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CLIMATE CHANGE, AGRICULTURAL PRODUCTION AND FOOD SECURITY IN SUDAN

Elwasila Saeed Elamin MOHAMED[1]

Abstract

This study investigates the nexus between climate change, agricultural production and food security in Sudan, utilizing time series data over the period 1970 to 2020. The study applies unit root tests with structural breaks and the bounds test for cointegration approach. The estimated models show that food security is directly negatively affected by climate change in terms of rainfall, although the effect of rainfall is positive on crop and livestock production. Energy use and GDP growth have positive effect on food security while food prices, exchange rate, food imports and foreign aid have negative effects. Increasing CO_2 emissions affect food security positively directly and indirectly through their positive effect on GDP growth. However, the positive effect of energy use on food security is almost offset by a negative effect of energy use on GDP growth. Structural breaks accounted for by dummy variables have no effects on food security. Collectively, these findings indicate the complexity of interactions of climate change and economic factors as determinants of food security in Sudan. The study concludes that food security is affected by climate change as a long term phenomenon rather than by short run weather fluctuations.

Keywords: *Climate Change, Agricultural Production, Food Security, Sudan*

Jel Classification: *Q54, Q10, Q18*

SUDAN’DA İKLİM DEĞİŞİKLİĞİ, TARIMSAL ÜRETİM VE GIDA GÜVENLİĞİ

Öz

Bu çalışma Sudan'da iklim değişikliği, tarımsal üretim ve gıda güvenliği arasındaki ilişkiyi 1970-2020 arasındaki zaman serisi verilerini kullanarak incelemektedir. Çalışmada yapısal kırılmalı birim kök testleri ve sınır testi ile eşbütünleşme yaklaşımı uygulanmaktadır. Tahmin edilen modeller, yağışın mahsul ve hayvancılık üretimi üzerindeki etkisinin olumlu olmasına rağmen, gıda güvenliğinin iklim değişikliğinden yağış açısından doğrudan olumsuz etkilendiğini göstermektedir. Enerji kullanımı ve GSYİH büyümesi gıda güvenliğini olumlu etkilerken, gıda fiyatları, döviz kuru, gıda ithalatı ve dış yardımların olumsuz etkileri bulunmaktadır. Artan CO_2 emisyonu gıda güvenliğini olumlu yönde doğrudan, GSYİH büyümesini ise olumlu yönde dolaylı olarak etkilemektedir. Bununla birlikte, enerji kullanımının gıda güvenliği üzerindeki olumlu etkisi, enerji kullanımının GSYİH büyümesi üzerindeki olumsuz etkisi ile neredeyse dengelenmektedir. Kukla değişkenler tarafından açıklanan yapısal kırılmaların gıda güvenliği üzerinde hiçbir etkisi bulunmamaktadır. Toplu olarak değerlendirildiğinde bu bulgular, Sudan'da gıda güvenliğinin belirleyicileri olarak iklim değişikliği ve ekonomik faktörlerin etkileşimlerinin karmaşıklığını göstermektedir. Çalışmada, gıda güvenliğinin kısa vadeli hava dalgalanmalarından ziyade uzun vadeli bir fenomen olarak iklim değişikliğinden etkilendiği sonucuna varılmıştır.

Anahtar Kelimeler: *İklim Değişikliği, Tarımsal Üretim, Gıda Güvenliği, Sudan*

Jel Sınıflandırması: *Q54, Q10, Q18*

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INTRODUCTION

It is now well known that global warming and climate change are caused by emissions of greenhouse gases (GHGs). Emissions of these gases are associated with all economic activities, but with varying contributions and intensities, which imply different policy implications on how to reduce emissions and to cope with climate change impacts at country level. Climate change means significant and persistent variation of the average weather conditions over long period of time and not the short term weather changes (IPCC, 2014). One major indicator of climate change is changes in rainfall over time, space and in quantities. Furthermore, erratic rainfall associates with both floods and droughts as extreme climate events. In addition, rainfall water is reduced by rising surface temperature which affect water availability for plant irrigation and for animals. Overall, these changes cause direct and indirect damages to agricultural production as well as direct human life losses.

Climate change impacts the four dimensions of food security negatively as it is well documented in various food security assessments conducted by the Food and Agriculture Organizations, for example (FAO, 2010). FAO (2018) states that climate variability and extremes were the main drivers of increases in global hunger and one of the leading causes of severe food crises. The FAO states that increasing climate instability and extremes reduce agricultural productivity with major impacts on food production, distribution and consumption, and implying new food security challenges (FAO, 2019).

In low-income countries in particular, unfavorable climate changes in terms of erratic rainfall and increased temperature, with extreme events of floods and droughts have deleterious impacts on agricultural production and on food security. Increases in the frequency and severity of extreme weather events can interrupt food production and distribution chains, and result in high food prices, which lead to social and political unrests, worsening the state of food security as happened in Egypt in 2011 (David, 2011). It was also documented that climate changes result in crop and animal loses and massive displacement of people in Syria since 2010, where more than one million Syrians were left extremely food insecure, and up to three million people were driven into extreme poverty (Caitlin et al., 2015). It has also been shown that climate change and declining rainfall as main causes of social conflict in Africa, through reduction of agricultural production resulting in severe food shortage and food insecurity in the continent (Haile, 2005; Hendrix and Salehyan, 2012). Furthermore, it has been documented that, in developing countries, climate changes disturb food production, distribution and transport with significant impacts on food systems and food security (Gregory et al., 2005; Brown et al., 2015).

The impacts of climate change on agriculture and food security are further compounded with other related factors such as armed conflicts (David and Lee, 2007), and people displacement (International Displacement Monitoring Centre (IDMC), 2016; Elwasila, 2020). Furthermore, in low income countries, high population growth rates also magnify the effects of climate changes on food security through reduced energy use per capita and reduced food per capita. These negative impacts become more severe where public and private adaptation measures are meager or nonexistent. In such situations, international assistances fall short to meet the basic needs of affected populations (Menghestab, 2005). At the individual level, food insecurity manifest as a reduced capacity to perform physically and mentally, which result in reduction of GDP by 10% at the individual country level (Brown et al., 2015). At a regional level, Kahsay and Hansen (2016) showed that climate changes reduce total output by 2.85 percent on average in the Horn of Africa region including Sudan.

However, climate change impacts on agriculture and food security can be reduced by investments in mitigation and adaptation measures. Examples include growing of climate resistant crops, greenhouse cropping, intensive use of tractors and energy, and use of environment friendly fertilizers and pesticides (IPCC, 2014). Nonetheless, these measures lead to increases in GHGs emissions, which could increase costs to farmers, worsen food production and food security (Hatfield et al., 2014; Ziska et al., 2014).

1. CLIMATE CHANGE AND FOOD SECURITY IN SUDAN

Food security is not separable from climate change and agriculture in Sudan, as agriculture in Sudan is dominated by the traditional and mechanized rain-fed sectors, with relatively smaller irrigated sector. The traditional and mechanized rain-fed sectors occupy more than 70% of the total cultivated land and employ about 75% of the agricultural population. Nevertheless, these sectors are characterized by low efficiency and low crop productivity, which reduces the share of the agricultural sector in the GDP (Siddig, 2009). Main agricultural and food crops in Sudan include maize, wheat, millet, vegetables and fruits, while main cash crops include cotton, sesame, groundnuts, sunflower, watermelon and watermelon seeds.

It has been documented that since the late 1960s, declined rainfall quantity and quality led to serious drought periods with negative consequences on cereals production in Sudan from the rain-fed farming practices (El-Dukheri et al., 2006). Over the past five decades Sudan has experienced three major famines coincided with droughts and floods, which aggravated conflicts over scarce natural resources, caused people displacement and worsened food security (Keen and Lee, 2007; Elwasila, 2020). Leory and Fana (2011) document that reduced rainfall in Darfur since 1983 has turned grazing land into desert and placed significant threats on the livelihood systems. In Eastern Sudan rainfall had dropped to zero during the 10 most severe droughts during 1980 to 1990 (Carlo B., 2010). With rising temperature and reduced water, these changes have led to stagnant agricultural yields, and coupled with relatively high population growth have already led to a fall in per capita food availability (Niang et al., 2014). Laura (2017) states that high temperatures and rainfall changes reduced crop productivity in Sudan and their effects are magnified with vulnerability of agriculture to climate change, and by the fact that the majority of Sudanese depend on agriculture for their foods and incomes.

Furthermore, Sudan is highly vulnerable to climate change with large threats to human security (Joshua et al., 2015). These vulnerabilities have been compounded of very low household and community resilience, low government capacity to response to climate disasters, reduced external assistances, worsened by prolonged years of armed conflicts (Elwasila, 2020). It is thus of importance to study the effects of climate changes in terms of fluctuating rainfall and the implied episodes of drought and floods over time on agricultural production directly and on food security at the country level as an outcome. Identifying these effects is of vital importance for designing public and private policies of mitigation and adaptation for enhancement of socio-economic development in general and food security in particular.

Food insecurity in Sudan is highly prevalent reflected by prevalence of high malnutrition in terms of Global Acute Malnutrition (GAM) and Severe Acute Malnutrition (SAM) which were both above the emergency thresholds (USAID, 2016). Regionally, in an analysis of 169 surveys, Nielsen (2009) found no significant difference in GAM and SAM between internally displaced persons (IDPs) and residents in Darfur. According to the 2017 Humanitarian Needs Overview of the UN Office for the Coordination of Humanitarian

Affairs (UNOCHA), 3.6 million of Sudanese were in severe need of food out of a total of 4.8 million people in need of humanitarian assistance in the country. In a recent report, 13.4 million people were in humanitarian need through 2021, of them 7.3 million need life-saving assistances, and 8.2 million people food security and livelihoods sector needs (UNOCHA, 2021).

According to the Swedish International Development Agency (SIDA, 2020), Sudan is one of the world's largest protracted humanitarian crises due to (i) large numbers of IDPs and refugees, (ii) climatic conditions leading to high levels of food insecurity, and (iii) escalating economic crisis which intensified the numbers of people in need.

In Sudan, the heavy rainfall over September 2020 caused devastating floods across 17 out of the 18 Sudanese states, destroyed more than 100,000 homes, and left more than 130 people dead (Slawson, 2020; Reuters, 2020). According to the FOA, the September 2020 floods have affected nearly one third of cultivated land and about 3 million people from agricultural households and their main crops were washed away just before harvest, and 108,000 head of livestock were lost (FAO, 2020). The United Nations estimates that 9.6 million people face acute food insecurity in Sudan, the highest number on record (UN News, 2020).

However, as long term phenomena, extended periods of droughts and water scarcity necessitate investments in water harvest projects as a flow resource during periods of heavy rain seasons, which can be used later. Harvesting, rain water also provides prevention and protection from river and flash floods. Such investments would help in maintaining food production and other products for sufficiency and food security, but they are not without costs. Given limited individual and government abilities to fund such investments, there is a need for international financial assistance to support adaptation to climate change impacts on agricultural production, maintenance of income and for food security (Brown et al., 2015).

The objective of this study is to investigate the effects of average rainfall, CO_2 emissions and energy use, together with economic growth factors directly on food security defined as the depth of food deficit, and indirectly through their effects on agricultural production in Sudan.

2. LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

2.1. Literature Review

Since the 1980s, extreme climate events in terms of floods and droughts have been frequently occurring in different parts of the world, causing disruption to food production and productivity (Shi et al., 2021). Santos et al. (2021) evaluate the drought behavior in the Odisha region of India over the period 1983 to 2018 by using the standardized precipitation index (SPI) and the new drought severity (DS). They document that half of the mean annual rainfall was concentrated in just two months, and showed that the DS significantly increases in the drought time in both the medium term and long term and oddly in the areas with the highest rainfall levels in the region. The authors provide policy recommendations for water resources management to face droughts severity. The implications of these findings are that food production and security are jeopardized with such events.

Shi et al. (2021) quantified the losses of crop yield and production from droughts and floods in China over the period 1982 to 2015. They show that draughts reduced maize and soybean yield and production, and that draughts and floods significantly decreased wheat yield and both draughts and floods reduced rice yield and production.

Ahmet et al. (2017) for 18 Middle East and North African (MENA) countries and Turkey, over the period of 1990-2014, found that food security is hampered by higher prices, poor water management, while food security can be enhanced by education and withdrawals of fresh water. Clemens et al, (2010) for the MENA countries including Sudan, argued that achieving food security required diversified economic growth, buffer against international oil and food prices, effective management of water resources and adaptation to climate changes. Laibuni et al, (2015) argued for effective and sustainable policies focusing on improving food production and productivity and regional trade for food security in East Africa countries. With a panel data from 57 developing countries, Abdul Manapa et al., (2017) found that the depth of food deficit (DFD) over the period 1990 to 2007 was significantly reduced by food import, food production, purchasing power and arable land, while sanitation services and GDP were found to have negative effects on food security.

Butt et al. (2005) investigated impacts of climate change on economic and food security through the agricultural sector on Mali. Under two scenarios, they showed that climate changes reduce crop yield by minus 17% to plus 6%, reduce forage yields by 5 to 36% and livestock animal weights by 14 to 16%, resulting in overall economic losses of 70 to $142 million, where producers gain and consumers lose. Climate change was found to increase the percentage of population at risk of hunger from 34% to 72%, but with cropping adaptation strategies, population at risk of hunger could effectively be reduced to 28%. Seydou et al. (2014) found that the major determinants of food security in Niger were drought, food prices, poverty and soil degradation.

Muhammad et al. (2018) studied the impacts of energy use, CO_2 emissions with a host of economic and trade factors on food production and food security in Pakistan over the period from 1964 to 2015 using the autoregressive distributed lags model (ARDL). They found that energy consumption and domestic credit have adverse effect on food production, while CO_2 has no adverse effect on food production, and physical capital, labor and trade openness have no significant effects. They also found that fertilizer use have positive effect where rising population has a negative impact on food production. Also, Naseem (2020) established asymmetrical long run relationship between nonrenewable energy use, food security and CO_2 emissions in Pakistan, showing that agricultural value added reduces CO_2 emissions, while energy use and population were found to increase emissions.

Nour and Eltayeb (2020) found a gender gap in food production and food security in that male-headed households produce more food than female headed in Kassala State of Sudan. They argue that increase in commercial agriculture leads to higher income and thus increased food security, but requiring well-functioning markets where the higher incomes can be used to replace the reduction in staple food crops. They recommend that policies should target households' incomes, smallholders' own production of food, diversify agricultural food crops, improve irrigation systems, and increase agricultural productivity through technology adoption.

Arshad (2022) used panel data methods to investigate the effect of financial inclusion on food security in developing countries over the period 2004-2019. Their study found that financial development, income, agriculture growth and education positively affect food security, while militarization and urbanization have a negative impact on food security. Affoh et al. (2022) investigated the effects of rainfall, temperature, and CO_2 emission on food availability, accessibility and utilization in a panel of 25 Sub-Saharan (SSA) countries from 1985 to 2018 by estimation of pool mean group panel ARDL. They showed that rainfall has significant positive effect on three food security dimensions in the long run, temperature is harmful to food availability and accessibility, while CO_2 emission has a positive impact.

2.2. Conceptual Framework

This study is empirical and quantitative in that it uses econometric methods for analysis of climate change, agricultural production and food security in Sudan based on an analytical framework, with reliable data. For this purpose, climate change, economic and trade indicators were selected to explain food security with the possibility of establishing meaningful comparisons. This study uses indicators which focus on conditions that affect the four dimensions of food security of availability, accessibility, utilization and stability according to definitions of FAO (2010) and Brown et al. (2015). The four dimensions are set to operate within climate change, trade and socio-economic context. The availability dimension is related to agricultural production reflected by crops and livestock production, which are directly affected by climate change in terms of rainfall, temperature and CO_2 emissions. The access dimension includes food prices, income and food trades. The utilization dimension concerns the impact from inadequate use of food, and therefore under nutrition and reflected by DFD. The stability dimension requires stability of all other dimensions including stable food supply, stable prices and exchange rates, with climate change beyond control of Sudan. To capture the direct and indirect effects of climate change, the study uses two measures of food security. The direct measure is the DFD as an outcome measure of food security, which embodies other measures of food security. DFD is defined as the calories needed to lift the undernourished people from their present status. It is thus embodying the actual food consumption in quantity and quality and the implied dietary energy requirements of the undernourished populations. In this sense, food security improvement needs reduced DFD at the individual and national level. The indirect measure is a crop and livestock production index.

Climate change factors are represented by annual average rainfall (ARF), which include years of floods and droughts as extreme events. ARF is the average precipitation in depth (mm per year) in the country, which is also associated with increasing air temperatures in Sudan since 1960s, and recently exceeded the cap of 1.5 ^{o}C agreed in Paris Climate Summit in 2015 (World Bank, 2021). Furthermore, over the period 1941 to 2000, average annual rainfall has been declining at a rate of 0.5% with greater annual variability and becoming unreliable, associated with rising temperature, which increased the rates of evaporation and drought events (World Bank, Climate Change Knowledge Portal, Sudan, 2021). Another climate change indictor is total or per capita CO_2 emissions. In fact, CO_2 emissions, rainfall and temperature were found to be interconnected (Affoh et al., 2022).

CO_2 emissions in Sudan are largely stemming from the agricultural practice and land use changes (Elwasila, 2020). Agriculture in Sudan is mostly rain-fed, and challenged by both the frequently repeated periods of draughts and floods indicating increasing unreliability of rainfall. These challenges are aggravated where only limited means of water harvesting for well-organized irrigation practices are available almost in all parts of the country. On the other hand, it has been observed that heavy rainfall concentrates close to the harvest season and thus causing major harvest losses (FAO, 2020). In all cases there are needs to increase energy use, which is restricted by increasing prices of gasoline and benzene, which together increases costs of food production, and coupled with high transportation costs, implying higher food prices for consumers, and thus negatively impacting food security at the national level. Thus, energy use per capita (ENP) is included to represent energy which has effects on CO_2 emissions on one hand and on all food security dimensions on the other hand.

Economic factors are represented by real GDP at 2015 prices, exchange rate, real food price index (FPI), and food trade, which reflect interactions of supply and demand of food at the national and international level and have proven impacts on food security. Local food prices are determined by local production and transportation of food as well as food trade. Local food production is represented by a composite of crop and livestock production index (CLP). Food price is represented by the real food price index. Exchange rate is represented by the conversion factor (DEC), which interacts with inflation rates, commodity prices, purchasing power and access to and utilization of food and accordingly the state of nutrition and food security at the individual and national levels. Food trade is represented by food imports (FOM) measured as percentage of merchandize imports, which is affected by global supply of food and international food prices. Foreign aid to Sudan has been mostly humanitarian of which food aid is a major component especially amid conflicts, displacements, which have continuously been aggravated by climate disasters.

Figure 1 unifies these factors as determinants of food security in Sudan. Data on all variables is processed from the WDIs (2021), except for the real food price index, which is sourced from USAID (2019) and FOA (2020).

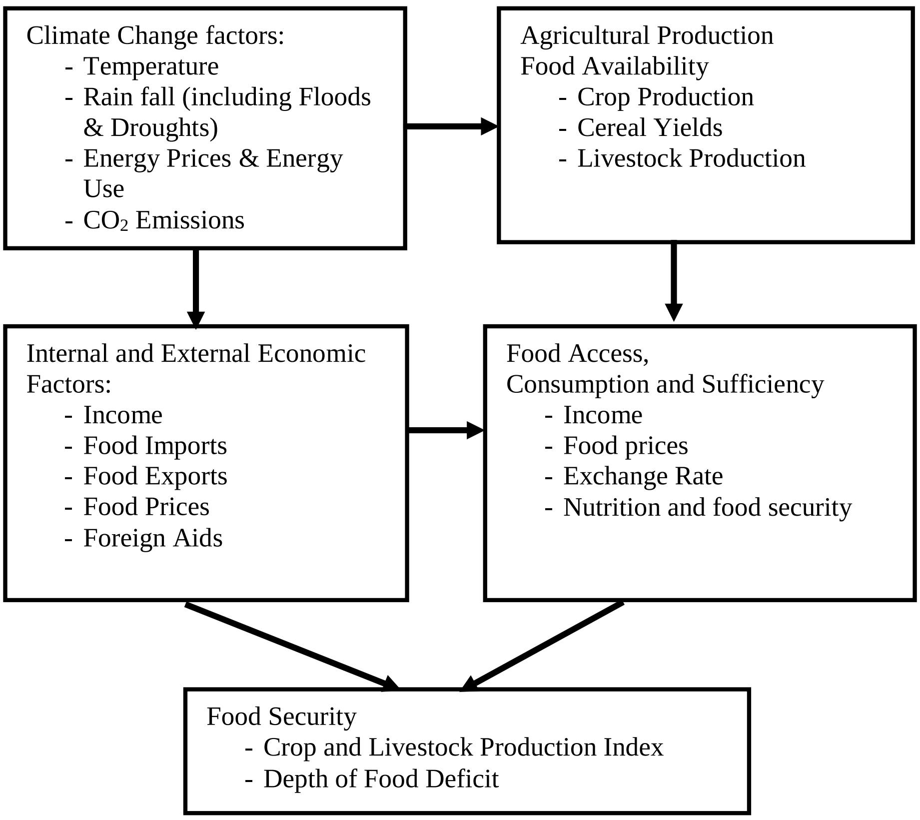

Figure 1: Determinants of Food Security

Figure 1 emphasizes the most important two challenges of food security, which are the availability and accessibility to food. Increased food availability requires increased agricultural production and productivity and trade, and effective distribution systems. Higher real incomes are necessary to enable people to buy sufficient food, which require efficient and stable local markets with stable exchange rates. In addition, there are needs for social protection systems to help disadvantaged groups to cope with chronic poverty and macroeconomic price shocks (AusAID, 2012). According to the varaibles set in Figure 1, Table 1 summaries a 10 year averages of the main agriculture, climate change and economic indicators of Sudan over the period 1970-2020.

Table 1: Main Agriculture, Climate and Economic Indicators of Sudan

	1970-1979	1980-1989	1990-1999	2000-2009	2010-2020	1970-2020
AGG	36.76	33.15	40.45	32.41	27.56	34.07
AGR	3.76	5.07	4.77	1.13	1.19	3.18
GDPG	4.28	3.39	4.41	7.1	2.74	4.38
CRPI	48.01	48.7	61.94	94.49	100.09	70.65
LSI	28.45	40.57	58.38	96.64	101.37	65.08
CLP	38.23	44.63	60.16	95.57	100.73	67.86
ENP	620.15	547.24	499.4	493.44	416.89	515.42
APDG	0.5	0.42	0.41	0.46	0.75	0.51
FOM	19.68	18.84	18.33	14.36	14.47	17.14
FOX	34.53	46.76	52.45	9.49	8.18	30.28
ARF	1569	848.1	1454.8	1712.9	580.455	1233.05
FPI	100.8	100.29	102.72	113.53	149.22	113.31
DFD	223.9	261.3	237.1	178.7	190.46	218.29
DEC	0.0003	0.002	0.853	2.414	28.643	6.382
CO_2	4514.08	3891.42	4636	10085	17770.9	8179.48

Table 1 reveals that agricultural contribution to GDP (AGG) has been declining except over the decade 1990 to 1999. This was associated with declining agricultural GDP growth (AGR), increrasing average price of diesel and gasoline (APDG), deteriorating value of the Sudanese currency (DEC), increasing real food price (FPI) and decreasing energy use per capita (ENP). On the other side, average rain fall (ARF) has been declining but peaked during 2000-2009, while CO_2 emissions have been steadily increasing, with increasing crop production index (CRPI), livestock production index (LSI) and a composite index of them (CLP). Food imports (FOM) have been declining while food exports (FOX) peaked over the decade 1990 to 1999 but then declined over the past two decades. Importantly, DFD seems constant over the past five decades.

3. STATISTICAL ANALYSIS

3.1. Descriptive Statistical Analysis

Table 2 presents the descriptive statistics and correlations of the study variables. From the Jarque-Bera (J-B) statistics, DFD, ENP and FOM look normally distributed while all other variables follow non-normal distribution including GDP, ARF, CO_2 and CLP. The variables highest kurtosis are exchange rate followed by foreign aid and energy use per capita.

Table 2: Descriptive Statistics and Correlations

	DFD	CLP	ARF^{mm}	ENP	CO_2	GDP$^{\$}$	FPI	DEC	FOM	AID$^{\$}$
Mean	218	68.51	1220	513.49	8368	37,000	114.01	6.82	17.08	575
Median	212	61.46	1600	507.81	5190	25,400	102.76	0.58	17.34	475
Max	297	116.30	1730	661.70	20480	87,600	165.99	155.72	25.88	2,140
Min	168	33.62	225	394.61	3190	10,600	87.57	0.0003	5.26	480
Std. D.	38.73	27.22	607	72.96	5792	25,000	22.18	23.54	4.52	589
Skew.	0.29	0.22	-0.66	0.19	0.99	0.79	0.99	5.39	-0.25	1.38
Kurt.	1.69	1.40	1.62	2.56	2.43	2.17	2.50	33.27	3.02	3.91
J-B	4.34	5.86	7.74	0.72	9.01	6.77	8.80	2193.15	0.51	18.01
Prob.	0.114	0.053	0.021	0.697	0.011	0.034	0.012	0.000	0.774	0.000
Obs.	51	51	51	51	51	51	51	51	51	51
	DFD	**CLP**	**ARF**	**ENP**	**CO_2**	**GDP**	**FPI**	**DEC**	**FOM**	**AID**
DFD	1.00									
CLP	-0.68	1.00								
ARF	-0.20	-0.10	1.00							
ENP	0.32	-0.80	0.46	1.00						
CO_2	-0.58	0.85	-0.39	-0.73	1.00					
GDP	-0.58	0.92	-0.38	-0.85	0.97	1.00				
FPI	-0.46	0.72	-0.35	-0.67	0.88	0.86	1.00			
DEC	-0.04	0.37	-0.27	-0.35	0.53	0.51	0.47	1.00		
FOM	0.27	-0.58	0.32	0.55	-0.56	-0.60	-0.47	-0.26	1.00	
AID	-0.48	0.66	-0.04	-0.46	0.59	0.58	0.61	0.08	-0.50	1.00

$^{\$}$ Million US Dollars, ^{mm} means millimeters

The correlation matrix in Table 2 shows that the DFD is mostly correlated with CLP, followed by CO_2 emissions and GDP. However, there is a positive correlation between food security defined by crop and livestock production index and GDP growth as well as with CO_2 emissions. Energy use per capita is strongly negatively correlated with GDP growth, while CO_2 emissions are strongly correlated with GDP growth and with food price index.

3.2. Econometric Analysis

This study adopts empirical-quantitative research design, with the analytical framework to capture the dynamic relationships between climate change, agricultural production, economic growth, trade and food security as outlined in Figure 1. The framework takes into account reviews and results of previous research in the field. In this study, the dependent variable is food security (FOS) measured directly by the DFD scaled to national average and indirectly by the the composite crop and livestock production index (CLP). The statistical empirical-quantitative method for analyzing the co-variations of the study variables is the ARDL bounds test model. Furthermore, the derived results from the case of Sudan can be validated and placed within the previous findings, and can be generalizable. The study uses annual time series secondary data on its selected variables covering the period 1970-2020. A general log linear model of food security in Sudan is written as:

$$L(FOS) = \alpha + \beta_1 L(ARF) + \beta_2 L(ENP) + \beta_3 L(CO_2)$$
$$+ \beta_4 L(GDP) + \beta_5 L(FPI) + \beta_6 L(DEC) + \beta_7 L(FOM) + \beta_8 L(AID) + \mu \ldots\ldots\ldots\ldots 1$$

μ is the regression residual, assumed to be not serially correlated and homoscedastic. The estimated coefficients represent elasticities.

An ARDL model based on Pesaran and Shin (1999) and Pesaran et al. (2001) to investigate the short-run dynamics and long run equilibrium of food security and its explanatory variables in accord with equation 1 is specified as follows:

$$\Delta L(FOS)_t = \alpha + \sum_{i=1}^{p} \alpha_{1i} L(FOS)_{t-1}$$
$$+ \sum_{t-1}^{p} \alpha_{2i} \Delta L(AFR)_{t-1} + \sum_{i=0}^{p} \alpha_{3i} \Delta L(ENP)_{t-1}$$
$$+ \sum_{i=0}^{p} \alpha_{4i} \Delta L(CO_2)_{t-i} + \sum_{i=0}^{p} \alpha_{5i} \Delta L(GDP)_{t-i}$$
$$+ \sum_{i=0}^{p} \alpha_{6i} \Delta L(FPI)_{t-i} + \sum_{i=0}^{p} \alpha_{7i} \Delta L(DEC)_{t-i}$$
$$+ \sum_{i=0}^{p} \alpha_{8i} \Delta L(FOM)_{t-i} + \sum_{i=0}^{p} \alpha_{9i} \Delta L(AID)_{t-i}$$
$$+ \beta_1 L(FOS)_{t-1} + \beta_2 L(ARF)_{t-1} + \beta_3 L(ENP)_{t-1}$$
$$+ \beta_4 L(CO_2)_{t-1} + \beta_5 L(GDP)_{t-1} + \beta_6 L(FPI)_{t-1}$$
$$+ \beta_7 L(FOM)_{t-1} + \beta_8 L(AID)_{t-1} + \eta ECT_{t-1} + \mu_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

The parameter *p* is the lag length, *Δ* is the difference operator and *η* is the coefficient of adjustment associated with error correction terms-it should be negative reflecting the strength and the speed of the reaction of the dependent variable to a deviation from the equilibrium relationship in one period. The short-run coefficients account for short-run fluctuations which are not due to deviations from the long-run equilibrium (Kripfganz and Daniel, 2018). The properties of the study time series data are checked by applying the two common unit root tests-the Augmented Dickey-Fuller (Dickey & Fuller, 1981) and Phillips-Perron (Phillips and Perron, 1988). Unit root tests are implemented in the cases of without breaks and with structural breaks, and in scenarios of intercept and intercept and linear trend. Table 3 summarizes the unit root test results without breaks, and Table 4 summarizes the test results with breaks.

Table 3: Unit Root Test

	Intercept				**Order of Integration**
	Level		**First Difference**		
	ADF	**PP**	**ADF**	**PP**	
L(DFD)	-1.328	-1.465	-3.636***	-6.282***	I(1)
L(CLP)	-0.903	-0.993	-11.072***	-11.494***	I(1)
L(ARF)	-2.004	-2.147	-6.555***	-6.531***	I(1)
L(CO_2)	-0.933	-1.278	-9.639***	-9.307***	I(1)
L(EPN)	-1.611	-1.537	-8.638***	-8.898***	I(1)
L(GDP)	0.219	-0.013	-4.612***	-4.480***	I(1)
L(FPI)	-0.793	-0.926	-6.111***	-6.052***	I(1)
L(DEC)	-0.154	0.147	-1.896	-2.973**	I(1)
L(FOM)	-3.101**	-2.811	-5.978***	-16.234***	I(0)&I(1)
L(AID)	-1.914	-4.659***	-5.855***	-6.005***	I(0)&I(1)
Variable	**Trend and Intercept**				**Order of Integration**
	Level		**First Difference**		
	ADF	**PP**	**ADF**	**PP**	
L(DFD)	-1.817	-1.905	-3.515**	-6.239***	I(1)
L(CLP)	-1.515	-2.624	-10.997***	-11.432***	I(1)

L(ARF)	-2.137	-2.300	-6.478***	-6.448***	I(1)
L(CO_2)	-1.789	-1.791	-10.408***	-10.408***	I(1)
L(EPN)	-3.099	-3.007	-8.650***	-8.883***	I(1)
L(GDP)	-2.883	-1.909	-4.566***	-4.304**	I(1)
L(FPI)	-2.014	-2.175	-6.084***	-6.014***	I(1)
L(DEC)	-3.619**	-1.899	-1.876	-2.793	I(0)
L(FOM)	-4.177**	-3.012	-5.902***	-15.900***	I(0)&I(1)
L(AID)	-2.542	-3.846**	-6.511***	-6.632***	I(0)&I(1)

***, **, indicate significance at 1% level and 5% level respectively

Table 4: Unit Root Tests with Breaks

	Intercept				**Order of Integration**
	ADF I(0)	**Break Year**	**ADF I(1)**	**Break Year**	
L(DFD)	-3.166	1992	-6.779***	1979	I(1)
L(CLP)	-4.463	1991	-11.205***	1991	I(1)
L(ARF)	-3.699	2011	-8.426***	2012	I(1)
L(CO_2)	-3.087	2001	-12.244***	1993	I(1)
L(EPN)	-2.820	2011	-10.671***	2012	I(1)
L(GDP)	-2.659	1994	-6.755***	1988	I(1)
L(FPI)	-5.922***	2006	-6.594***	1986	I(0)&I(1)
L(DEC)	-1.964	1987	-5.618**	1975	I(1)
L(FOM)	-5.933***	2007	-7.497***	2007	I(0)&I(1)
L(AID)	-7.788***	2000	-9.453***	1974	I(0)&I(1)
Trend and Intercept					
Variable	**ADF I(0)**	**Break Year**	**ADF I(1)**	**Break Year**	**Order of Integration**
L(DFD)	-3.380	1994	-6.993***	1984	I(1)
L(CPL)	-2.858	1995	-11.096***	2014	I(1)
L(ARF)	-4.164	1991	-7.266***	2011	I(1)
L(CO_2)	-4.004	1990	-12.425***	1993	I(1)
L(EPN)	-4.161	1993	-9.030***	2006	I(1)
L(GDP)	-4.242	1983	-7.702***	1989	I(1)
L(FPI)	-5.701**	2006	-6.438***	2011	I(0)&I(1)
L(DEC)	-4.479	1987	-5.794**	1999	I(1)
L(FOM)	-6.060***	2007	-7.758***	2007	I(0)&I(1)
L(AID)	-5.593**	2007	-10.150***	1975	I(0)&I(1)

***, **, indicate significance at 1% level and 5% level respectively

The unit root test results show that, in all cases of intercepts and trends, the variables of concern follow a combination of integration order and stationary at level I(0) and first difference I(1). The first variable witnessed breaks was foreign aid (1974 and 1975), DFD broke in 1992 and 1994, while CLP broke in 1991 and 2014. Rainfall witnessed two breaks in 2011 and 2012. Most breaks occurred during the decades of 1990 and 2000s. Over these two decades, average GDP growth and average rainfall had their highest values, while DFD had its lowest value during 2000-2009.

The ARDL specified in equation 2 is estimated to explore the long run relationship between food security and the concerned co-variables by performing an F-test for the joint significance of the lagged-level variables. The null hypothesis of no cointegration of equation 2 is:

$$H_0 : \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = \beta_7 = \beta_8 = 0$$

The alternative hypothesis is:

$$H_1 : \beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq \beta_5 \neq \beta_6 \neq \beta_7 \neq \beta_8 \neq 0$$

Existence of cointegration in the bounds testing approach according to Pesaran and Shin (1999) is ascertained by critical values for the F-statistic against the lower bound for all variables cointegrated of the order I(0) and the upper bound for all variables cointegrated of the order I(1). If the F-statistic lies above the upper bound value, the conclusion is existence of cointegration.

Upon estimation of a general vector autoregressive model, the lag order criteria came to be the same for food deficit, crop and livestock production and GDP growth each estimated as the dependent variable. The criteria reveal a lag of 3 to the optimal lag order for estimation of the ARDL bounds test models. The bounds test for food security measured by the depth of the DFD and CLP were conducted separately. The effect of food security on GDP growth was also estimated. The results are summarized in Table 5.

Table 5: Bounds Test Results

Estimated Models	F. Stat.	I(0)/I(1) [Prob.]	Lag Order	Break Year	Conclusion
DFD = F(CLP, ARF, ENP, CO_2, GDP, FPI, DEC, FOM, AID)	5.80	2.76/4.05[0.000]	3	1979	Cointegration
CLP = F(DFD, ARF, ENP, CO_2, GDP, FPI, DEC, FOM, AID)	4.68	2.76/4.05[0.000]	3	1991	Cointegration
GDP = F(DFD, CLP, ARF, ENP, CO_2, FPI, DEC, FOM, AID)	15.94	2.76/4.05[0.000]	3	1988	Cointegration

K = 9; I(0)/I(1) from Pesaran et al. (1999), Case II: Restricted Intercept No Trend

The validity of the estimated bounds test models is judged by the behavior of the error terms, which are supposed to be normally distributed, homoscedastic and serially uncorrelated, and that the coefficients must be stable over time (Kripfganz and Daniel, 2018). The stability of the estimated models is confirmed by the finding that the plots of CUSUM and CUSUMQ for DFD, CLP and GDP, which all lie within the 5 percent critical values, as shown in Figure 2 through Figure 7.

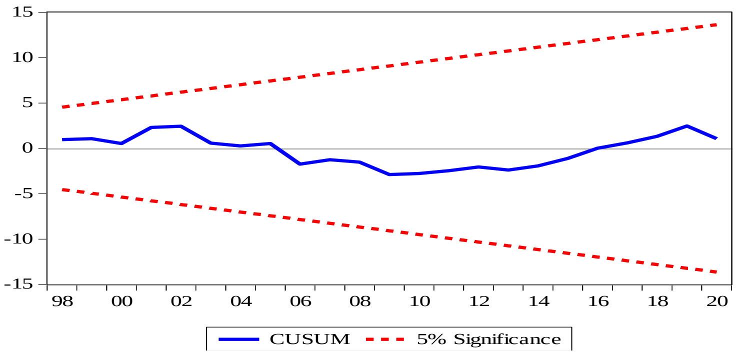

Figure 2: DFD CUSUM

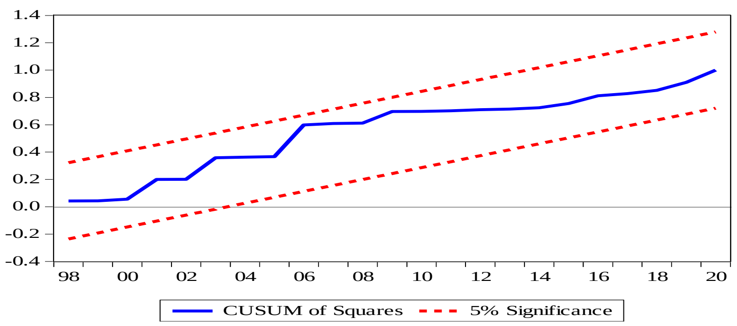

Figure 3: DFD CUSUMQ

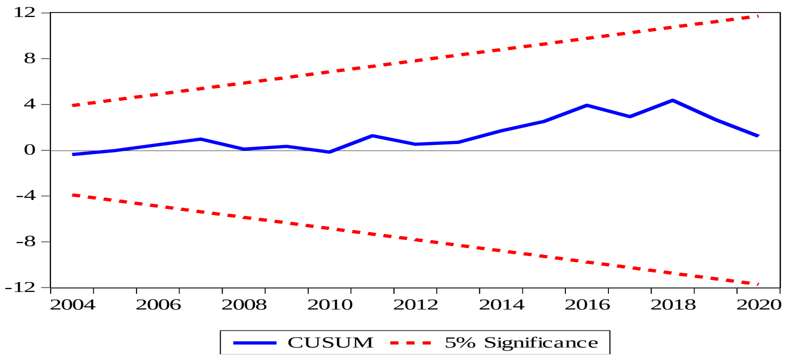

Figure 4: CLP CUSUM

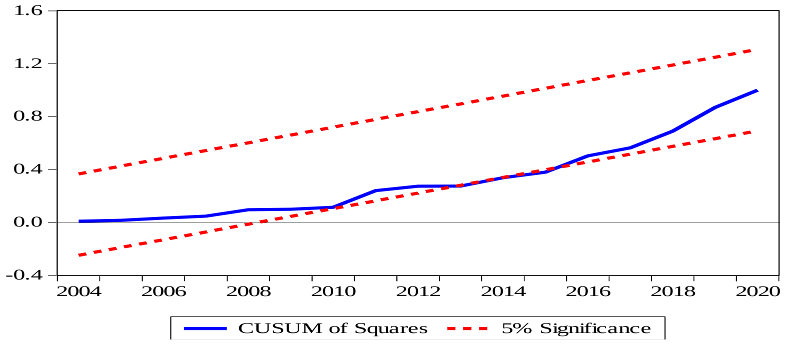

Figure 5: CLP CUSUMQ

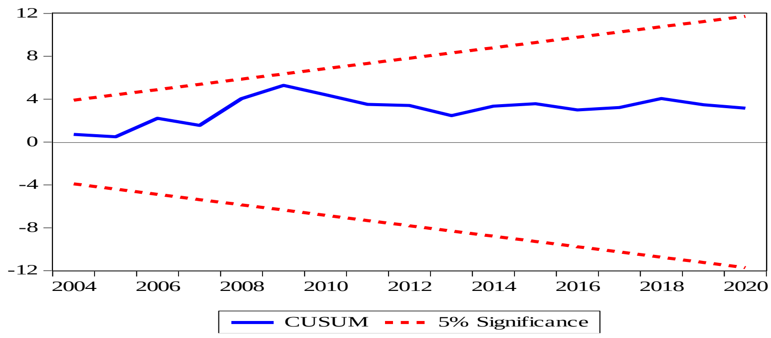

Figure 6: GDP CUSUM

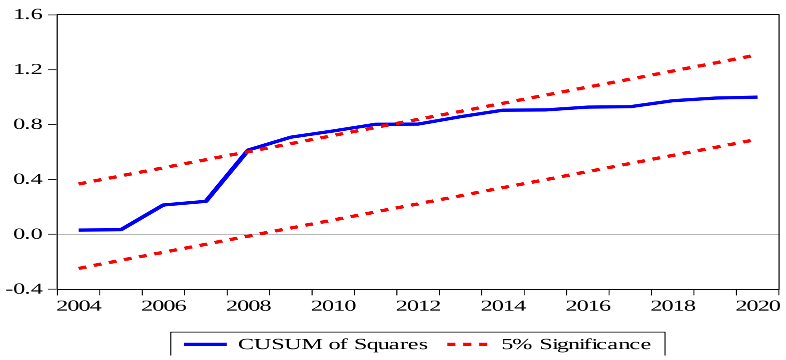

Figure 7: GDP CUSUMQ

The estimated ARDL models long run coefficients are presented in Table 6.

Table 6: ARDL Long Run Forms: Case 2: Restricted Constant and No Trend

Model 1: DFD			Model 2: CLP			Model 3: GDP		
Variable	*Beta*	Prob.	Variable	*Beta*	Prob.	Variable	*Beta*	Prob.
L(DFD)	--	--	L(DFD)	0.11	0.615	L(DFD)	-0.36	0.098*
L(CLP)	0.27	0.237	L(CLP)	--	--	L(CLP)	1.36	0.000***
L(ARF)	-0.11	0.005*	L(ARF)	0.15	0.051**	L(GDP)	--	--
L(ENP)	1.88	0.001***	L(ENP)	-2.47	0.308	L(ARF)	0.001	0.984
L(CO_2)	-0.10	0.335	L(CO_2)	0.07	0.625	L(ENP)	-2.00	0.001***
L(GDP)	0.62	0.005**	L(GDP)	-0.28	0.618	L(CO_2)	0.60	0.005**
L(FPI)	-0.83	0.007**	L(FPI)	-0.09	0.744	L(FPI)	-1.31	0.015**
L(DEC)	-0.07	0.009**	L(DEC)	0.08	0.033**	L(DEC)	-0.02	0.374
L(FOM)	-0.15	0.014**	L(FOM)	0.10	0.342	L(FOM)	0.04	0.719
L(AID)	-0.05	0.046**	L(AID)	0.02	0.426	L(AID)	-0.031	0.271
C	-16.44	0.010**	C	25.28	0.391	C	40.53	0.000***
EC = L(DFD) - (0.27L(CLP) -0.11L(ARF) + 1.88L(ENP) - 0.10L(CO_2) + 0.62L(GDP) - 0.83L(FPI) -0.07L(DEC) - 0.15L(FOM) -0.05L(AID)- 16.44)			EC = L(CLP) - (0.11L(DFD) + 0.15L(ARF) -2.47L(ENP) +0.07L(CO_2) -0.28L(GDP) - 0.09L(FPI) + 0.08L(DEC) + 0.10L(FOM) + 0.02L(AID) + 25.28)			EC = L(GDP) - (-0.36L(DFD) + 1.36L(CLP) + 0.001L(ARF) - 2.00L(ENP) + 0.60L(CO_2) - 1.31L(FPI) -0.02L(DEC) + 0.04L(FOM) -0.03 L(AID) + 40.53)		

**, and * indicate significance at 1% and 5% level respectively

Table 6 shows that in the long run, rainfall, food price index, exchange rates, food imports and foreign aids have negative effects on food security as measured by DFD, while energy use and GDP have positive effects on DFD. However, food security as measured by CLP is found to be affected significantly and positively by rainfall and exchange rates. On the other hand, while CLP and CO_2 emissions are found to affect GDP growth positively, the DFD, energy use and food price index show larger negative effect on GDP growth. Food imports have no significant effects on either crop and livestock production or on GDP growth.

Table 7 shows the short run dynamic coefficients for the three estimated ARDL models. The estimations show that food security defined DFD is not affected by rainfall, crop and livestock production and energy use. However, their effects seem to be embodied in the negative effect of GDP on DFD, through the mostly negative effects of CLP, ARF and ENP on GDP growth (Model 3). DFD is found to be negatively affected by CO_2 emissions. Food imports have no effect of DFD and on CLP at all lags, while foreign aids have immediate negative effect on DFD, immediate positive effect on CLP, but negative effect at lag 1. On the other hand, foreign aids have negative effect on GDP at lag 0 and 1.

Table 7: ARDLs Short Run Dynamics

Variable	Model 1: DFD		Model 2: CLP		Model 3: GDP	
	Alpha	Prob.	*Alhpa*	Prob.	*Alpha*	Prob.
ΔL(DFD)	--	--	0.38	0.000***	-0.09	0.076*
ΔL(DFD)$_{t-1}$	--	--	-0.52	0.000***	-0.37	0.000***
ΔL(CLP)	--	--	--	--	-0.05	0.278
ΔL(CLP)$_{t-1}$	--	--	-0.53	0.002***	-0.45	0.000***
ΔL(CLP)$_{t-2}$		--	-0.66	0.000***	-0.28	0.000***
ΔL(ARF)	--	--	0.18	0.000***	0.04	0.000***
ΔL(ARF)$_{t-1}$	--	--	--	--	-0.03	0.004***
ΔL(ENP)	--	--	-0.97	0.000***	0.06	0.519
ΔL(ENP)$_{t-1}$	--	--	1.17	0.000***	0.61	0.000***
ΔL(CO_2)	-0.31	0.000***	-0.25	0.001***	-0.20	0.000***

$\Delta L(CO_2)_{t-1}$	-0.15	0.007***	-0.35	0.000***	-0.18	0.000***
$\Delta L(CO_2)_{t-2}$	-0.19	0.001***	0.08	0.107*	--	--
ΔL(GDP)	-0.40	0.008***	--	--	--	--
$\Delta L(GDP)_{t-1}$	-0.26	0.143	--	--	--	--
$\Delta L(GDP)_{t-2}$	-0.65	0.001***	--	--	--	--
ΔL(FPI)	-0.10	0.239	0.27	0.008***	-0.18	0.001***
$\Delta L(FPI)_{t-1}$	0.17	0.058*	0.35	0.002***	0.22	0.000***
$\Delta L(FPI)_{t-2}$	0.27	0.004***	0.38	0.002***	0.23	0.000***
ΔL(DEC)	0.07	0.005***	-0.07	0.016**	--	--
$\Delta L(DEC)_{t-1}$	0.13	0.001***	-0.21	0.000***	--	--
$\Delta L(DEC)_{t-2}$	0.06	0.078*	-0.14	0.004***	--	--
ΔL(FOM)	--	--	-0.01	0.713	-0.02	0.173
$\Delta L(FOM)_{t-1}$	--	--	--	--	-0.05	0.001***
$\Delta L(FOM)_{t-2}$	--	--	--	--	0.04	0.004***
ΔL(AID)	-0.10	0.000***	0.14	0.000***	-0.07	0.000***
$\Delta L(AID)_{t-1}$	--	--	-0.04	0.004***	-0.05	0.000***
DUM	0.02	0.370	-0.04	0.042**	0.01	0.287
ECT_{t-1}	-065	0.000***	-072	0.000***	-0.36	0.000***
R^2 = 0.78; Adj.R^2 = 0.69; SER = 0.036; SSR = 0.043; LL = 100,56; AIC = -3.565; SC = 2.980; HQ = -3.344; DW = 2.10 Diagnostic Tests χ_{Norm}: = 3.43; P(0.180) $\chi_{Auto.}$: = 0.29; P(0.596); DW = 2.03 χ_{Hetero}: = 1.06; P(0.445); DW = 2.04			R^2 = 0.92; Adj.R^2 = 0.86; SER = 0.035.; SSR = 0.033; LL = 106.35; AIC = -3.556; SC = -2.737; HQ = -3.247; DW = 2.50 Diagnostic Tests χ_{Norm}: = 2.60; P(0.272) χ_{Norm}: = 2.94; P(0.113); DW = 2.28 χ_{Norm}: = 0.71; P(0.795); DW = 2.63		R^2 = 0.94; Adj.R^2 = 0.89; SER = 0.017; SSR = 0.001; LL = 141,30; AIC = -5.012; SC = -4.194; HQ = -4.703; DW = 2.57 Diagnostic Tests χ_{Norm}: = 4.24; P(0.114) χ_{Norm}: = 2.25; P(0.153); DW = 2.35 χ_{Norm}: = 0.41; P(0.984); DW = 2.40	

***, ** and * indicate significance at 1% and 5% and 10% level respectively

Diagnostic tests results reported in Table 6 support the validity of the three estimated ARDL bounds test models.

DISCUSSIONS AND CONCLUSION

This study aimed to investigate the interactions of climate change, agricultural production, and economic factors in affecting food security in Sudan. The empirical results from the estimated three ARDL bounds test models consistently show that climate change in terms of rainfall, including periods of floods and droughts, as well as CO_2 emissions have adverse impact on food security in Sudan. The negative effects of climate change and agricultural production on food security are more evident in the long run than in the short run. This can be explained in three grounds.

First, for climate change to impact food security in Sudan, it needs longer time to materialize, which is consistent with definition of climate change as long term phenomenon.

Secondly, the short run fluctuations of food supply and food consumption are mitigated by immediate coping strategies during climate disasters. This suggests that the widely practiced informal social networks including family, relative and neighbours support seem effective in helping the affected communities in Sudan in coping with food shortages during times of extreme climate events and disasters.

Thirdly, the short run negative effects are partly mitigated indirectly by positive effects of energy use, rainfall and food prices on agricultural production and on GDP growth. Meanwhile, economic growth contributes significantly to enhance food security directly through reduction of the depth of food deficit. Yet, economic growth without equality is necessary but not sufficient for food security, confirming the FAO (2012). Furthermore, the positive effect of GDP growth on food security is associated with increasing CO_2 emissions with GDP growth.

The policy relevance from the findings of this study to Sudan's government is that ending hunger and achieving food security at the national level cannot be envisioned without addressing climate change impacts on agriculture in both the medium and long term as highlighted in the UN (2014) and Perez-Escamilla (2017). Nevertheless, climate change and extreme climate disasters are beyond the control of the government, and the government has limited abilities to provide coping mechanisms to famers and pastoralists including insurance against harvest failure during unfavorable climatic conditions, mitigation of agricultural and food production losses due to climate disasters, which are all necessary for enhancement of food security. As such, there is an urgent need for international support in terms of funding adaptation efforts by farmers, households, as well for the public finance of investment in water harvest projects and climate change defense measures.

Foreign aids and humanitarian assistances, particularly food are required to support food security in situations of climate change disasters and prolonged war and armed conflicts. Concerned humanitarian organizations need to secure sufficient fund for food transportation during times of hard climate conditions including periods of droughts and frequent floods events. These actions cannot be effectively completed without proper cooperation and coordination with central and local governments in accessing the food insecure people in remote and areas prone to conflicts. Meanwhile, the study argues for a paradigm transformation of foreign aid from humanitarian assistance during crises to planned development projects for adaptation to climate changes including water harvest projects, and for income generating activities in Sudan, particularly in rural areas.

The study adds to empirical research in the field of climate change, agriculture, food trade and aid and food security, where reliable results are derived with well-known econometric methods. Thus, its findings can be generalized to other countries of similar conditions where climate changes have evident negative impacts on agriculture and food production. The study suggests further anthropometric-economic studies focusing on investigating food security by population age groups, regions, and according to the type of settlement and household level, taking into account varying vulnerabilities to climate change and agriculture factors.

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