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The Impacts of Climate Change, Carbon Dioxide Emissions (CO_2) and Renewable Energy Consumption on Agricultural Economic Growth in South Africa: ARDL Approach

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Abstract: One of the most affected economies by climate change is the agricultural sector. Climate change measured by temperature and precipitation has an impact on agricultural output, which in turn affects the economy of the sector. It is anticipated that using renewable energy will lower carbon emissions that are directly related to climate change. The main objective of this study was to evaluate the impact of carbon dioxide emissions (CO_2), renewable energy usage, and climate change on South Africa's agricultural sector from 1972 to 2021. The nexus was estimated using an Auto Regressive-Distributed Lag (ARDL) Bounds test econometric technique. In the short run, findings indicated that climate change reduces agricultural economic growth and carbon dioxide emissions increase as agricultural economic growth increases. The use of renewable energy was insignificant in the short and long run. Carbon dioxide emissions granger causes temperature and renewable energy unilateral. An ARDL analysis was performed to evaluate the short and long-term relationship between agricultural economic growth, climate change, carbon dioxide emissions and renew able energy usage. The study adds new knowledge on the effects of climate change and carbon emissions on the agricultural economy alongside the use of renewable energy which can be used to inform economic policy on climate change and the energy nexus in the agricultural sector. Study findings point to the prioritization of biomass commercialization, rural and commercial farming sector bioenergy regulations and socioeconomic imperatives research is crucial in order to promote inclusive participation in the production of renewable energy.

Keywords: climate change; ARDL; South Africa; renewable energy consumption; carbon dioxide emission; agricultural GDP

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1. Introduction

The changing climatic conditions will result in significant food insecurity due to an unprecedented population increase and global food supply chain disturbances. Climate variables like temperature and rainfall have a substantial impact on agricultural output. Both industrialized and poor countries are currently extremely concerned about climate change. The economic impact of climate change on agriculture has been well documented. Initial work by [1,2] identified carbon dioxide emissions (CO_2) as the key determining factor for climate change. The human-caused greenhouse gas emissions (GHGs) are primarily to blame for the 0.9 °C increase in mean temperature since the eighteenth century. This is however predicted to rise to 1.5 °C by 2050, and even higher [3]. The goal is to limit global warming to well below 2 degrees and aim for 1.5 degrees. This is a target that emanated from the 21st Conference of Parties (COP21) where the Paris Agreement was enacted in 2015. The adverse consequences of climate change on various economic sectors have already been felt by many nations and every fraction of temperature increase results in loss of life or livelihood, the agricultural sector being the most hard-hit [4–8]. The major problem is that evidence has shown that improving the environment while expanding the economy cannot coexist. However, with the use of renewable energy, this is possible [9].

The agricultural sector is a strategic economic sector in developing economies, especially in Africa. However, the fight against poverty is seriously threatened by climate change shocks in developing countries where the agriculture industry plays a crucial role in enhancing living conditions and guaranteeing food security [10].

Keeping an economically healthy environment balance is necessary for Africa, especially with the estimated population growth of 1.7 and 2.5 billion people by 2030 and 2050 respectively [11]. In this context, food supply and the preservation of natural resources are major priorities. Thus, finding sustainable ways of growing the economy without deteriorating the environment is critical. The immense future food demand will exert pressure on natural resources, more especially energy resources. Growing the agricultural economy using renewable energy is therefore vital now and will become more important in the future. The use of renewable energy not only reduces carbon emissions but also improves the quality of life. In addition, the world has a better reason to transition to renewable energy due to the looming inevitable world fossil fuel reserves depletion. It has now been established that the world has finite fossil fuel resources and in less than 70 years, oil and gas would be depleted. In a 2009 study [12] it was estimated the remaining world reserves of oil, coal, and gas would deplete in 35, 107, and 37 years, respectively. However, if global fossil fuel usage remains at 2006 levels, then, the world's reserves of gas, coal, and oil could last for 40, 200, and 70 years, respectively. This estimation is crucial and reminds the world that when oil and gas are depleted, alternative energy should be in place, especially for Africa. The 2006 levels cannot be assured given the projected population growth and energy demands, which means that, if sufficient action is not taken, the rate of depletion could be accelerated even further.

About more than 70% of South Africa's economy heavily depends on coal. The effects of climate change on South Africa's overall economic growth [13] have been primarily negative. Future climate change in South Africa is expected to continue to significantly impede job development, economic growth, and inequality reduction measures [14]. Of recent, various investments pledges from COP26 were made geared towards renewable energy transition, about $8.5 billion green energy plan pledge was made during the COP26 climate meeting in Glasgow in 2021 by the US, UK, France, and Germany to help South Africa transition away from coal. However, the overall price tag for renewable energy transition for South Africa is estimated at $250 billion spanning over the next three decades [15]. A clear indication of how difficult it will be for developing countries to transition without climate finance. This explains why the current renewable energy supply and consumption are still low in South Africa as the sector still lacks investments. Although the agricultural sector has a huge potential to participate in the renewable energy transition through bioenergy production in Africa, a lack of public investment hampers this opportunity [16]. Additionally, Africa's emissions stand to be significantly higher if carbon intensity increases going against global climate goals. An indication that Africa's renewable energy must be developed, and this requires climate finance commitments from the developed economies [17].

The role of South Africa in environmental degradation in the continent has been well documented and as it stands, South Africa is the top carbon dioxide emitter in the continent and emits almost half of the emissions [18]. Of the economic subsectors, the agricultural sector is one of the most vulnerable to climate change. The World Bank predicts that the production of high-value export agricultural products, cereal crops and intensive livestock production will be negatively impacted by climate change in South Africa [19]. However, on contrary, important tropical crop productivity like sugarcane is projected to rise as a result of climate change trends, albeit these benefits may be countered by an increase in the diversity and distribution of pests. These future projections have economic implications, especially in investments for South Africa. Thus, climate change resilience is important for economic growth as it will be mostly used in future as a barometer for investments. With a score of 47.4 and a ranking of 96th place out of 182 nations in the 2022 ND-GAIN Index, South Africa is acknowledged as being vulnerable to the effects of

climate change. A country's score decreases with its level of vulnerability while increasing with its capacity to strengthen its resilience. The ND-GAIN Index is a climate change vulnerability and resilience tool that takes into account a country's political, geographic, and social factors and its capacity to deal with climate change. It is a tool used by businesses and the public sector to better prioritize investments [20]. The score indicates a dire need for the country to intensify climate change reduction initiatives. South Africa's climate change woes are real as they have been recently felt across the country for the past 2 years through flooding and are expected to intensify in the near future. As the biggest carbon emitter in the continent, reducing emissions is important and also a challenge. The paper evaluates the connection between climate change, carbon emissions and renewable energy consumption on agricultural economic growth. Prior studies have modelled the relationship between economic growth, fossil energy consumption and carbon emissions. And some estimated climate change and cereal production. This study introduces new insights by modelling climate change (using precipitation and temperature), renewable energy usage and carbon emission and agricultural value added as a share of GDP, a proxy for agricultural economic growth.

2. Theoretical Framework

The paper first examines the growth and environment nexus focusing on pollution level (CO_2) and climate variability measured by rainfall and temperature. The nexus will be examined under the Environmental Kuznets Curve (EKC) framework which provides four possible testable hypotheses, thus, feedback, conservation, growth, and neutrality hypothesis [21]. Thus, the relationship between economic growth and the environment can take any of the four hypothesis outcomes. The EKC framework stems from Grossman and Krueger's work [22] which posits that as the economy grows the level of pollution will grow in the short run while in the long-run the levels are expected to reduce. The reduction is based on the notion that as economies grow, more resources are available for disposal and therefore can be re-directed to improving the environment. The framework can therefore explain the impact of pollution and climate variability on the agricultural economy. Secondly, the paper examines the growth-renewable energy consumption nexus. The study hypothesizes that climate change will decrease agricultural economic performance. This is premised on the fact that generally increased rainfall and temperatures which are usually excessive have a negative impact on agricultural productivity and this is usually through floods and drought spells. This relationship can be examined under the treadmill theory which looks at various macroeconomic variables such as natural resource consumption, technology, finance, innovation, and human capital impact on growth [23]. The focus here will be on the use of natural resources. According to the International Energy Agency (IEA), global energy consumption rose by roughly double the average annual pace since 2010 [24]). An indication that as the population grows energy consumption will increase putting more pressure on natural resources. The energy growth environment nexus hypothesizes that as the economy grows energy consumption increases automatically increasing pollution levels which will reach a peak after which the emissions will reduce [25,26]), this will be as a result of better environmental quality policy implementations and societal pressure on the government for quality of life. Currently, there is no consensus in the literature on the impact of renewable energy consumption on the economy as some findings have shown positive, negative and neutral impacts on the economy. As such the study hypothesizes that renewable energy consumption will have a positive [27] and negative impact [28].

3. Literature Review

3.1. Agricultural Economic Growth and Environmental Degradation

Various studies have shown that there is a linear relationship between economic growth and CO_2. The same relationship is expected from the agricultural economy sub-sector in South Africa. Balsalobre-Lorente et al. [29] found that agriculture has a negative impact on the environment in BRICS countries between 1990 to 2017 using the bootstrap

Dumitrescu and Hurlin panel causality test. The study recommended the adoption of cleaner energy processes to attract foreign clean energy investments. During the 1971–2016 period Pata also observed A bidirectional causal relationship between agriculture and environmental degradation in BRICS countries [30]. Similar findings also indicated that the agricultural sector increases Indonesia's GHGs from 1970 to 2015 period [31], a signal that confirms the energy growth hypothesis. The study recommended an increase in the use of renewable energy. A study found new insights in Kazakhstan as agricultural productivity improved environmental quality from 1996 to 2020 using the Dynamic Ordinary Least Squares (DOLS) analysis approach [32]. These contrary findings also confirm that the link between agricultural economic activity and emissions varies by region. Using the common correlated effects mean group estimator (CCEMG) technique, it was discovered that during the 1991–2019 period in Bangladesh and Turkey, agricultural activities reduced environmental degradation while in contrast, agricultural activities increased carbon emissions in Mexico [33]. In Azerbaijan, an increase in agricultural GDP reduced CO_2 during the 1992–2014 period using the ARDL bounds test method [34]. Using cointegration methods an inverse relationship was observed between agricultural productivity and CO_2 in Bangladesh from 1972 to 2018 [35]. A study also assessed the validity of the agricultural-induced environmental Kuznets curve (EKC) on the top ten agricultural countries for the period 1997–2016 using an augmented mean group (AMG) estimator and found that agriculture reduces CO_2 emissions in most countries [36]. Using Gregory–Hansen cointegration test modelling for Turkey between 1970 and 2017, agricultural economic activities were found to positively affect CO_2 emissions [37]. An inverse relationship between carbon dioxide emissions and agricultural productivity using the social accounting matrix (SAM) in Ethiopia was also observed [38]. In the middle east region, from the Kingdom of Saudi Arabia, an estimation by Emam found that agriculture affected the environment negatively from 1990 to 2019 period using ARDL bounds methods [39]. Data from 47 developing countries during the 1976–2017 period using dynamic panel data estimators also showed that agricultural production reduced environmental quality [40]. The research findings suggest that the relationship between agricultural economic growth and environmental quality is subject to context as it can either be positive or negative. However, evidence suggests that poor nations in low-latitude regions will pay a high price for climate change's negative effects on economic growth [41].

3.2. Agricultural Economic Growth and Renewable Energy Consumption

Energy has become a major input in the agricultural economy. In light of the catastrophic damage that fossil fuel consumption has caused in the world over the years, the use of renewable energy has been hailed as environmentally friendly with documented various spin-off benefits. Various studies have shown both a linear and non-linear relationship between renewable energy consumption and agricultural economic growth. Tan et al. modelled 35 European countries and found that renewable energy use had positive and significant impacts on agricultural productivity [42]. From 1980 to 2011, the usage of renewable energy led to increased agricultural output in five nations in North Africa (Algeria, Egypt, Morocco, Sudan, and Tunisia), the study also suggested using renewable energy to boost agricultural production to lessen global warming [43]. In Tunisia, using data spanning from 1980 to 2011, a long-term bidirectional causality between agricultural GDP and renewable energy was noted. It was suggested that subsidies for the use of renewable energy be provided to the agricultural industry to increase its ability to compete in the global market [44]. In 35 sub-Saharan African countries from 1995 to 2017, a two-way causal relationship between renewable energy consumption and agricultural output using the FMOLS, DOLS, Panel Pedroni and Kao, Westerlund bootstrap cointegration and CIPS unit root test techniques was discovered [45]. A positive relationship was found in ASEAN countries between renewable energy consumption and the agricultural economic sector [46] In Indonesia, renewable energy consumption was also found to be positively correlated with agricultural economic growth based on data from 1986 to 2020 [46]. In contrast, us-

ing panel fixed effect regression and a two-step system Generalized Method of Moments (GMM) estimator, a negative relationship between renewable energy consumption and agriculture GDP in South Asian Association for Regional Cooperation (SAARC) countries from 2000 to 2017 was discovered [47]. The nexus between renewable energy consumption and agricultural GDP is also diverse and contextual.

3.3. Agricultural Economic Growth and Climate Change

Climate change effects on agriculture have been largely negative and well-documented in various studies. Climate change was found to reduce agricultural output in South Africa using the ARDL approach with 1960 to 2017 data [48]. In Turkey, an increase in precipitation was found to affect agricultural GDP positively, while the increase in temperature had a negative effect on agricultural GDP during the 1961–2013 period using the ARDL approach [49]. According to the findings of the ARDL approach, from 1975 to 2015 in Nigeria, climate change had little impact on agricultural productivity [50]. In India, Bangladesh, Pakistan, Nepal, Bhutan, and Sri Lanka climate change had a substantial impact on the agriculture industry between 1990 and 2014 period using the ARDL approach [51]. In Iran, using the ARDL technique within the SAM model framework data from 1991 to 2014, adverse climate change conditions had a negative impact on agricultural growth [52]. Based on data from 1961 to 2019 using ARDL and panel estimators, rising temperatures were observed to have a negative long-term relationship with the agricultural growth in 32 Sub-Saharan African nations [53]. Egypt's agricultural sector was also negatively impacted by climate change between 1990 and 2020. ARDL findings also indicated a decline in the agricultural GDP as a result of rising temperatures [54]. There was no evidence of a negative impact of climate change on agriculture in a study which involved eight South Asian countries between 1960 and 2016 using the ARDL analysis approach [55]. In a study utilizing data from 1992/1993 to 2017/18 in Ethiopia, it was discovered that climate change had a long-term negative impact on agricultural GDP [56]. A 1990–2020 analysis employing nonlinear autoregressive distributed lag (NARDL) also found that increases in rainfall and temperature have a detrimental effect on crop output in the long run [57]. Although in some instances, climate change benefits the sector through changes in patterns of some pests in the crop production system there is enough evidence that climate change negatively impacts agricultural growth. This finding was found in similar studies which observed a decrease in agricultural exports in other countries and while in other countries there was an increase in imports as a result of climate change [58]. This shows the instability that comes with climate change, clearly indicating how important it will be for countries to be food secure in future. Food security now strongly anchors on global competitiveness; however, climate change has redefined agricultural competitiveness, for food security to be ensured in the future competitiveness should also account for climate change effects [59].The major concern in agriculture is the systematic food insecurity that can be created as a result of climate change. This is because climate change shocks in agriculture do not only affect producers but also disrupt the supply chain [60]. This is because the agricultural sector is too sensitive to climate change such that even an increase of 1 to 2 degrees Celsius makes a huge difference in crop production and can have devastating effects, especially in the tropics [61]. Coupled with institutional constraints and lack of technology, the adverse effects are expected to cause poverty and low crop productivity [62]. Systematic food insecurity arises when there is high price volatility emanating from interconnected global supply chain disruptions [63]. Disruptions can occur at any stage along the supply chain, thus at production, storage, processing, distribution, retail and markets, and also at the consumption stage [64]. Although global open markets create resilience for countries it also creates huge vulnerabilities if countries are over-dependent on others. Climate change causes crop failure reducing the supply quantities in the markets which causes price volatility, when these climate change shocks hit, crop yield reduces and farmers intensify production in the next cycles, however, the costs are paid by the consumers creating a negative trend in agricultural welfare [65]. In the South African context, where prime land

is in the hands of the few, continuous negative welfare will weaken social cohesion. In the context of climate change, it will be important for the agricultural sector to pay attention not only to economic competitiveness but also to green competitiveness as this has a bearing on the sustainability and economic growth of the sector [66].

3.4. Data Period

According to the recent UN Climate Change report, over the past 50 years, agricultural output has been reduced by global warming. This has food insecurity implications especially in developing economies [67]. Climate change has a direct impact on the agricultural economy. Based on the UN observations there is a need to evaluate how climate change has affected the South African agricultural economy over the said period. Climate variability has made farming challenging as the weather has become unpredictable. The El Niño-Southern Oscillation (ENSO) natural cycle in the Pacific Ocean has been affecting agriculture in different ways. ENSO has three phases, thus, El Niño, neutral and La Niña state [68]. In South Africa, the El Niño cycle is characterised by cooler weather, heat weaves, less rains and drought detrimental to the agricultural sector while during La Niña, warmer weather and more rains are expected and usually favourable for the agricultural sector. The neutral ENSO is desirable for agriculture as it resembles normal patterns and is predictable. But due to global warming, the world is experiencing El Niño and La Niña cycles the more. Although La Niña would benefit the agricultural sector, the nature of the cycle brings excessive rains negatively affecting productivity due to excessive rains which sometimes create floods. On the other hand, La Niña causes animal loss and distress due to heat waves, uncontrollable pests' infestations, and water stress in crop production amongst others. Since the 1970s severe summer droughts in South Africa have been observed to occur under El Niño conditions and the trend is strengthening [69]. South Africa has been experiencing a decrease in rainfall since the late-1970s in the northern eastern parts [70] while in the coastal areas, a 50% intensity increase in rainfall was observed for the last 30-year period except for 1984 due to cyclone Demoina that occurred in that January [71]. The climate change that has taken place for the last 50 years is of interest in this study and due to the availability of data the study estimates the linkages between climate change, the agricultural economy and renewable energy. Based on the records, South Africa has experienced various episodes of ENSO over the past 50 years. South Africa has experienced notably low agricultural output by 50% below average during the El Niño years in the past (1972/73, 1982/83, 1991/92 and 1994/95) in the maize production. And some of the observed La Niña years were 1971/72; 1973/74; 1981/82; 1988/89; 2000/01; 2007/08 and 2008/09 [72]. However, the most severe drought event was identified in 1973 followed by 1995 [73]. The variations are more frequent as a result of climate change. Various studies have shown that the adverse effects of climate change can be mitigated by the use of renewable energy amongst others. Renewable energy was not seriously considered as a possible source of energy before the 1970s [74]), during the 1961–1972 period there were no energy crises, and from 1973–1982 (the energy crises phase) the need for alternative energy source was of importance, during 1983–1997 (low energy prices phase) the world started conversations about the ozone layer depletion and sustainable development concept gained a centre stage, and from 1998 (post-Kyoto protocol) climate change adverse effects were more notable and renewable energy was proving to be a necessary alternative [75]. In South Africa, the current phase can be categorised as the energy crisis. The data period under examination stems from 1972 to 2021 and encompasses different eras of climate change and clean energy developments. The level of pollution was also low primarily due to demand factors such as population size, and natural resource demand for developmental activities amongst others. Over the years a lot of progress has been made globally in terms of discussions around the negative impacts of climate change on the environment. These efforts have also impacted the way countries view climate change. Table 1 below shows some of the notable global efforts that have influenced climate change actions globally.

Table 1. Some of the climate change global commitments.

Year	Host	Commitment	Source
1945	San Francisco	United Nations (UN)-focus on peace, security, human rights, and development-2nd world war aftermath.	[76]
1972	Stockholm	United Nations Conference on the Human Environment (UNCHE)-global efforts on climate change action began	[77]
1982	Nairobi	UN Environment Programme (UNEP)-Stockholm follow up	[78]
1985	Vienna	Convention for the Protection of the Ozone Layer	[79]
1989	Montreal	The Montreal Protocol-fund establishment for agricultural and manufactured goods substances depleting the ozone in developing country.	[79]
1992	Rio de Janeiro	United Nations Conference on Environment and Development (UNCED)/Earth Summit-Sustainable development concept brought in, and Agenda 21 action plan created.	[80]
1994	Rio de Janeiro	United Nations Climate Change Framework Convention (UNFCCC)-focused on mitigation of carbon emissions. The decision-making body of UNFCCC is the Conference of Parties (COP).	[67]
1995	Berlin	The first conference of Parties (COP1) was held	[67]
1997	New York	United Nations General Assembly Special Session (UNGASS) on Sustainable Development/Earth Summit II-Agenda 21 5-year review progress.	[81]
1997	Kyoto	Kyoto Protocol	[82]
2002	Johannesburg	United Nations World Summit on Sustainable Development (WSSD)-feedback on Rio de Janeiro convention progress/Political Declaration-corporate accountability and responsibility introduced.	[83]
2015	Paris	2015 Paris Agreement was negotiated at COP21 in Paris: works on 5-year cycle based long-term low greenhouse gas emission development strategies (LT-LEDS) which talks to the nationally determined contributions (NDCs) outlining CO2 emissions targets. starting in 2024 country reporting on progress will be done under an enhanced transparency framework (ETF).	[67]

4. Methods

The study's data period used was from 1972 to 2021 for all variables. The annual agricultural GDP in 2015 constant USD (AGR_GDP) was obtained from the World Bank Development Indicators (WDI). The annual carbon dioxide emissions (CO_2) in million tonnes (Mt) and the consumption of renewable energy (RENC) (which includes hydro-electricity, nuclear, solar, wind, geothermal, biomass, and other sources) in terawatt-hours (TWh) were sourced from BP statistics. Climate change variables represented by annual mean temperature (TEMP) and annual precipitation (PREC) were sourced from World Bank Climate Change Knowledge Portal (CCKP). To solve for multicollinearity problem all the variables were turned into natural logarithms. In addition, the natural logarithm forms allow the variables to be interpreted as elasticities. The analysis of cointegration using the combination of I(0) and I(1) variables, thus variables that are stationary at a level and those that become stationary only after first differencing have attracted more attention in recent years. The method of cointegration is preferred as it partitions the model into the short run and long run [84]. The model enables assessments of both the immediate and long-term effects implications. The ARDL methodology is also appropriate for small-sample data estimation. The weakness of the model is that it only considers one level of linkages between the variables and also assumes linearity between the dependent and independent variables. The technique is not suitable for bigger sample sizes [85–89]. Figure 1 summarizes the

analytical steps employed in the study. The first step was to identify relevant variables that would explain the agricultural economic growth and the impact that climate change and clean energy have had. This was followed by identifying a suitable range of data that would best explain climate change effects on the agricultural economy (1972–2021). This data was chosen based on the fact that green energy was starting to receive attention within this range. The choice of variables was also informed by other authors as shown in Table 2. Descriptive statistics were analyzed after which the unit root test was performed using the 1st generation unit root tests (ADF and PP). Exogenously, the structural break was not observed using the CUSUM plot test in the data and therefore the 2nd generation unit root tests were not used. A bounds test was then performed to check for cointegration after which the ARDL model was estimated with a long and short-run estimation. The model's robustness was then checked using FMOLS, DOLS and CCR models. Stability tests were performed to check for autocorrelation and heteroskedasticity. Lastly, a granger causality test was performed to determine the direction of causality within the series.

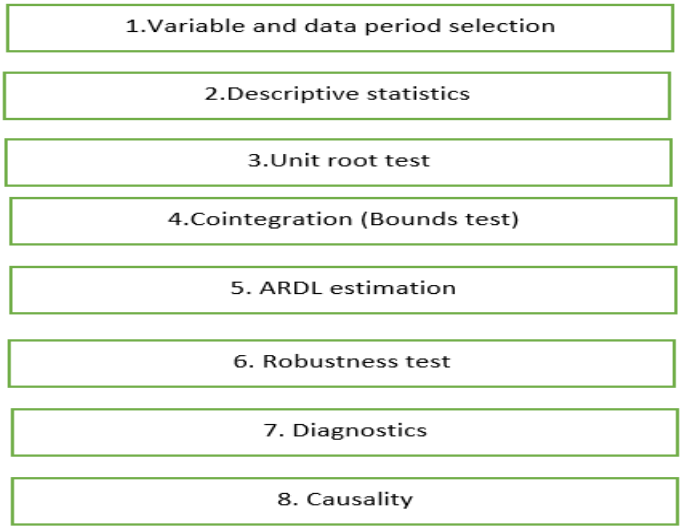

Figure 1. Study analytical techniques steps.

Table 2. Climate change variables and methodology studies.

Authors	Country	Period	Variables	Outcomes	Technique
[88]	Somalia	1985–2016	• Temperature • Rainfall • CO_2 • Agric labour • Land-Cereal production • Crop production index (DV)	• Short-run = rainfall ↓ production • Long-run = rainfall ↑ production • Short-run & Long-run = temperature ↓ production • CO_2-no impact	• ARDL • DOLS • Granger causality
[86]	Bangladesh	1961–2019	• Temperature • Rainfall • CO_2 • Sea surface temperature (SST) • Sunshine • Wind speed • Marine fish production (DV)	• Short-run & Long-run = SST, rainfall, sunshine ↑ production • Short-run & Long-run = temperature ↓ production • Short-run = CO_2 = ↓ production	• ARDL • FMOLS

Table 2. *Cont.*

Authors	Country	Period	Variables	Outcomes	Technique
[87]	Nigeria	1971–2018	• Temperature • Rainfall • Ecological footprint • Carbon footprint • Rice production (DV)	• Long run = rainfall ↓ production • Long-run = footprint ↑ production • Long-run = carbon footprint ↓ production • Short-run & Long-run = fertilizer ↑ production	• ARDL
[88]	Ethiopia	1990–2020	• Temperature • Precipitation • CO_2 • Arable land • Fertilizer • Labour force • Cereal production (DV)	• Short-run & Long-run = precipitation ↑ production • Short-run & Long-run = temperature ↓ production • Short-run = labour ↑ production • Long-run = CO_2, fertilizer, arable land ↑ production	• ARDL
[54]	Egypt	1990–2020	• Temperature • Rainfall • CO_2 • Cultivated area • Agric. investment • Agric. GDP (DV)	• Long-run = precipitation, temperature ↓ Agric. GDP	• ARDL
[89]	Pakistan	1979–2018	• Temperature • Rainfall • Sown area • Irrigated area • Rice production (DV)	• Long run = precipitation ↑ production • Short-run & Long-run = temperature ↓ production • Long-run = central region rainfall ↓ production • Long-run = Southern & western region rainfall ↑ production	• ARDL & NARDL
[90]	Gambia	1971–2020	• Rainfall • Agric. Value $ • GDP per capita • GDP current • Population • Food production • Rice production (DV)	• production↑ Agric. Value • ↑rainfall ↓ production • Short-run = population ↓ production	• ARDL • Granger causality
[3]	Vietnam	1990–2020	• Temperature • Rainfall • CO_2 • Fertilizer consumption • Energy consumption • Land-under cereal • Agric. Value (DV)	• Short run = energy consumption ↑Agric value • Short-run & Long-run = fertilizer ↑Agric value • ↑rainfall ↓ production • Short-run = population ↓ production	• ARDL
[91]	China	1978–2018	• Temperature • Rainfall • Agriculture credit • Agriculture labour • Farming size • Mechanical farming rate • Cereal production • (DV)	• Temperature = ↓ production • rainfall ↑ production • Long-run = credit ↑ production • Mechanical farming rate ↑ production	• ARDL

Table 2. *Cont.*

Authors	Country	Period	Variables	Outcomes	Technique
[92]	Somalia	1980–2018	• Temperature • Rainfall • Rural population • Maize under cultivation • Political instability • Maize production (DV)	• Long run = temperature, rainfall, political instability ↓ production • Short run = rainfall ↑ production	• ARDL • DOLS

In Equation (1), the multivariate sample model is shown. Table 3 shows the description of the variables used in the study and Table 4 lists the descriptive statistics for the variables used in estimation.

Table 3. Variables description.

Variable	Description	Data Source
LAGR_GDP	Agriculture value added, a share of GDP (2015 constant US$)	WDI
LCO2	CO_2 Emissions from Energy (Mt)	BP
LRENC	Renewable energy consumption (TWh)	BP
LTEMP	Mean annual temperature (°C)	CCKP
LPREC	Annual precipitation (mm)	CCKP

Table 4. Descriptive Statistics.

	LNAGR_GDP	LNCO2	LNPREC	LNTEMP	LNRENC
Mean	22.383	5.796	6.161	2.890	3.151
Median	22.373	5.879	6.149	2.894	3.643
Maximum	23.037	6.165	6.531	2.959	4.788
Minimum	21.793	4.982	5.765	2.828	0.565
Std. Dev.	0.303	0.350	0.160	0.028	1.171
Skewness	0.199	−0.889	0.184	−0.012	−0.815
Kurtosis	2.336	2.655	2.867	2.765	2.456
Jarque-Bera	1.248	6.837	0.319	0.117	6.150
Probability	0.536	0.033	0.853	0.943	0.046
Sum	1119.129	289.818	308.048	144.505	157.539
Sum Sq. Dev.	4.510	6.003	1.247	0.039	67.229

The general estimation of the relationship is expressed as follows:

$$Y_t = \alpha_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon_t \quad (1)$$

The relationship in a fitted form can be expressed as follows:

$$LnAgr_GDP_t = f(LnCO2_t,\ LnRENC_t,\ LnTEMP_t, LnPREC_t) \quad (2)$$

where *lnAgr_GDP* denotes the log of the gross domestic product of agriculture, *lnRENC* denotes the log of consumption of renewable energy, *lnCO2* denotes the log of carbon emissions, *lnTEMP* and *lnPREC* denote the log of annual mean temperature and the log of annual precipitation.

The equation can be further fitted as follows:

$$LnAgr_GDP_t = \alpha_0 + \beta_1 LnCO2_t + \beta_2 LnRENC_t + \beta_3\ LnTEMP_t + \beta_4 LnPREC_t \quad (3)$$

The ARDL model is specified in Equation (4) where φ_1 and ϑ_1 capture long and short-run elasticities coefficients, while ε_t is a white noise disturbance term, p and q stand for the lag lengths of the regressand and regressors, respectively.

$$\Delta LnAgr_GDP_t = \alpha_0 + \varphi_1(LnCO2)_{t-1} + \varphi_2(LnRENC)_{t-1} + \varphi_3(LnTEMP)_{t-1} + \varphi_4(LnPREC)_{t-1} + \sum_{i=1}^{p} \vartheta_1\Delta(LnAgr_GDP)_{t-1} + \sum_{i=1}^{q} \vartheta_2\Delta(LnCO2)_{t-1} + \sum_{i=1}^{q} \vartheta_3\Delta(LnRENC)_{t-1} + \sum_{i=1}^{q} \vartheta_4\Delta(LnTEMP)_{t-1} + \sum_{i=1}^{q} \vartheta_5\Delta(LnPREC)_{t-1} + \varepsilon_t \quad (4)$$

The first component of the equation represents the long run and is specified as follows:

$$\Delta LnAgr_GDP_t = \alpha_0 + \varphi_1(LnCO2)_{t-1} + \varphi_2(LnRENC)_{t-1} + \varphi_3(LnTEMP)_{t-1} + \varphi_4(LnPREC)_{t-1} + \varepsilon_t \quad (5)$$

The series in the model are tested for long- and short-run causality using the Error Correction Model (ECM). At least one direction of the series' causation is established by the ECM component.

The equation below is specified as follows:

$$\Delta LnAgr_GDP_t = \alpha_0 + \sum_{i=1}^{p} \vartheta_1\Delta(LnAgr_GDP)_{t-1} + \sum_{i=1}^{q} \vartheta_2\Delta(LnCO2)_{t-1} + \sum_{i=1}^{q} \vartheta_3\Delta(LnRENC)_{t-1} + \sum_{i=1}^{q} \vartheta_4\Delta(LnTEMP)_{t-1} + \sum_{i=1}^{q} \vartheta_5\Delta(LnPREC)_{t-1} + \varepsilon_t \quad (6)$$

$$\Delta LnAgr_GDP_t = \alpha_0 + \varphi_1(LnCO2)_{t-1} + \varphi_2(LnRENC)_{t-1} + \varphi_3(LnTEMP)_{t-1} + \varphi_4(LnPREC)_{t-1} + \sum_{i=1}^{p} \vartheta_1\Delta(LnAgr_GDP)_{t-1} + \sum_{i=1}^{q} \vartheta_2\Delta(LnCO2)_{t-1} + \sum_{i=1}^{q} \vartheta_3\Delta(LnRENC)_{t-1} + \sum_{i=1}^{q} \vartheta_4\Delta(LnTEMP)_{t-1} + \sum_{i=1}^{q} \vartheta_5\Delta(LnPREC)_{t-1} + \omega ECM_{t-1} + \varepsilon_t \quad (7)$$

ECM is the speed of adjustment measuring long-run disequilibrium correction. The component displays the rate of convergence to equilibrium in the presence of shocks. With a number less than or equal to 1, it is anticipated that the ECM will be negative. The presence of cointegration in the model confirms a long-term relationship.

5. Results

5.1. Descriptive Statistics

Table 4 displays the descriptive statistics for each variable in the study. The mean value of the dependent variable *LNAGR_GDP* is 22.4 and the standard deviation is 0.30. The mean values of explanatory variables, *LNCO2, LNRENC, LNTEMP* and *LNPREC*, were 5.79, 6.16, 2.89 and 3.15 respectively, and the standard deviations were 0.35, 0.16, 0.03 and 1.17 respectively. All variables' kurtosis values were less than 3. Figure 2 shows the historical trend of the variables.

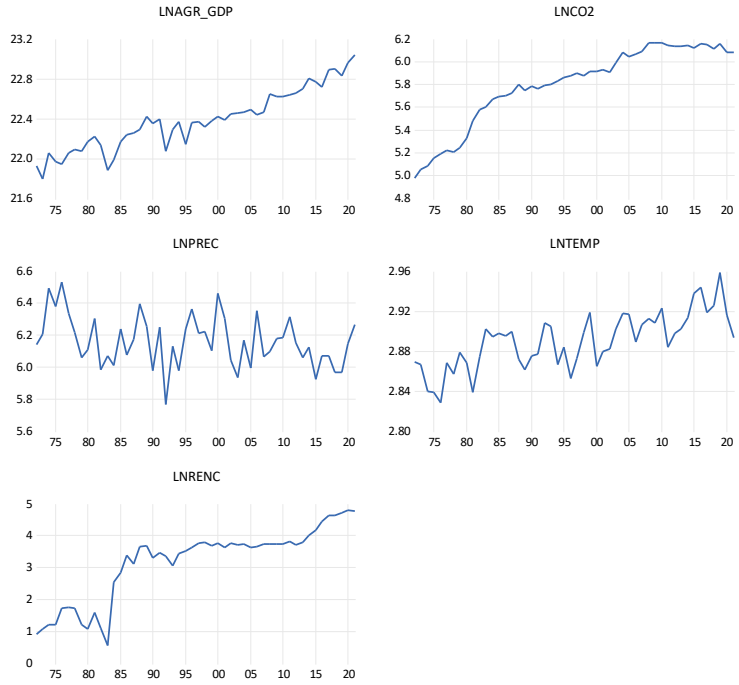

Figure 2. Historical trend of each variable.

5.2. Coefficient Correlation

Table 5's findings revealed a stronger correlation between agricultural GDP and carbon emissions (0.85), and renewable energy consumption (0.86). A moderate correlation (0.64) was observed between annual temperature and agricultural GDP. There was a negative weak correlation between annual precipitation and agricultural GDP, carbon dioxide emissions, annual temperature and renewable energy consumption.

Table 5. Correlation Matrix.

	LNAGR_GDP	LNCO2	LNPREC	LNTEMP	LNRENC
LNAGR_GDP	1.000	0.848	−0.228	0.637	0.860
LNCO2	0.848	1.000	−0.328	0.726	0.900
LNPREC	−0.228	−0.328	1.000	−0.634	−0.216
LNTEMP	0.637	0.726	−0.634	1.000	0.631
LNRENC	0.860	0.900	−0.216	0.631	1.000

5.3. Unit Root Test

The presence of a unit root or non-stationarity in a series results in explosiveness in the estimation which cannot provide reliable inference [93]. When the variance, covariance, and mean are constant, a series is stationary [94] It is therefore important that series must only be integrated of order (0) and order I (1) and not order I(2) or higher. According to Table 6 findings, the series were stationary at both level (0) and the first difference I(1). Therefore, the analysis can use the ARDL approach [95]. The unit root null hypothesis was rejected as none of the variables was of order I(2). Unit root analysis is carried out using the Dickey-Fuller (DF-GLS), Augmented-Dickey-Fuller (ADF), Phillips-Perron (PP), Kwiatkowski-Phillips-Schmidt-Shin (KPSS), Narayan and Popp, and second-generation unit root tests such as Zivot and Andrews' suitable for data with structural breaks [96]. The commonly used Augmented Dickey-fuller (ADF) [97] and Phillips-Perron (PP) [98] were used in the study. Results in Table 6 show that all variables in the ADF unit root tests are integrated at I(1), but in the PP tests, only the agricultural GDP is integrated at I(0) and the other variables are integrated at I(1).

Table 6. Unit root test analysis.

Series	Model	ADF	ADF-P	PP	PP-P
At Level-I(0)		τ_μ τ_τ τ	**Value**	τ_μ τ_τ τ	**Value**
LNAGR_GDP	Intercept (t_m)	1.680	0.999	−0.552	0.872
	Intercept & Trend (t_t)	−4.723	0.002	−4.760	0.002
	None (t)	2.622	0.997	2.704	0.998
LNCO2	Intercept (t_m)	−3.184	0.027	−3.674	0.008
	Intercept & Trend (t_t)	−0.967	0.939	−1.128	0.914
	None (t)	3.376	1.000	2.799	0.998
LNPREC	Intercept (t_m)	−5.356	0.000	−5.326	0.000
	Intercept & Trend (t_t)	−5.775	0.000	−5.764	0.000
	None (t)	−0.010	0.674	0.360	0.785
LNTEMP	Intercept (t_m)	−2.999	0.042	−2.894	0.053
	Intercept & Trend (t_t)	−4.833	0.002	−4.614	0.003
	None (t)	1.593	0.971	0.562	0.834
LNRENC	Intercept (t_m)	−1.550	0.500	−1.550	0.500
	Intercept & Trend (t_t)	−2.560	0.300	−2.520	0.318

Table 6. *Cont.*

Series	Model	ADF	ADF-P	PP	PP-P
At Level-I(0)		τ_μ τ_τ τ	**Value**	τ_μ τ_τ τ	**Value**
	None (t)	0.856	0.892	0.856	0.892
At 1st difference-I(1)					
d(LNAGR_GDP)	Intercept (t_m)	−8.386	0.000	−14.089	0.000
	Intercept & Trend (t_t)	−4.597	0.004	−14.185	0.000
	None (t)	−7.494	0.000	−9.172	0.000
d(LNCO2)	Intercept (t_m)	−6.063	0.000	−6.083	0.000
	Intercept & Trend (t_t)	−7.225	0.000	−7.224	0.000
	None (t)	−2.031	0.042	−5.220	0.000
d(LNPREC)	Intercept (t_m)	−11.577	0.000	−20.258	0.000
	Intercept & Trend (t_t)	−11.454	0.000	−20.281	0.000
	None (t)	−11.702	0.000	−20.706	0.000
d(LNTEMP)	Intercept (t_m)	−5.386	0.000	−20.296	0.000
	Intercept & Trend (t_t)	−5.318	0.000	−21.071	0.000
	None (t)	−5.057	0.000	−14.111	0.000
d(LNRENC)	Intercept (t_m)	−7.830	0.000	−7.830	0.000
	Intercept & Trend (t_t)	−4.049	0.014	−7.773	0.000
	None (t)	−7.541	0.000	−7.556	0.000

ADF general equation is specified as follows:

$$\Delta x_t = \delta x_{t-1} + \sum_{i=1}^{m} \varphi \Delta x_{t-1} + \varepsilon_t$$

5.4. Cointegration Test

The bounds test determines the existence of the long-run relationship between endogenous and exogenous variables. The ARDL bounds test has desirable properties when compared to Engle and Granger [99], Johansen [100] and Johansen and Juselius [101] tests which require variables integrated of the same order while the bound test can test the cointegration of variables of different orders. The series were stationary at a level I(0) and the first difference I(1) in the study. The decision rule of the cointegration is determined by the F statistic value. The tests generate a lower and upper bound critical value. If the F values are higher than the lower and upper values, the null hypothesis of no cointegration can be rejected. If the F-value lies between the lower and the upper, then cointegration is deemed inconclusive. Table 7 shows ARDL bounds test results.

Table 7. ARDL Bounds Test.

			Critical Values						
			10%		**5%**		**1%**		**Outcome**
Lag Length	**F-Statistic**	**k**	**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**	**Lower Bound**	**Upper Bound**	
ARDL(3,2,3,3,0)	4.314459	4	2.402	3.345	2.85	3.905	3.892	5.173	
									Cointegrated

The alternative hypotheses and null for the Bound test are as follows:

$$H_0 = \delta_1 = \delta_2 = \delta_3 = 0$$
$$H_1 \neq \delta_1 \neq \delta_2 \neq \delta_3 \neq 0$$

Results show a long-run relationship between series at 5% and 10% levels of significance. The ARDL model can be used to estimate a long run and an error correction model.

5.5. Lag Selection

The best lags for the ARDL model were determined with the commonly used Akaike Information Criterion (AIC). The unrestricted Vector autoregressive (VAR) model optimal lag length selection is shown in Table 8 using LogL, LR, FPE, AIC, SC and HQ criteria. AIC criteria indicated the fourth lag as the best lag for the model.

Table 8. Lag length selection.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	131.4737726	NA	0.000000	−5.49886	−5.300094	−5.424401
1	284.0767282	265.3964	0.000000	−11.04681	−9.854222 *	−10.60006 *
2	309.3340288	38.43502 *	0.000000	−11.058	−8.871582	−10.23896
3	332.2327498	29.8679	0.000000	−10.96664	−7.786395	−9.775302
4	362.9502096	33.38854	0.000000	−11.21523 *	−7.041154	−9.651594

* Indicates lag order selected by the criterion.

5.6. ARDL Error Correction and Long-Run Results

Table 9 shows the error correction model results. The lagged difference coefficients are significant and negative as expected. The renewable energy consumption variable was not significant in the short-run model. This was expected as South Africa's renewable energy consumption is still low and expensive. The error correction term of −0.239 is the speed of adjustment. This implies that with carbon emissions and climate change, the agricultural GDP will restore its long-term equilibrium position at 24% per year. With an adjustment time of around 4 years (1/0.24) the equilibrium will converge. The lagged carbon dioxide emissions were positive and statistically significant at the 1% level. The positive coefficient of carbon dioxide is expected as per the Environmental Kuznets Curve hypothesis which explains the linear relationship between economic growth and carbon dioxide emissions. The theory posits that as carbon emissions increase, economic growth will also increase. The negative coefficient of temperature and precipitations are also *a priori* expectations. As temperatures stabilise agricultural economic growth is expected to improve. The results indicate that a 1% increase in annual temperature and precipitation will decrease agricultural GDP by 0.5% and 0.6% respectively. An increase in climate change measured by temperature and rainfall decreases agricultural economic growth. This is expected as high temperatures and rainfall negatively affect agricultural productivity in the short run. Although high temperatures are associated with drought, more rainfall will be expected to moderate the impact, however, the results suggest that an increase in rainfall also has negative effects on agriculture. Another plausible reason could be when the rains eventually occur, they do so excessively and mostly during off-seasons. A common problem brought about by climate change.

Table 9. Short-run estimates.

Dependent Variable: LNAGR_GDP				
Selected Model: ARDL (3, 2, 3, 3, 0)				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
ECM	−0.239 ***	0.044	−5.483	0.000
ΔLNAGR_GDP$_{t-1}$	−0.356 ***	0.118	−3.010	0.005
ΔLNAGR_GDP$_{t-2}$	−0.419 ***	0.125	−3.365	0.002
ΔLNCO2$_t$	0.072	0.265	0.271	0.788
ΔLNCO2$_{t-1}$	0.932 ***	0.278	3.352	0.002
ΔLNPREC$_t$	0.012	0.102	0.117	0.908
ΔLNPREC$_{t-1}$	−0.602 ***	0.155	−3.883	0.000
ΔLNPREC$_{t-2}$	−0.281 **	0.106	−2.660	0.012
ΔLNTEMP$_t$	−0.494	0.845	−0.585	0.562
ΔLNTEMP$_{t-1}$	−4.110 ***	1.114	−3.689	0.001
ΔLNTEMP$_{t-2}$	−1.841 **	0.827	−2.228	0.032
R-squared	0.614	Mean dependent var		0.021
Adjusted R-squared	0.507	S.D. dependent var		0.108
S.E. of regression	0.076	Akaike info criterion		−2.112
Sum squared residuals	0.209	Schwarz criterion		−1.679
Log-likelihood	60.622	Hannan-Quinn criteria		−1.949
F-statistic	5.730	Durbin-Watson stat		2.028
Prob(F-statistic)	0.000 ***			

Denotes, ** 5% and *** 1% level of statistical significance.

In the long run, as indicated in Table 10, the increase in precipitation and temperature were positively significant at 10% and 1% levels respectively, indicating that a rise of 1% in precipitation and temperature will improve agricultural GDP by 2.6% and 21.2%. The null hypothesis of no causality within the series is rejected at the 1% level of significance as Table 11 shows that there is a bidirectional causal relationship between the agricultural GDP and temperature. Unidirectional causation was observed between renewable energy consumption and agricultural GDP, suggesting that renewable energy granger causes agricultural GDP. As expected, carbon dioxide emissions granger causes temperature. A bi-directional causation relationship was also observed between renewable energy and carbon dioxide emissions. Carbon dioxide emissions granger causes temperature and renewable energy unilaterally. An expected outcome was that climate change will cause renewable energy consumption due to its environmental and economic positive attributes, the results confirmed this a priori expectation. However, renewable energy consumption also contributes to temperature increases, suggesting that although renewable energy improves environmental quality, it is not necessarily a zero-emission energy option but an option which reduces emissions that is most suited for environmental quality improvement. This is because raw materials for other forms of renewable energy from biofuel, biodiesel and co-generation will still require fossil energy use. Amongst others, this could be through the burning of fuel during planting, harvesting, and processing. Livestock management also plays a major role in emissions in the agricultural sector.

Table 10. ARDL Long-run results.

Variable *	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
LNCO2(−1)	−0.739	0.732	−1.011	0.318
LNPREC(−1)	2.556 *	1.381	1.850	0.071
LNTEMP(−1)	21.219 ***	9.467	2.241	0.030
LNRENC	0.305	0.206	1.484	0.145

Denotes, * 10% and *** 1% level of statistical significance.

Table 11. Pairwise Granger Causality Tests.

Null Hypothesis:		F-Statistic	Prob.
LNCO2 does not Granger Cause LNAGR_GDP		0.620	0.542
LNAGR_GDP does not Granger Cause LNCO2		0.108	0.898
LNPREC does not Granger Cause LNAGR_GDP		0.555	0.578
LNAGR_GDP does not Granger Cause LNPREC		1.943	0.156
LNTEMP does not Granger Cause LNAGR_GDP	***	5.456	0.008
LNAGR_GDP does not Granger Cause LNTEMP	***	7.148	0.002
LNRENC does not Granger Cause LNAGR_GDP	*	2.495	0.094
LNAGR_GDP does not Granger Cause LNRENC		0.422	0.658
LNPREC does not Granger Cause LNCO2		2.318	0.111
LNCO2 does not Granger Cause LNPREC		1.876	0.166
LNTEMP does not Granger Cause LNCO2		0.093	0.911
LNCO2 does not Granger Cause LNTEMP	***	7.331	0.002
LNRENC does not Granger Cause LNCO2	*	2.740	0.076
LNCO2 does not Granger Cause LNRENC	***	4.439	0.018
LNTEMP does not Granger Cause LNPREC		0.174	0.841
LNPREC does not Granger Cause LNTEMP		1.010	0.373
LNRENC does not Granger Cause LNPREC		0.882	0.421
LNPREC does not Granger Cause LNRENC	***	3.684	0.033
LNRENC does not Granger Cause LNTEMP	***	4.196	0.022
LNTEMP does not Granger Cause LNRENC	***	4.755	0.014

* 10% *** 1% Denotes rejecting the null.

5.7. Diagonoistic Test

Various diagnostic tests are typically employed to evaluate the model's stability. Table 12 showed that the model's residuals were normally distributed and that serial correlation and heteroskedasticity were absent. The stability structure of the model utilizing cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) is shown in Figure 3. The centre lines display stable coefficients at a 5% level of significance.

Table 12. ARDL diagnostic test.

Diagnostic Statistics	*p*-Values	Outcome
Breusch-Godfrey LM	0.641	No serial correlation
Breusch-Pagan-Godfrey	0.606	No Heteroskedasticity
Jarque-Bera Test	0.373	Normal residuals

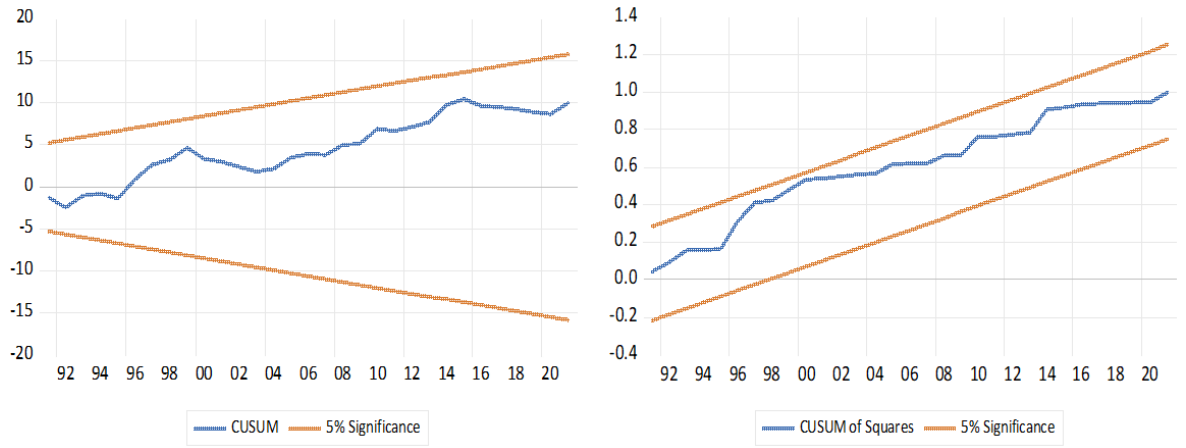

Figure 3. CUSUM and CUSUMSQ plots.

5.8. Model Robustness

Two variables were significant in the long-run model at a 10% and 1% level of significance. Annual precipitation and annual mean temperature were all statistically significant in the long run at 10% and 1% levels of significance. The variable of interest would be temperature as it was significant at a 1% level. Table 13 demonstrates that FMOLS, DOLS, and CCR models' findings confirmed that temperature was a significant variable in measuring climate change and agricultural economic growth. The temperature was significant in all three cointegration models. In conclusion, the ARDL long-run model was validated by the FMOLS, DOLS, and CCR models.

Table 13. Alternative results.

Dependent Variable: LNAGR_GDP														
FMOLS					DOLS					CCR				
Variable	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**	**Variable**	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**	**Variable**	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
LNCO2	0.213	0.253	0.841	0.405	LNCO2	−0.046	0.279	−0.165	0.870	LNCO2	0.216	0.246	0.877	0.385
LNPREC	0.317	0.278	1.141	0.260	LNPREC	0.596	0.424	1.406	0.170	LNPREC	0.494	0.387	1.275	0.209
LNTEMP	3.910	2.159	1.811	0.077	LNTEMP	9.910	3.171	3.125	0.004	LNTEMP	5.332	2.698	1.977	0.054
LNRENC	0.118	0.066	1.798	0.079	LNRENC	0.104	0.085	1.234	0.227	LNRENC	0.102	0.071	1.440	0.157
C	7.539	6.998	1.077	0.287	C	−9.993	10.346	−0.966	0.342	C	2.368	9.232	0.256	0.799
R^2	0.7				R^2	0.8				R^2	0.7			

6. Discussion

This study looked at the relationships between climate change, carbon emissions, renewable energy consumption and the agricultural economy. For the short-run, an error correction model was estimated, and a cointegration test was done to ascertain long-run cointegration. The results of the bounds test showed that the series had a long-term relationship. The results showed that climate change slowed agricultural economic growth in the short run while carbon dioxide emissions increased with an increase in agricultural economic growth. It was expected that carbon dioxide emissions would increase with an increase in agricultural economic activities. This is in line with the environmental Kuznets Curve framework which hypotheses that a linear relationship exists between economic growth and carbon dioxide emissions [102]. Similar findings were observed by various authors.

A relationship between carbon dioxide and economic growth alongside other variables during the 1971–2013 period in South Africa was observed [103]. However, an inverse relationship between economic growth and emission levels in South Africa from the 1994 to 2019 period was reported [104]. The findings suggest that the nexus can be negative or positive based on the period of interrogation. Between 1996 and 2014, 23 Sub-Saharan African nations' economies grew in tandem with their carbon emissions [105]. In another study economic growth caused carbon emissions in various 35 African countries from 1980 to 2016 period [106]. Using pooled ordinary least square a nexus between carbon emissions and economic growth was observed in 20 Sub-Saharan African countries from 2000 to 2020 [107]. Shahbaz et al. assessed this relationship for China during the 1970–2012 period under globalization using ARDL bounds, and Bayer and Hanck tests, and results showed a relationship between economic growth and CO_2 emissions [108]. A systematic review of research from 175 articles dealing with the CO_2 and economic growth nexus between 1995 and 2017 confirmed a link existence and a bidirectional causality [109].

Using the fully modified ordinary least square (FMOLS) method, economic growth was found to have a significant impact on the CO_2 emissions in Bangladesh using the 1972 to 2017 series [110]. Between 1994 and 2016, a Panel Smooth Transition Regression model for 40 nations was estimated. The findings indicated CO_2 emissions as a driver of economic growth [111]. Using DOLS, FMOLS and CCR cointegration models, a similar relationship between economic growth and carbon emissions from 1990 to 2019 in Nepal [112] was observed. A relationship between economic growth and CO_2 emission for selected South Asian economies during the 1985–2018 period using a fully modified ordinary least square

technique was found [113]. Other studies showed carbon dioxide emissions as drivers of economic growth in various countries [114–124].

The study results also showed that climate change reduced agricultural economic growth in the short run, however, in the long run, climate change has a positive impact on agricultural economic growth. A study on agricultural economic growth and climate change in Thailand from 1995 to 2019 using the ARDL bounds approach showed that temperature had a negative impact on the agricultural economy, while rainfall was positively associated with growth in the agricultural economy [125]. In a study using the ARDL approach looking at agriculture, climate change, and economic growth from 1971 to 2020 in Bangladesh, the study concluded that climate change had no impact on economic development [90]. In another climate change study, findings were consistent with the results as the study also found temperature not to have an impact on wheat production in the short run while it proved to be crucial over the long term [126]. Rainfall was found to decrease production in the short run but the temperature increased production in the long run in Malaysia from 1969 to 2018 [127].

Looking at other studies on climate change and agriculture, findings show that climate change in Pakistan did not show a negative impact on wheat output between 1960 and 2009 [128]. Using the ARDL econometric modelling approach similar results on rice production in Pakistan from 1968 to 2014 period were observed [129]. Annual temperature and other climatic conditions had a negative impact on production in Pakistan from 1970 to 2018 period [130]. Climate change was found to have a negative impact on crop production in India from 1993 to 2019 period [131]. Climate change variables were found to have an impact on cotton productivity in Pakistan during the 1981–2015 period [132]. A study spanning from 1980 to 2019 found that a rise in temperature decreases income per capita growth in fragile states in Sub-Saharan Africa [133].

Although other studies had found a positive relationship between climate change and renewable energy consumption [134], the study results showed an insignificant relationship between renewable energy consumption and climate change in the short and the long run. In a climate change, renewable energy and economic growth nexus in Turkey between 1980 and 2019 period using ARDL and Toda-Yamamoto causality tests, revealed that the use of renewable energy use lowered temperature [135]. Carbon dioxide emissions were also not significant in the long run. A study in four ASEAN countries from 1990 to 2016 revealed that renewable energy use moderates the effect of carbon emission on agricultural production [10].

7. Conclusions and Policy Recommendations

An ARDL analysis was performed to evaluate the short and long-term relationship between agricultural economic growth, climate change, carbon dioxide emissions and renewable energy usage. The detrimental consequences of climate change on the agricultural economy are widely documented. The most vulnerable people in South Africa receive their livelihoods from the country's key agricultural sector. Following global advocacy for transition into renewable energy, it is imperative to assess the nexus between climate change, carbon emissions, renewable energy, and the agricultural economy. Already in the literature, there is compelling evidence that the detrimental effects of climate change have a negative impact on economic growth. The most hard-hit sub-sector is the agricultural economy due to its dependence on temperature and rainfall conditions. The use of renewable energy is expected to not only improve economic growth but also reduce carbon emissions and consequently climate change. However, the effect of renewable energy use on economic growth has been both positive and negative in various countries. The negative impacts are accounted for by the lack of investments, high costs and low uptake, especially in Africa.

This study used an error correction model to analyse the short-run relationship between the agricultural economy, climate change, renewable energy consumption and carbon dioxide emissions. A priori, the agricultural economy was expected to increase as carbon

dioxide emissions increased as hypothesised by the Environmental Kuznets Curve. The estimation results were consistent with this expectation as agricultural economic growth increased with carbon emissions in the first lagged period in the short run. However, the relationship becomes insignificant in the long run. Renewable energy consumption was expected to reduce agricultural economic growth due to its infancy stage which has a lot of inefficiencies. However, the results revealed that renewable energy use was insignificant in both the short and long run. Considering the current low scale of renewable energy consumption in South Africa, the findings are expected. Climate change was expected to reduce agricultural economic growth. As extreme temperatures and rainfall are known to negatively affects agricultural productivity. As per expectations, climate change measured by annual precipitation and the annual mean temperature had an inverse relationship with the agricultural economy in the short run, indicating that as climate change increases, the agricultural sector's economic growth is reduced. However, in the long run, climate change showed a positive impact on the agricultural economy. A finding that has also been observed in other studies. A plausible reason could be, as population size increases globally, food security becomes a priority and as such as climate change increases, more pressure is put on food production. As a result, more biotechnology, mechanization and resources will be invested in the agricultural sector to ensure food security ultimately increasing the overall agricultural economy activities.

This study contributes to knowledge production of renewable energy and climate change impact discourse in the agricultural economy. A key sector in South Africa earmarked to generate a million jobs as per the National Development Plan 2030 (NDP) to curb the high levels of inequality and poverty. The are plans to transition to renewable energy generally in the country, however, the operational plans in the agricultural sector are yet to be discussed. The paper's contribution gives some insights into the future priorities for policymakers in the clean energy and agriculture nexus to ensure inclusive green development. Most notably, the study indicates that climate change is negatively affecting the agricultural sector in the short run, this has food security, income, and trade implications for the country. The long-term benefits will however need a coordinated effort from policymakers.

South Africa is a country with a long history of unjust wealth allocation due to the historical apartheid regime. In fact, currently, the country is the most unequal in the world according to the World Bank poverty vulnerability report. Many argue that in addition to mal administration depleting public resources, the unjust allocation of resources from the past is the core of the problems. The country is also the most polluting within the continent and is automatically expected to be wearing bigger shoes in terms of remedial action initiatives. At the local level, the country is currently debating the land redistribution question in order to address some of the historical imbalances. A consensus has not been reached yet by various political parties on how the land question should be handled. What does this mean for the agricultural sector? The sector stands to experience some major shifts in the coming years that could improve not only the economy but the welfare of the people or impede it. The current study shows a very low uptake of renewable energy in the country. However, this uptake can increase in South Africa if proper investments are made in the agricultural sector to boost production. Three strategies are proposed for policy recommendations. The sector currently burns a lot of biomass in rural and commercial farms that could be used for bioenergy if the sector is coordinated, and a market is created (Biomass commercialization). (1) This must be initiated by the government with proper policy in place detailing biomass commercialization, something that is currently missing. (2) When biomass is commercialized, it is only then that the sector can harness the feedstock waste and use it for bioenergy that will feed energy to the national grid. This is not possible currently in the farming sector and biomass is largely treated as waste. Commercialization will create a market for biomass in the sector. In summary, the proposed strategies for policy makers will be to intentionally introduce a policy on rural and commercial farming participation in bioenergy production detailing the modalities of regulations, tariffs and

finance support. This will encourage investments at the local level. (3) An aggressive R & D should be rolled out to specifically unpack socioeconomic issues of priority, this will ensure that the transition becomes a just one and the voices of communities at the local level be heard. The voices of local communities have proven to be essential in modern politics and therefore proper involvement of communities ensures investment security and better adoption. The study also recommends that investments in agricultural technology (biotechnology and mechanization) be intensified in order to offset the loss of productivity due to loss of yield, arable land, natural disasters, and due to El Niño and La Niña effects. Clearly, the agricultural economy has a linear relationship with carbon emissions which is undesirable but expected. As renewable energy consumption was not significant in the study, an indication of its impact on the economy, a concerted effort to design a policy that provides guidelines and regulation of green energy in the agricultural sector and commercialization of biomass will ensure more participation in renewable energy production specifically by the agricultural sector as the sector has more feedstock from farmers that can be used for renewable energy production. As community involvement is important, this approach will ensure grassroots participation and ultimately improve clean energy consumption. The R & D outcomes are expected to pinpoint areas of priority and concern. This will encourage the farming industry to participate in the production of renewable energy through the production of bioenergy. There is more room for creating a conducive environment, however, these will be the necessary areas of focus based on the study findings that suggest the low impact of renewable energy and the serious impact of climate change on the agricultural economy.

Future Areas of Research

The study determined the drivers of agricultural economic growth in the short run and the long run with climate change (rainfall and temperature), carbon emissions and renewable energy consumption consideration under the 1972 to 2021 period. Renewable energy consumption and climate change were found to be negatively affecting the agricultural sector in the short run while climate change was observed to improve the agricultural sector in the long-term. The study also recommended biomass commercialization, policy on regulations of rural and commercial farmer participation in the production of bioenergy and R & D on socioeconomics dynamics of producers to unpack key areas of priority and to solicit the voices of the communities on the ground on how green energy transition should unfold in the agricultural sector. However, the findings of the study were limited as few variables were used in the model, there is room for the inclusion of more variables in future studies that can build up on what was found. Moreover, advanced techniques can also be employed in the study. In the context of climate change, there is also a need to determine the agricultural sector's level of economic competitiveness in comparison with green competitiveness. Although green competitiveness tools have not been fully built, it is an opportunity to develop some. This will become important when measuring the resilience of the agricultural sector in the face of climate change.

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