3.029
3	324.441	79.515	9.71e-13*	−6.020*	1.766	−3.133
N_2O						
Lag	LL	LR	FPE	AIC	SC	HQ
0	−85.378	NA	9.63e-09	4.244	4.569	4.365
1	167.445	402.218	1.89e-12	−4.338	−1.419*	−3.256*
2	237.800	86.345*	1.89e-12	−4.627	0.887	−2.582
3	325.599	75.826	1.56e-12*	−5.709*	2.401	−2.701

Note: LR: sequentially modified LR test statistic (each test at 5% level); FPE: Final prediction error; AIC: Akaike information criterion; SC: Schwarz information criterion; HQ: Hannan-Quinn information criterion.

3.3. VECM Model Estimations

A VECM version of Equation (1) is estimated for CH_4 emissions and of Equation (2) for N_2O emissions, both on lag length of 2 according to LR criterion as in **Table 6**. Summary results of the estimated VECM for CH_4 and N_2O emissions are reported in **Table 7**.

The VECM models estimates show that the coefficients of N_2O emissions with respect to economic growth and agricultural growth are much higher and more significant than the coefficients of CH_4 with respect to economic growth and agricultural growth. Results of the two models for both types of emissions show that low level of economic growth is also associated with low level of emissions, but while it is found that emissions of CH_4 increase significantly with the squared value of the GDP per capita, this does not hold for emissions of N_2O in the long run. Positive coefficients for both CH_4 and N_2O emissions with respect to the squared value of GDP per capita contradict predications of the EKC in the case of Sudan, more strongly and clearly for CH_4 emissions. Also, N_2O emissions are better correctly adjusting back to equilibrium than CH_4 emissions in response to shocks in the system. The VECM models for both types of emissions proved to be stable and not miss-specified as depicted by **Figure 6** for CH_4 and in **Figure 7** for N_2O.

Table 7. CH_4 and N_2O VECM summary results.

CH_4 VECM						
Variable	Short Run			Variable	Long Run	
	Coefficient	T. stat.	P. value		Coefficient	T. stat.
ECT_{t-1}	**−0.16**	−2.063	0.040*	$L(CH_4)_{t-1}$	1.00	
$dL(CH_4)_{t-1}$	−0.18	−1.032	0.303	$L(GDPP)_{t-1}$	−4.17	−4.828**
$dL(CH_4)_{t-2}$	0.00	4.9e-05	1.000	$L(GDPP)^2_{t-1}$	0.32	4.743**
$dL(GDPP)_{t-1}$	*−1.45*	*−1.260*	*0.209*	$L(CPIN)_{t-1}$	*−1.88*	*−8.371****
$dL(GDPP)_{t-2}$	0.75	0.600	0.549	$L(EUP)_{t-1}$	−0.27	−0.394
$dL(GDPP)^2_{t-1}$	0.12	1.293	0.198	$L(OIL)_{t-1}$	−0.09	−0.584
$dL(GDPP)^2_{t-2}$	−0.08	−0.742	0.459	$L(TOP)_{t-1}$	−0.53	−4.547**
$dL(CPIN)_{t-1}$	−0.47	−3.145	0.002**	$L(FDI)_{t-1}$	0.07	6.515***
$dL(CPIN)_{t-2}$	−0.24	−1.611	0.109	C	13.35	
$dL(EUP)_{t-1}$	0.97	2.202	0.029*			
$dL(EUP)_{t-2}$	0.19	0.439	0.661			
$dL(OIL)_{t-1}$	0.18	1.199	0.232			
$dL(OIL)_{t-2}$	−0.20	−1.309	0.192			
$dL(TOP)_{t-1}$	0.08	0.762	0.447			
$dL(TOP)_{t-2}$	0.03	0.279	0.781			
$dL(FDI)_{t-1}$	0.01	1.245	0.215			
$dL(FDI)_{t-2}$	0.01	1.344	0.180			
C	0.06	3.237	0.001**			

N_2O VECM						
Variable	Short Run			Variable	Long Run	
	Coefficient	T. stat.	P. value		Coefficient	T. stat.
ECT_{t-1}	**−0.34**	−3.404	0.001**	$L(N_2O)_{t-1}$	1.00	
$d(L(N_2O)_{t-1}$	0.06	0.334	0.739	$L(GDPP)_{t-1}$	−1.55	−1.879*
$d(L(N_2O)_{t-2}$	0.08	0.514	0.608	$L(GDPP)^2_{t-1}$	0.09	1.341
$d(L(GDPP)_{t-1}$	0.60	0.341	0.733	$L(CPIN)_{t-1}$	−2.03	−9.512***
$d(L(GDPP)_{t-2}$	1.42	0.744	0.458	$L(EUP)_{t-1}$	0.59	0.902
$d(L(GDPP)^2_{t-1}$	−0.06	−0.428	0.669	$L(OIL)_{t-1}$	0.15	1.010
$d(L(GDPP)^2_{t-2}$	−0.14	−0.917	0.365	$L(TOP)_{t-1}$	−1.01	−9.070***
$d(L(CPIN)_{t-1}$	−1.01	−4.855	0.000***	$L(FDI)_{t-1}$	0.09	8.742***
$d(L(CPIN)t-2$	−0.55	−2.485	0.014**	C	4.08	
$d(L(EUP)_{t-1}$	1.82	2.766	0.006**			
$d(L(EUP)_{t-2}$	0.69	1.080	0.282			
$d(L(OIL)_{t-1}$	0.38	1.689	0.095*			
$d(L(OIL)_{t-2}$	−0.33	−1.490	0.138			
$d(L(TOP)_{t-1}$	−0.03	−0.198	0.844			
$d(L(TOP)_{t-2}$	−0.17	−1.102	0.272			
$d(L(FDI)_{t-1}$	0.02	2.241	0.026**			
$d(L(FDI)_{t-2}$	0.01	2.129	0.035**			
C	0.10	3.807	0.000***			

As presented in Table 8 the estimated VECM for both CH_4 and N_2O pass robustness requirements and all validity diagnostic tests of normality, autocorrelation, and heteroscedasticity. Data in the table also show that the N_2O VECM model is better fitted than that of CH_4.

Table 8. Robustness and diagnostic tests.

CH_4			N_2O		
Robustness			***Robustness***		
R-squared = 0.48; Adj. R-squared = 0.14;			R-squared = 0.58; Adj. R-squared = 0.30;		
SSR = 0.183; SER = 0.084; F. stat. = 1.42;			SSR = 0.400; SER = 0.124; F. stat. = 2.10;		
LL = 58.15; AIC = −1.82; SC = −1.10			LL = 40.99; AIC = −1.05; SC = −0.32; SW = 2.02		
Diagnostic Tests			***Diagnostic Tests***		
	Stat.	*P.* value		Stat.	*P.* value
Normality	27.91	0.032	Normality	15.41	0.495
Autocorrelation	116.40	0.576	Autocorrelation	113.06	0.661
Heteroskedasticity	1237.75	0.386	Heteroskedasticity	1233.51	0.418
Stability: VEC specification imposes 7 unit roots, none of them is outside the unit root circle			Stability; VEC specification imposes 7 unit roots; none is outside the unit circle		

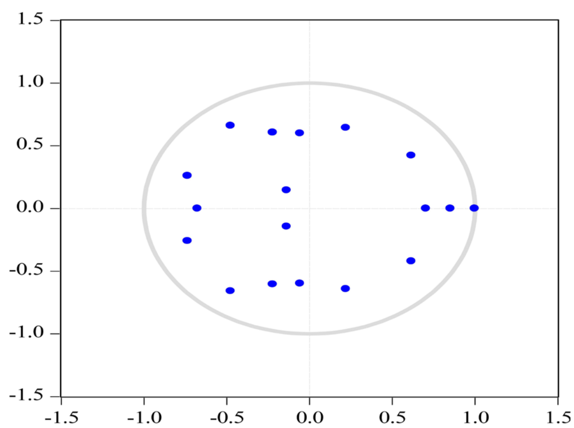

Figure 6. CH_4 VECM stability: inverse roots of AR characteristic polynomial.

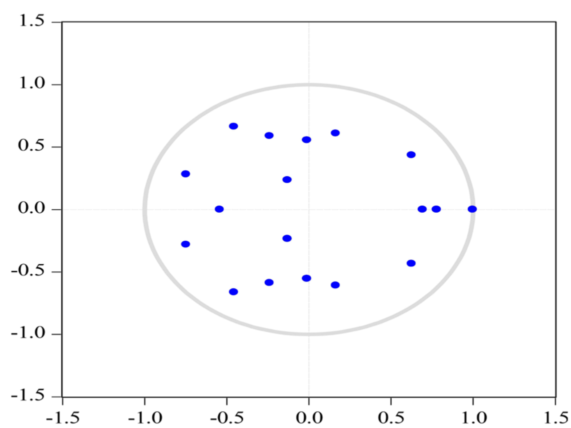

Figure 7. N_2O VECM stability: inverse roots of AR characteristic polynomial.

Granger non-causality or exogeneity of variables is also tested through the Wald test in order to judge which variables lead and which lag the others, for both CH_4 and N_2O emissions. As in Table 9, CH_4, EUP and CPIN are found to be lagging (endogenous variables) and all other variables of interest are leading highly exogenous, which is consistent with the results of cointegration and VECM results. For N_2O, all variables are found leading highly exogenous and only N_2O is found to be lagging (endogenous variable).

In accordance with the VECM, impacts on CH_4 and N_2O and their volatility with economic and agricultural growth shocks are also assessed through the impulse response function (IRF). As in Table 10 CH_4 is largely explained by its own lagged shocks, followed by TOP, FDI, and the squared value of GDPP, with the least contribution coming from GDPP and CPIN. Table 10 also shows that N_2O is largely explained by its own lagged shocks, followed by TOP, FDI, and the GDPP, with the least contribution coming from squared value of GDPP, OIL and CPIN.

The method of variance decomposition shows that variations in CH_4 are much explained by CH_4 itself, TOP and FDI, than by EUP and CPIN. GDPP contributes the least in explaining variations in CH_4 as reported in Table 11. Also, the method of variance decomposition shows that variations in N_2O are much explained by N_2O itself, TOP and FDI, than by GDPP, OIL. CPIN, the squared value of GDPP and EUP contribute the least in explaining variations in N_2O as reported in Table 11.

Table 9. $CH_4$and N_2O Granger causality/block exogeneity wald test.

CH_4 Granger Causality/Block Exogeneity Wald Test				
Dependent Variable	Chi-sq	DF	Prob.	Decision
L(CH_4)|L(GDPP), L(GDPPP)^2, L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI)	21.05	14	0.100	Reject
L(GDPP)|L(CH_4), L(GDPP)^2, L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI)	13.82	14	0.463	Accept
L(GDPP)^2)|L(CH_4), L(GDPP), L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI)	13.97	14	0.452	Accept
L(CPIN)|L(CH_4), L(GDPP), L(GDPP)^2, L(EUP), L(OIL), L(TOP), L(FDI)	23.22	14	0.057	Reject
L(EUP)|L(CH_4), L(GDPP), L(GDPP)^2, L(OIL), L(CPIN), L(TOP), L(FDI)	23.77	14	0.049	Reject
L(OIL)|L(CH_4), L(GDPP), L(GDPP)^2, L(EUP), L(CPIN), L(TOP), L(FDI)	14.85	14	0.389	Accept
L(TOP)|L(CH_4), L(GDPP), L(GDPP)^2, L(EUP), L(OIL), L(CPIN), L(FDI)	14.63	14	0.404	Accept
L(FDI)|L(CH_4), L(GDPP), L(GDPP)^2, L(EUP), L(OIL), L(CPIN), L(TOP)	7.65	14	0.907	Accept
N_2O Granger Causality/Block Exogeneity Wald Test				
Dependent Variable	Chi-sq	DF	Prob.	Decision
L(N_2O)|L(GDPP), L(GDPP)^2, L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI)	32.40	14	0.004	Reject
L(GDPP)|L(N_2O), L(GDPP)^2, L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI)	13.66	14	0.475	Accept
L(GDPP)^2)|L(N_2O), L(GDPP), L(EUP), L(OIL), L(CPIN), L(TOP), L(FDI)	13.81	14	0.464	Accept
L(CPIN)|L(N_2O), L(GDPP), L(GDPP)^2, L(EUP), L(OIL), L(TOP), L(FDI)	20.44	14	0.117	Accept
L(EUP)|LL(N_2O), L(GDPP), L(GDPP)^2, L(OIL), L(CPIN), L(TOP), L(FDI)	20.12	14	0.126	Accept
L(OIL)|L(N_2O), L(GDPP), L(GDPP)^2, L(EUP), L(CPIN), L(TOP), L(FDI)	13.25	14	0.507	Accept
L(TOP)|L(N_2O), L(GDPP), L(GDPP)^2, L(EUP), L(OIL), L(CPIN), L(FDI)	15.19	14	0.365	Accept
L(FDI)|L(N_2O), L(GDPP), L(GDPP)^2, L(EUP), L(OIL), L(CPIN), L(TOP)	6.29	14	0.959	Accept

Table 10. Response of L(CH_4) and L(N_2O).

Response of L(CH_4)								
Period	L(CH_4)	L(GDPP)	L(GDPP)^2	L(CPIN)	L(EUP)	L(OIL)	L(TOP)	L(FDI)
1	0.084	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.072	0.006	0.030	−0.014	0.022	0.022	0.022	−0.017
3	0.063	−0.009	0.013	0.007	0.014	0.011	0.028	−0.020
4	0.060	0.009	0.018	0.011	0.012	0.005	0.036	−0.026
5	0.070	0.005	0.001	−0.006	0.013	0.008	0.028	−0.034
6	0.060	0.006	−0.001	0.008	0.010	0.016	0.041	−0.032
7	0.062	0.006	−0.013	0.005	0.009	0.017	0.040	−0.026
8	0.064	0.003	−0.012	0.005	0.015	0.023	0.049	−0.031
9	0.063	0.004	−0.019	0.008	0.014	0.026	0.052	−0.028
10	0.065	0.004	−0.021	0.007	0.018	0.026	0.057	−0.025
Response of L(N_2O)								
Period	L(N_2O)	L(GDPP)	L(GDPP)^2	L(CPIN)	L(EUP)	L(OIL)	L(TOP)	L(FDI)
1	0.124	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.113	−0.006	0.036	−0.037	0.025	0.034	0.035	−0.042
3	0.096	−0.017	0.020	−0.006	0.012	0.008	0.042	−0.054
4	0.086	0.027	0.030	0.002	−0.013	−0.011	0.068	−0.067
5	0.100	0.029	0.019	−0.030	−0.004	0.006	0.045	−0.092
6	0.094	0.041	0.019	−0.011	−0.012	0.014	0.077	−0.095
7	0.081	0.054	0.000	−0.015	−0.010	0.019	0.078	−0.077
8	0.094	0.049	−0.002	−0.020	0.001	0.031	0.090	−0.078
9	0.090	0.053	−0.003	−0.012	0.000	0.037	0.101	−0.075
10	0.092	0.054	−0.007	−0.017	0.007	0.032	0.107	−0.067

Table 11. Variance decomposition of L(CH_4) and N_2O.

Variance Decomposition of L(CH_4)									
Period	S.E.	L(CH_4)	L(GDPP)	L(GDPP)^2	L(CPIN)	L(EUP)	L(OIL)	L(TOP)	L(FDI)
1	0.084	100.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.123	80.9183	0.254	6.039	1.365	3.178	3.155	3.076	2.015
3	0.145	77.591	0.554	5.157	1.186	3.290	2.830	5.997	3.395
4	0.165	73.040	0.746	5.120	1.346	3.083	2.269	9.286	5.112
5	0.185	72.230	0.669	4.055	1.160	2.965	1.977	9.605	7.339
6	0.203	69.111	0.654	3.384	1.121	2.718	2.287	12.173	8.554
7	0.219	67.479	0.630	3.244	1.025	2.526	2.558	13.756	8.781
8	0.237	64.686	0.556	3.020	0.914	2.546	3.126	16.016	9.137
9	0.255	62.109	0.505	3.157	0.893	2.491	3.712	18.042	9.091
10	0.273	59.719	0.465	3.320	0.846	2.587	4.152	20.128	8.785

Continued

Variance decomposition of $L(N_2O)$									
Period	S.E.	$L(N_2O)$	L(GDPP)	$L(GDPP)^2$	L(CPIN)	L(EUP)	L(OIL)	L(TOP)	L(FDI)
1	0.124	100.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	0.189	79.036	0.093	3.625	3.837	1.785	3.291	3.422	4.912
3	0.224	73.971	0.632	3.374	2.783	1.557	2.439	6.002	9.243
4	0.262	64.997	1.545	3.770	2.048	1.376	1.963	11.070	13.231
5	0.302	59.760	2.100	3.247	2.513	1.052	1.517	10.512	19.299
6	0.343	53.907	3.068	2.811	2.051	0.938	1.355	13.156	22.714
7	0.374	50.049	4.662	2.363	1.883	0.862	1.388	15.465	23.328
8	0.408	47.294	5.365	1.984	1.823	0.723	1.747	17.867	23.195
9	0.442	44.631	6.031	1.701	1.637	0.618	2.199	20.476	22.707
10	0.473	42.701	6.539	1.505	1.559	0.564	2.382	22.937	21.814
Cholesky Ordering: $L(CH_4)$ L(GDPP) $L(GDPP)^2$ L(CPIN) LEUP) L(OIL) L(TOP) L(FDI)									

3.4. Granger Causality Analysis

Long run causal relationships between CH_4, N_2O with the same set of their explanatory variables are tested by method of Granger causality. Results show a bi-directional causal relationship between agricultural growth and CH_4 emissions, while a unidirectional relationship is fund to run from agricultural growth to N_2O emissions. For both CH_4 and N_2O emissions, causal relationships between the independent variables, causal relationships are found to be concentrated around economic and agricultural growth. Granger causality results for CH_4 and N_2O are summarized and presented in Table 12.

Table 12. Granger causality tests results for CH_4 and N_2O.

CH_4				
H_0: CH_4 as the dependent	F-Stat.	Prob.	Decision	Direction of causality
H_0: L(GDPP) does not Cause $L(CH_4)$	0.231	0.795	Accept	None
H_0: $L(CH_4)$ does not Cause L(GDPP)	1.690	0.198	Accept	None
H_0: $L(GDPP)^2$ does not Cause $L(CH_4)$	0.282	0.756	Accept	None
H_0: $L(CH_4)$ does not Cause $L(GDPP)^2$	1.654	0.204	Accept	None
H_0: L(CPIN) does not Cause $L(CH_4)$	3.347	0.045	Reject	*CPIN to CH_4*
H_0: $L(CH_4)$ does not Cause L(CPIN)	2.993	0.062	Reject	*CH_4 to CPIN*
H_0: L(EUP) does not Cause $L(CH_4)$	1.016	0.371	Accept	None
H_0: $L(CH_4)$ does not Cause L(EUP)	0.346	0.710	Accept	None
H_0: L(OIL) does not Cause $L(CH_4)$	0.390	0.680	Accept	None
H_0: $L(CH_4)$ does not Cause L(OIL)	1.968	0.153	Accept	None
H_0: L(TOP) does not Cause $L(CH_4)$	1.201	0.311	Accept	None
H_0: $L(CH_4)$ does not Cause L(TOP)	0.004	0.996	Accept	None
H_0: L(FDI) does not Cause $L(CH_4)$	0.274	0.762	Accept	None
H_0: $L(CH_4)$ does not Cause L(FDI)	4.130	0.023	Reject	*CH_4 to FDI*

Continued

H_0: Independents				
H_0: L(CPIN) does not Cause L(GDPP)	3.377	0.044	Reject	CPIN to GDPP
H_0: L(OIL) does not Cause L(GDPP)	5.031	0.011	Reject	OIL to GDPP
H_0: L(TOP) does not Cause L(GDPP)	7.302	0.002	Reject	TOP to GDPP
H_0: L(OIL) does not Cause $L(GDPP)^2$	4.594	0.016	Reject	OIL to $(GDPP)^2$
H_0: L(CPIN) does not Cause $L(GDPP)^2$	3.449	0.042	Reject	CPIN to $(GDPP)^2$
H_0: L(TOP) does not Cause $L(GDPP)^2$	7.232	0.002	Reject	TOP to $(GDPP)^2$
H_0: L(CPIN) does not Cause L(OIL)	3.550	0.038	Reject	CPIN to OIL
H_0: L(FDI) does not Cause L(OIL)	4.129	0.023	Reject	FDI to OIL
H_0: L(OIL) does not Cause L(FDI)	2.430	0.101	Reject	OIL to FDI
H_0: L(CPIN) does not Cause L(FDI)	8.518	0.001	Reject	CPIN to FDI
	N_2O			
H_0: N_2O as the dependent	F-Stat.	Prob.	Decision	Direction of causality
H_0: L(GDPP) does not Cause $L(N_2O)$	0.818	0.449	Accept	None
H_0: $L(N_2O)$ does not Cause L(GDPP)	2.449	0.099	Reject	*N_2O to GDPP*
H_0: $L(GDPP)^2$ does not Cause $L(N_2O)$	0.773	0.468	Accept	None
H_0: $L(N_2O)$ does not Cause $L(GDPP)^2$	2.396	0.104	Reject	*N_2O to $(GDPP)^2$*
H_0: L(CPIN) does not Cause $L(N_2O)$	5.826	0.006	Reject	*CPIN to N_2O*
H_0: $L(N_2O)$ does not Cause L(CPIN)	1.323	0.278	Accept	None
H_0: L(EUP) does not Cause $L(N_2O)$	0.993	0.380	Accept	None
H_0: $L(N_2O)$ does not Cause L(EUP)	1.137	0.331	Accept	None
H_0: L(OIL) does not Cause $L(N_2O)$	0.953	0.394	Accept	None
H_0: $L(N_2O)$ does not Cause L(OIL)	2.562	0.090	Reject	*N_2O to OIL*
H_0: L(TOP) does not Cause $L(N_2O)$	1.139	0.331	Accept	None
H_0: $L(N_2O)$ does not Cause L(TOP)	0.093	0.912	Accept	None
H_0: L(FDI) does not Cause $L(N_2O)$	0.715	0.495	Accept	None
H_0: $L(N_2O)$ does not Cause L(FDI)	2.872	0.068	Reject	*N_2O to FDI*
H_0: Independents				
H_0: L(CPIN) does not Cause L(GDPP)	3.377	0.044	Reject	CPIN to GDPP
H_0: L(OIL) does not Cause L(GDPP)	5.031	0.011	Reject	OIL to GDPP
H_0: L(TOP) does not Cause L(GDPP)	7.302	0.002	Reject	TOP to GDPP
H_0: L(OIL) does not Cause $L(GDPP)^2$	4.594	0.016	Reject	OIL to $(GDPP)^2$
H_0: L(CPIN) does not Cause $L(GDPP)^2$	3.449	0.042	Reject	CPIN to $(GDPP)^2$
H_0: L(TOP) does not Cause $L(GDPP)^2$	7.232	0.002	Reject	TOP to $(GDPP)^2$
H_0: L(CPIN) does not Cause L(OIL)	3.550	0.038	Reject	CPIN to OIL
H_0: L(FDI) does not Cause L(OIL)	4.129	0.023	Reject	FDI to OIL
H_0: L(OIL) does not Cause L(FDI)	2.430	0.101	Reject	OIL to FDI
H_0: L(CPIN) does not Cause L(FDI)	8.518	0.001	Reject	CPIN to FDI

4. Discussions and Conclusion

This study comparatively investigated the effects of economic growth, agricultural growth and energy use on methane and nitrous oxide emissions in Sudan using annual time series data over the period 1970-2016. The estimated OLS models for emissions of both gases indicate positively signed and statistically significant coefficients of the relationship between the squared GDP per capita and CH_4 and N_2O emissions. These results indicate that the EKC hypothesis does not hold for both gas emissions in Sudan. However, the study has established a long run equilibrium relationship for emissions of both CH_4 and N_2O in their relation to economic growth, agricultural growth and energy use in presence of trade openness and inflows of foreign direct investments. Emissions of N_2O are found to have more and persistent co-movements with economic growth, agricultural growth and energy use than emissions of CH_4. For CH_4 emissions, the estimated VECM shows that emissions of this trace gas are significantly affected by economic growth, TOP and FDI with no effect of agricultural growth in the short run, while its emissions are found to be significantly affected by economic growth, agricultural growth, TOP and FDI in the long run. It also shows nonexistence of an EKC in the long run which is consistent with the OLS finding. For N_2O, the VECM model results show that emissions of this trace gas are more significantly than CH_4 affected by energy use, agricultural growth and FDI in the short run, while significantly affected by economic growth, agricultural growth, TOP and FDI in the long run. Also, no EKC is found for N_2O emissions. Impulse response and variance decomposition analysis confirm that emissions of N_2O are more responsive to economic growth, agricultural growth and energy use than emissions of CH_4. Granger causality test shows existence of only one bidirectional relationship between CH_4 and agricultural growth and only one unidirectional relationship running from CH_4 to FDI. For N_2O there exists only one unidirectional relationship running from agricultural growth to N_2O while there is unidirectional relationship running from N_2O emissions to GDPP, the squared value of GDPP, OIL consumption and FDI with no sign of significant feedback effects. These results suggest that policies toward control of N_2O emissions will have significant negative effects on economic growth, and inflows of FDI may likely be discouraged with stringent environmental policies toward nitrous oxide emissions.

The study concludes that N_2O emissions are more responsive to changes in economic and agricultural growth compared with CH_4 emissions. Furthermore, energy use only affects N_2O emissions with no effect on CH_4 emissions. Oil consumption has no effect on emissions of both CH_4 and N_2O. Results from Granger causality analysis suggest that economic growth could be pursued without significant environmental harm from both CH_4 and N_2O emissions. However, policies toward control of N_2O emissions in particular should be set and implemented with caution as their effects on emissions will be transmitted to negatively affecting economic growth, and inflows of FDI. Furthermore, the findings suggest that Sudan should adopt energy efficiency measures, expansion of production and use of liquefied petroleum gas and place restrictions on production and use of fuel woods and charcoal for low carbon economy and green growth. Again, such policy measures should more effective if cautiously directed to control of N_2O emissions within the country INDCs for the purpose of dealing with climate change obligations, more through than to CH_4 emissions control. As a least developed country (LDC) Sudan is not obliged to pursue a GHG emission reduction target. However, the country has set plans to reduce GHG emissions and pursue low-carbon development, promoting sustainable resource management in balancing national economic objectives and sustainable development requirements. Notwithstanding that Sudan INDCs give priority to energy, forestry and waste sectors in mitigation of CO_2, CH_4 and N_2O emissions, Sudan Intended Nationally Determined Contributions (Republic of Sudan, 2015). Also, within the INDCs, the energy intensity of the economy defined as total primary energy use per unit of GDP can also be reduced by relocation of resources from energy intensive sectors to labour and capital intensive sectors. The emission intensity of energy, represented by CO_2 per unit of energy can also be decreased by substitution of fuels (with lower emission factors) and through increases of renewable energies in the country's energy mix.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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