

Article

Farm-Gate-Level Analysis of Crop Production and Emissions in Africa's Regional Trading Bloc Member States

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Abstract

An in-depth analysis of the drivers of agricultural emissions at the farm-gate level is crucial for achieving net-zero emissions by 2050. This study examines the short- and long-run effects of crop production on farm-gate emissions in the regional trading bloc (RTB) member states in Africa. Crop production was proxied by cereals, roots and tubers, vegetables, and fruits production, and emissions were split into methane (CH₄) and nitrous oxide (N₂O) emissions. Data on these variables were collected from 30 RTB member states from 1990 to 2022 and were analyzed using the cross-sectionally augmented autoregressive distributive lag approach. The pooled mean group was used as a robustness check, and a sensitivity analysis was conducted to ensure the reliability of the study findings. The results revealed that cereal production increases farm-gate CH₄ and N₂O emissions in the short and long run. The average increase ranges from 1.0021 to 1.0033 kilotons CO₂-eq yr⁻¹ for CH₄, and from 1.0024 to 1.0035 kilotons CO₂-eq yr⁻¹ for N₂O. In addition, fruit production increases farm-gate CH₄ emissions by an average of 1.0023 kiloton CO₂-eq yr⁻¹ in the long run. Thus, cereal production has a more adverse effect on N₂O than CH₄ emissions, while the opposite is true for fruit production in the RTB member states' Nationally Determined Contributions. With respect to mediation, cropland expansion (proxied by area harvested) plays a partial intermediary role in the impact of crop production on farm-gate CH₄ and N₂O emissions in the short run and CH₄ emissions in the long run. However, it assumes a full mediation role in the long run and has an effect on crop production in farm-gate N₂O emissions. Therefore, targeted use of nitrogen fertilizer and crop rotations to reduce cereal-related N₂O and CH₄ emissions, respectively, would be viable strategies. The use of a drip irrigation system in fruit production to reduce CH₄ emissions and the scaling up of secured subsidies should also be explored. Finally, these recommendations should be incorporated into the Africa's RTB member states' Nationally Determined Contributions and the African Union's Agenda 2063.



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1. Introduction

The global surface temperature rose by 1.1 degrees Celsius between 1850 and 1900 and between 2011 and 2020. Such a trend is expected to continue, partly due to the increase

in greenhouse gas (GHG) emissions caused by human activities [1], posing a challenge to achieving poverty alleviation, reducing hunger, and attaining net-zero emissions by 2050. These anthropogenic sources of GHG emissions include the combustion of fossil fuels for energy generation and industrial operations [2], which contribute to climate change. In parallel, the agricultural sector is the second major contributor to GHG emissions. It contributed mainly to agricultural methane (CH₄) and nitrous oxide (N₂O) emissions through the application of manure, nitrogen fertilizer, and traditional flooding methods during crop production at the farm-gate [1,3,4]. Even though Africa's GHG emissions per capita are comparatively low, their levels are increasing as a result of rising human activity. Despite farm-gate CH₄ and N₂O gaining traction in recent times due to their increasing contribution to GHG emissions at the farm-gate level, the continent's major driver of these GHG emissions is carbon dioxide (CO₂) [5–7].

Crops are the primary division of the agricultural sector, which is geared towards increasing food security, reducing malnutrition, and increasing trade [8,9]. The achievement of the role of crops has become critical as crop production and animal numbers will need to increase by 60 percent from 2006 levels to meet the food demand for 9.7 billion people in 2050. Approximately 80 percent of the desired increase in food demand in developing nations is expected to be achieved through greater cropping intensity and yields, with the remaining 20 percent coming from the expansion of arable land [10,11], which risks an increase in emissions.

Similarly, Africa's regional trading bloc (RTB) member states made commitments under the Malabo Declaration (MD) to accelerate growth in the agricultural sector, achieve food security, and improve livelihoods [12]. This has resulted in a 2.5 percent surge in agricultural output across the RTBs in Africa, with significant contributions from crops, such as cassava and cereals [5]. The increase in production across the RTBs was necessitated by their primary aim of increasing the volume of traded goods across member and non-member states [13,14].

These African RTB member states are dual contributors to emissions, as they can promote and reduce emissions simultaneously through crop trade [15]. They can reduce emissions of countries that are biophysically less endowed or facing crop failure, droughts, and flooding by lessening the pressure on the environment for crop production through the reinvestment of trade earnings in sustainable production systems, such as intercropping. They can also stimulate people's desire for better environmental quality as a result of the increase in income from crop trade [16–18]. Conversely, RTB member states can increase emissions through cropland expansion in the production of traded crops and the movement of crop products across country borders [13,14]. Moreover, Africa's RTBs have developed frameworks and research capacities to adapt to the agricultural sector's climate vulnerabilities and to identify the drivers and abatement factors of farm-gate emissions (FGEs) [19]. Hence, the RTB member states have a role to play in determining FGEs in Africa.

Thus, the link between crop production and FGEs at the RTB member states' level in Africa is warranted and requires further investigation to understand the drivers of crop-induced FGEs at that level and mitigate them. In this connection, a study from the Food and Agriculture Organization revealed that FGEs in 2023 were 29.04 percent of CO₂ equivalent emissions, with crops accounting for 7.98 percent [20]. To have a better understanding of the contribution of each crop category to agricultural emissions, various researchers have studied the relationship between crop production categories and agricultural emissions. For cereals, rice production is a predominant driver of CO₂ equivalent emissions. Globally, rice contributes 10–30 percent of CH₄ and 11 percent of N₂O. In China, while CO₂ equivalent emissions per kg of rice production in a year range from 0.83 to 0.85, N₂O emissions from double-cropping (10.68 CO₂ equivalent emissions per kg of rice production) are the greatest,

and in Japan, emissions from rice production are 341 g of N₂O emissions per hectare in a season [4,21–24]. In addition, ranking the grain crops by carbon footprint showed that rice is the highest emitter, followed by wheat and maize in China [25,26]. For vegetables, ref. [27] reported that the average emission factors for N₂O were 0.13 percent for the cucumber crop, excluding drain reuse (open hydroponic method), and 0.31 percent for the cultivation of tomatoes with drain recycling (closed hydroponic technology) in Germany. Furthermore, in Sub-Saharan Africa, ref. [7] revealed that, among other variables, vegetables emit 48 to 113.4 kg N₂O-N ha⁻¹ yr⁻¹. For the mixed category of crops, [28] showed that the contribution of cereals, such as maize and rice, to crop emissions is more than twice that of roots and tubers (potato) globally. However, intercropping maize and potatoes immediately after nitrogen fertilization reduced N₂O emissions by 19.0–20.6 percent [29]. Conversely, the production and trade of vegetables and fruits across borders harm the environment due to the carbon- and water-intensive nature of developing countries' imports, which is caused by the expansion of cropland [30]. Among recent cross-country studies applying econometric analysis, ref. [28] employed the multivariate approach among other techniques to identify the drivers of agricultural GHG emissions and explore potential mitigation strategies.

Although earlier studies on the effects of crop production on agricultural emissions produced insightful findings, significant gaps still exist. First, the majority of studies lack a comprehensive evaluation of the cereals, roots and tubers, vegetables, and fruits on farm-gate CH₄ and N₂O emissions at the African RTB member state level, instead concentrating on particular crop categories or individual crop effects on specific emission components based on geographical areas. Second, there is a lack of research on the use of the panel autoregressive distributive lag (ARDL) regression technique to study short- and long-run drivers of agricultural emissions from various crop categories. Third, the mediating role of cropland expansion and production systems in determining the influence of crop production on FGEs is also ignored. These gaps may have arisen from member states not addressing agricultural emissions issues as a collective. On the one hand, some studies neglected the role of RTBs in emission mitigation, while on the other hand, member states, researchers, and policy-makers focused on CO₂ as the key source of GHG emissions on the African continent. Thus, this raises doubts about the member states' commitment to emission mitigation.

This study intends to fill these gaps by examining the short- and long-run effects of crop production (proxied by cereals, roots and tubers, vegetables, and fruits) on farm-gate emissions at the regional trading bloc member state levels in Africa. This objective is studied by (1) zooming into the different sub-components of crop production, such as cereals, roots and tubers, and fruits, and linking them to the predominant (CH₄ and N₂O) emissions components at the farm-gate level; (2) specifying an augmented Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model and employing the cross-sectionally augmented-ARDL (CS-ARDL) model to estimate the short- and long-run effects of crop production on farm-gate CH₄ and N₂O emissions in Africa's RTB member states; and (3) determining the intermediary role of cropland expansion and production systems in the crop production effect on farm-gate CH₄ and N₂O emissions in Africa's RTB member States.

Thus, with the introduction of carbon financing, the imposition of taxes on dirty goods at the international trade level, and the coordination of the activities of the RTBs in Africa, this study is important, as it reveals specific crops that are notorious emitters of GHGs. Using this information, the various blocs will be empowered to design a coordinated approach to minimizing emissions and to determine the amount of money producers of dirty goods can be charged by environmentalists at the RTB member state level.

2. Conceptualization of Crop Production and Farm-Gate Emissions

2.1. Crop Production and Farm-Gate Level Emissions Framework

The conceptualization of the crop–emissions nexus is crucial in illustrating the pathway through which crop production influences emissions at the farm-gate level. Figure 1 can be characterized as a farm-gate level crop production and emissions framework flowing from left to right. It depicts the link between farm-gate crop production and emissions within the STIRPAT framework. The far left-hand side describes the farm-gate crop production activities, such as on-farm machinery use, irrigation, and crop residue burning that occur before the product leaves the farm and condition emissions. Furthermore, from the immediate left–center, crop value chains flow from downstream production to farm-gate production, and upstream production processes emit GHGs in the process. However, the focus of the study is on the farm-gate level. Farm-gate crop production is disaggregated into cereals, roots and tubers, vegetables, and fruits. Moreover, crop production is substituted for affluence within the STIRPAT logic. At the center, the augmented STIRPAT model demonstrates the environmental impact (I) of crop production (A), technology (T), and population (P). Even though technology and population drivers of emissions may play a role in crop production processes at the farm-gate level, they are assumed to be exogenously determined. The immediate right highlights the action mechanism, that is, the mechanism through which crop production affects emissions. Specifically, it provides the links on how cropland expansion and production systems might influence or moderate emissions at the farm-gate level. Lastly, from the far right, farm-gate emissions (environmental impact), which represent emissions from crop production activities at the farm-gate, capture only CH₄ and N₂O emissions. Thus, to produce crops such as cereals, roots and tubers, vegetables, and fruits at the farm-gate level, activities like on-farm machinery use, irrigation, crop residue burning, fertilizer and pesticides application, and land preparation and tillage were undertaken in the process, which may influence farm-gate CH₄ and N₂O emissions.

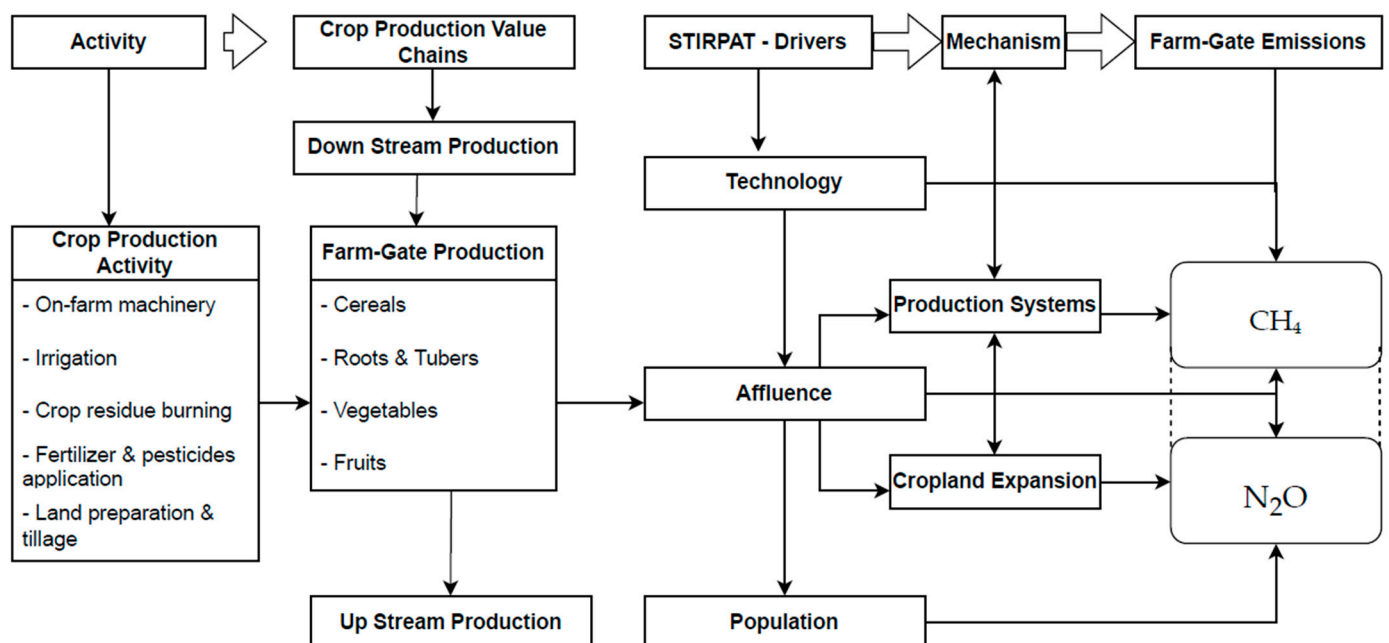


Figure 1. Farm-gate-level crop production and emissions framework. Source: Constructed by the author.

The link between crop production and farm-gate emissions poses several questions, such as why exclude the role of technology in determining crop production at the farm-gate? Therefore, to validate the link between crop production and CH₄ and N₂O emissions at the farm-gate within the framework of the STIRPAT, the following issues were addressed:

first, the study assumed the independency of the individual crop categories and technology and population and treated them as control variables: Technology and population may have a role to play in determining crop production, such as the increase in consumers and producers and mechanization in crop production at the farm-gate level. However, since the variable of interest is crop production/affluence, their role was isolated at the farm-gate level. These variables were treated as control variables within the STIRPAT framework because the STIRPAT is a dynamic regression framework whose drivers can be held constant to isolate the impact of a specific driver. Therefore, technology can be isolated when the focus is on affluence or population, thereby eliminating the variation in emissions from mechanization [31]. Population is a scale variable that affects the upstream production process through an increase in demand for crop output rather than the farm-gate production system [32]. It was treated as an exogenous variable.

Furthermore, including the yields of cereals, roots and tubers, vegetables, and fruits simultaneously in the model may introduce multicollinearity among these crop categories, potentially affecting the stability and accuracy of parameter estimates. However, these groups relate to different agronomic and economic farming methods, which have unique methods of management and GHG emission profiles [33]. Hence, integrating the production volumes of cereals, roots and tubers, vegetables, and fruits may not result in multicollinearity. Nonetheless, to determine whether these assumptions are valid, a multicollinearity test was conducted.

Second, within the STIRPAT model, affluence represents agricultural production when applied to the agricultural sector [2,34]. Agriculture is a key economic sector in Africa. It employs more than two-thirds of Africa's population, with over 70 percent engaged in crop production, and contributes about 71 percent of farmers' income [35]. Notwithstanding, crop production and its related inputs are significant drivers of agricultural emissions at the farm-gate level. For instance, refs. [36,37] employed land under cereal cultivation and fertilizer use for cereal production as proxies for agricultural production to determine the effect of agricultural production and other variables on GHG emissions. The study revealed that fertilizer consumption promotes GHG emissions. In addition, cereal production increased due to the doubling of the area harvested for maize, millet, and sorghum and almost quadrupled rice area. This increased farmers' income and GHG emissions [37,38]. However, the increase in wheat productivity limits land area expansion and reduces emissions [39]. In this sense, crop production can be an approximation for affluence when determining the effect of crop production on farm-gate CH₄ and N₂O emissions. This is plausible because crop production makes up a sizeable proportion of farmers' income, which is a significant driver of agricultural emissions. Some studies, such as [40] employed farmers' income as a proxy for agricultural production.

The third issue is the exclusion of CO₂ emissions as a preferred model in our study. The main drivers of climate change are GHGs, such as CO₂, CH₄, and N₂O [5]. At the global level, countries have made commitments in the Paris Agreement to limit warming to 1.5 °C [41]. In Africa, member states have developed the African Union's Climate Change and Resilient Development Strategy and Action Plan (2022–2032) and the AU's Agenda 2063 to mitigate and adapt to the effects of climate change [5]. However, the focus of these climate mitigation and adaptation measures is on CO₂ emissions, which are the dominant component of GHG emissions in Africa [6]. Moreover, the majority of the African studies on agricultural GHG emissions are centered on CO₂ emissions [42–45]. The focus on CO₂ emissions in Africa is understandable because of the persistence of CO₂ emissions. However, due to the short atmospheric lifespan of non-CO₂ emissions and methane's ability to absorb and release infrared radiation (heat), non-CO₂ emissions have recently

received significant attention as a potentially more effective strategy in mitigating global warming [46]. Thus, this is the reason for the focus on CH₄ and N₂O emissions models.

2.2. Analysis of the Mechanism of Crop Production Affecting Farm-Gate Methane and Nitrous Oxide Emissions

2.2.1. Analysis of the “Cropland Expansion” Effect Mechanism

The widespread conversion of edges of protected areas, adjacent cropland, and remnant forests has made cropland expansion a critical factor in sustainable agricultural space [47]. The increase in harvested crop area may be a result of crop prices, the quest to meet food requirements, urbanization, population pressure, and the enhancement of agricultural livelihoods [48–50]. Arguably, all of the highlighted reasons for farmland extension are directly or indirectly connected to crop production. Thus, the production of crops can promote FGEs by expanding agricultural land. The loss of forest due to the increase in land use for producing crops substantially degrades forest reserves. This threatens biodiversity, increases emissions, and exacerbates the impact of climate change [51]. By categorizing cropland into land converted to farmland and arable land remaining agricultural land [52] showed that CO₂ emissions were highest for land converted to cropland, while the emission factor proved to be dependent on farmland remaining arable land. The effect of expanding cropland on emissions is exacerbated by agricultural intensification, which causes the loss of carbon stock [53]. However, croplands have an enormous opportunity to sequester carbon by using improved land use management methods in crop production processes, which may partially compensate for the reduction in soil organic carbon driven by global warming [54]. Furthermore, cropland expansion can also be limited through the implementation of a crop production Moratorium [55]. Thus, in Africa, where an increase in agricultural production is realized through the expansion of agricultural land, this study proxies cropland expansion by the area harvested [56].

2.2.2. Analysis of the “Production Systems” Effect Mechanism

There is a close connection between the production systems and FGEs. In fact, food production systems are part of the emissions originating from human activities that lead to global climate change [57]. However, production systems, such as double-cropping maize, protect land, increase grain production, boost income and consumption, help achieve food security, and reduce emissions [58]. Thus, sustainable production systems are crucial, especially for developing countries that are heavily reliant on paddy for food. Despite the potential of production systems, gaps in crop yields and environmental sustainability still exist, which can be attributed to the conventional agricultural practices adopted by farmers [59]. This can be attributed to both the desire and ability of farmers to change. In this regard, to reduce the use of manual labor, farmers may shift from manual cultivation to mechanization, adopting diversification, pesticides, and improving fertilizer application to mitigate the risk of crop failure [60]. In comparison of different production systems, ref. [61] revealed that the application of inorganic fertilizer is more productive than organic fertilizer. Ref. [62] showed that the application of fertilizer and pesticides increases agricultural production and productivity. However, the implementation of an efficient fertilizer strategy, such as nutrient expert for potato, reduces agricultural emissions [63]. Conversely, tillage and inter-cropping can influence the accumulation and distribution of soil organic carbon [64]. Furthermore, mixed and intercropping are more efficient in reducing N₂O fluxes than the application of fertilizer [65]. Hence, this study proxy the production system by cereal emission intensity following similar work of [57] because cereal is the most important food crop in Africa. Moreover, to examine the combined effects of various production practices adopted on emissions through their intensities, and the availability of data.

3. Materials and Methods

3.1. Regression Strategy

This study hypothesized the existence of short- and long-run effects of crop production on farm-gate CH₄ and N₂O emissions. To test these hypotheses, regression models were estimated using the strategy in Figure 2. A common mistake researchers make in panel model specification is to specify a static model instead of a dynamic model. When a model is misspecified, there is a good chance that the estimated residuals from the regression equation will exhibit some autocorrelation [66]. Thus, a dynamic model is specified because there is the belief that past emissions are associated with current emissions. Consequently, in our estimation strategy, a cross-sectional dependence (CD) test was first conducted using the [67] tests to examine the strength of CD, with the null hypothesis of weak CD. In the presence of CD, the second-generation unit root test was conducted because it is robust in dealing with CD [68]. The Pesaran cross-augmented Dickey–Fuller (Pescadf) test based on the individual Dickey–Fuller or augmented Dickey–Fuller means [69] was employed.

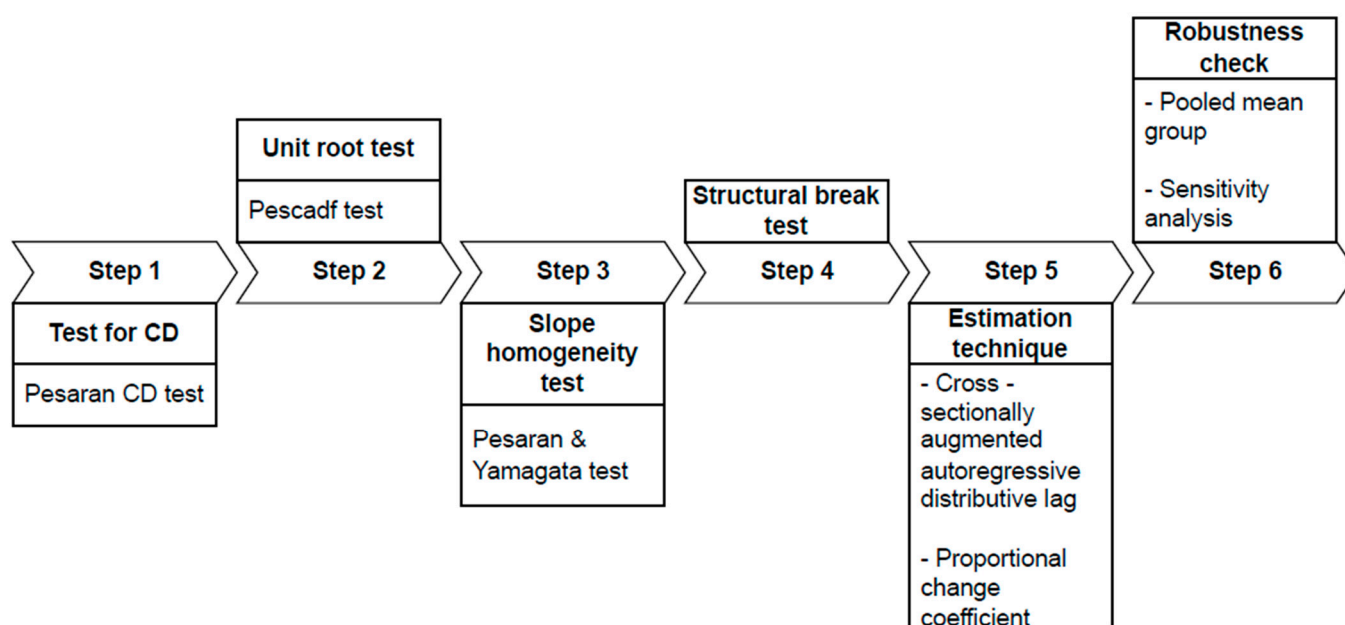


Figure 2. The regression strategy. Source: Constructed by the Author.

With large cross-section and time dimensions, the standardized version of Swamey's test to test for slope homogeneity was used, because the incorrect imposition of slope heterogeneity will result in biased and inconsistent results [70]. Furthermore, the prevalence of policy shifts or shocks in macroeconomics warrants a structural breaks test as its omission will lead to misleading inferences. In the presence of CD, slope heterogeneity, and structural breaks, the cross-sectional augmented autoregressive distributive lag (CS-ARDL) model that controls for these problems was employed. The estimated coefficients obtained from the regressions were interpreted using proportional changes. A robustness check was also conducted to validate the regression results, using the pooled mean group (PMG) estimation technique, followed by a sensitivity analysis. Stata 17 (StataCorp, College Station, TX, United States) [71] was used to conduct all empirical estimations.

3.2. Theoretical Specification of the Regression Model

Researchers have developed several models of climate change human drivers. Typical of such theories is the environmental impact of population, affluence, and technology (IPAT). This theory, by [72], shows that population (P), affluence (A), and technology (T) are the drivers of environmental degradation. The IPAT provides the foundation for several

other climate change theories, such as the STIRPAT. The STIRPAT, developed by [31], improves on the IPAT by incorporating a stochastic term and non-unit elasticity of the environmental impact of each driving force. Since the study examines the effects of crop production on FGEs by running a regression, the STIRPAT model was adopted to illustrate the stochastic relationship between crop production and FGEs, as shown by [73]. The theoretical specification of the STIRPAT is depicted in the following equation:

$$I = e^{\beta_0} P^{\beta_1} A^{\beta_2} T^{\beta_3} e^{\varepsilon} \quad (1)$$

Taking the natural logarithm throughout yields:

$$\ln I = \beta_0 + \beta_1 \ln P + \beta_2 \ln A + \beta_3 \ln T + \varepsilon \quad (2)$$

where β_i 's are the coefficients to be estimated, $\ln$, natural logarithm, and ε is the error term assumed to be normally distributed.

3.3. Empirical Model Specification of the Primary Regression Models

Ref. [74] employed the STIRPAT model to study emissions in economies at various stages of development. For instance, ref. [75] proxied environmental degradation with CO₂ and N₂O emissions, while ref. [40] proxied affluence with crop production indices. Several other proxies have been proposed for population and technological driving forces of emissions. Hence, we use N₂O and CH₄ emissions indicators for FGEs because they are the two most prevalent emission components in the agricultural sector [26]. Additionally, to explicitly distinguish the contribution of the crop sector's primary output to emissions at the farm-gate level, affluence is proxied by cereals, roots and tubers, vegetables, and fruit production. This is because they are the crops that are commonly grown in the member states for which data is available and they contribute significantly to the gross domestic product (GDP) of these member states.

The study employed agricultural investment (Tech) and rural population (Rupop) as proxies for technology and population, respectively, and observe them as control variables. Thus, the dynamic augmented STIRPAT panel model is specified to investigate the relationship between crop production and FGEs in selected African RTB member states as follows:

$$\ln \text{Methane}_{it} = \beta_0 + \beta_1 \ln \text{Methane}_{it-1} + \beta_2 \ln \text{Cereal}_{it} + \beta_3 \ln \text{Roots and tubers}_{it} + \beta_4 \ln \text{Vegetable}_{it} + \beta_5 \ln \text{Fruit}_{it} + \beta_6 \ln \text{Tech}_{it} + \beta_7 \ln \text{Rupop}_{it} + \varepsilon_{it} \quad (3)$$

$$\ln \text{Nitrous oxide}_{it} = \beta_0 + \beta_1 \ln \text{Nitrous oxide}_{it-1} + \beta_2 \ln \text{Cereal}_{it} + \beta_3 \ln \text{Roots and tubers}_{it} + \beta_4 \ln \text{Vegetable}_{it} + \beta_5 \ln \text{Fruit}_{it} + \beta_6 \ln \text{Tech}_{it} + \beta_7 \ln \text{Rupop}_{it} + \varepsilon_{it} \quad (4)$$

where i 's represent member states, t 's, years, and $t - 1$ previous year.

3.4. Mediating-Effect Model

Crop production can affect farm-gate CH₄ and N₂O emissions through cropland expansion (proxied by area harvested) and production systems (proxied by cereal emission intensity). To examine the action mechanism of crop production on CH₄ and N₂O emissions, model (Equation (5)) is formulated based on the conceptual framework.

$$\ln M_{it} = \alpha_0 + \alpha_1 \ln M_{it-1} + \alpha_2 \ln \text{Crops}_{it} + \varepsilon_{it} \quad (5)$$

$$\ln \text{Methane}_{it} = \pi_0 + \pi_1 \ln \text{Methane}_{it-1} + \pi_2 \ln \text{Crops}_{it} + \pi_3 \ln M_{it} + \varepsilon_{it} \quad (6)$$

$$\ln \text{Nitrous oxide}_{it} = \omega_0 + \omega_1 \ln \text{Nitrous oxide}_{it-1} + \omega_2 \ln \text{Crops}_{it} + \omega_3 \ln M_{it} + \varepsilon_{it} \quad (7)$$

where $Crops_{it}$ represents crop production. It is the sum of cereals, roots and tubers, vegetables, and fruits production. It is treated as control variable in the mediation models.

In Equations (5)–(7) M_{it} is the mediating variable, which represents cropland expansion and production systems, and α_i , π_i , and ω_3 are the parameters to be estimated. The remaining symbols and variables correspond to those in Equations (3) and (4).

3.5. Method of Estimation

3.5.1. Diagnostic Tests of the Variables in the Primary Regression Models

Cross-Sectional Dependence Test

The motivation behind the application of the CD is because these RTB member states are interconnected in the sense that they share common languages, cultures, and traditions. In addition, they belong to the same blocs, hence there is the likelihood that they share similar trade policies, and with globalization, participate in regional or global value chains. Thus, to test for CD in the panel data set, the [67] test for weak CD was employed. This test is used because it can be applied to balanced and unbalanced panels. Moreover, it is more robust in detecting CD in large time and cross-sectional units [67]. The null hypothesis is weak CD.

$$CD_{Weak} = \sqrt{\frac{2}{n(n-1)}} \sum_{i=1}^{n-1} \sum_{q=i+1}^n \frac{\sqrt{Q\hat{\alpha}_{iq}}}{\sqrt{\hat{\beta}_{iq}}} \quad (8)$$

where $Q\hat{\alpha}_{iq}$ is the correlation between the sample residuals, $\hat{\beta}_{iq}$ is a reliable predictor of the variance.

Second-Generation Unit Root Test

With the assumption of CD, the [69] test for stationarity is used to determine the unit root of the variables because of its simplicity. The Pesaran unit root test is predicated on the statistical significance of specific cross-sectionally augmented Dickey–Fuller test statistics. Additionally, it modified the Im Pesaran Shin t-bar test statistic to test for stationarity when the residuals are correlated, and CD is present. Hence, the name cross-sectional specific augmented Im Pesaran Shin (CIPS). The null hypothesis of the CIPS is that there is no unit root.

$$CIPS = \sum_{i=1}^N CADF_i N^{-1} \quad (9)$$

where N is the number of cross-sectional units, and i represents units.

Test for Slope Homogeneity

With the assumption of stationarity of the variables, the study test for slope homogeneity across the panel units using the [70] test for homogeneous slope because it is more applicable for larger panels. Under the null hypothesis of slope homogeneity, Pesaran and Yamagata estimated two test statistics as illustrated in (Equations (10) and (11)):

$$\tilde{S} = \sum_{i=1}^N \left(\hat{\rho}_i - \tilde{\rho}_{wfe} \right)' \frac{X_i' M_t X_i}{\hat{\vartheta}_i} \left(\hat{\rho}_i - \tilde{\rho}_{wfe} \right) \quad (10)$$

where $\hat{\rho}_i$ is the pooled ordinary least squares estimator of the slope coefficients, $\tilde{\rho}_{wfe}$ is the weighted fixed effect of the slope coefficients, the identity matrix is given as M_t , and the estimator of ϑ_i^2 is $\tilde{\vartheta}_i^2$. The standardize dispersion statistic ($\tilde{\Delta}$) is given as:

$$\tilde{\Delta} = \left(\frac{\tilde{S}-k}{\sqrt{2k}} \right) \sqrt{N} \quad (11)$$

where $\tilde{S}$ is the Swamy test statistic, N is the number of cross-sectional units, and k is the degree of freedom.

Test for Structural Breaks

Structural breaks may be prevalent, particularly in macroeconomic data, due to policy shifts or shocks. These changes, whether known or unknown, may affect the interpretation of regression results and inferences. As such, [76] proposed a model to detect multiple breaks in panel data. The panel data model, consisting of a structural break k , is written as:

$$y_{i,t} = x'_{i,t}\alpha + q'_{i,t}\beta'_{k+1} + e_{i,t} \quad (12)$$

$$\text{for } t = T_k+1, \dots, T,$$

where $y_{i,t}$ is the endogenous variable and $\hat{x}_{i,t}$ and $\hat{q}_{i,t}$ are exogenous variables. α and $\beta_1, \dots, \beta_{k+1}$ are vectors of coefficients. $e_{i,t}$ means error term and $T_1, \dots, T_k$ represent the structural break dates.

The error term allowed unobserved heterogeneity through the specification of an interactive fixed effects model shown as:

$$e_{i,t} = f'_t\delta_i + \epsilon_{i,t} \quad (13)$$

where f_t is the unobserved common factor, δ_i is the factor loading, the idiosyncratic error is $\epsilon_{i,t}$, and the interactive effect is $f'_t\delta_i$.

The f is likely to be correlated with the exogenous variables. To capture this, the exogenous variables is specified:

$$x_{i,t} = \tau'_{x,i}f_t + \mu_{x,i,t} \quad (14)$$

$$q_{i,t} = \tau'_{q,i}f_t + \mu_{q,i,t} \quad (15)$$

where $\tau_{x,i}$ and $\tau_{q,i}$ are factor loadings. The idiosyncratic errors are $\mu_{x,i,t}$ and $\mu_{q,i,t}$. f_t captures the correlation of the independent variables within and across cross-sections.

3.6. Cross-Sectionally Augmented Autoregressive Distributed Lag

Assuming our model is dynamic with a mixed order of integration, autocorrelation, endogeneity, long-run relationship, heterogeneous slopes, and structural breaks, the study is open to three dynamic common correlation effect estimation methods: cross-sectional augmented distributed lag (CS-DL), the CS-ARDL, and the error-correction model augmented autoregressive distributed lag (ECM-ARDL) models. However, in this study, the CS-ARDL model is employed to overcome the limitation of the CS-DL; it does not estimate the error correction term (ECT) that accounts for the speed of adjustment in the long-run equilibrium. Also, the CS-ARDL and the ECM-ARDL are similar long-run estimation techniques, as they account for ECT and produce numerically equivalent regression output [77]. We specify the CS-ARDL (p_y, p_x) model as:

$$\Delta Y_{it} = \tau_i + \varnothing_i \left(Y_{it-1} - \alpha_i X_{it-1} - \varphi_{1i} \bar{Y}_{t-1} - \varphi_{2i} \bar{X}_{t-1} \right) + \sum_{j=1}^{p_y-1} \mu_{ij} \Delta Y_{it-j} + \sum_{j=0}^{q-1} \varpi_{ij} \Delta X_{it-j} + \lambda_{1i} \bar{\Delta Y}_t + \lambda_{2i} \bar{\Delta X}_t + \varepsilon_{it} \quad (16)$$

where p_y and p_x are the number of lags of cross-sectional averages of the endogenous and exogenous variables respectively, Y_{it} (nitrous oxide and methane emissions) is the endogenous variable, τ_i is the constant, $\varnothing_i$ is the speed of adjustment; which shows the speed at which the emissions converge to long run equilibrium after a short-run shock such as COVID, and the commitment to pegging emissions, α_i is a vector of the slope parameters of the exogenous variables, and lagged endogenous variables. X_{it} is a vector of the independent variables $\bar{Y}_{t-1}$ and $\bar{X}_{t-1}$ are the long-run unobserved factors $\bar{Y}_t$ and $\bar{X}_t$ are the short-run unobserved factors.

The lag length of the endogenous and exogenous variables is selected by adding no lags for the endogenous variable. Only its contemporaneous cross-sectional averages are included. However, for the exogenous variables, the floor of $(\sqrt[3]{t})$ lags of the exogenous variables is added.

where t represents the study period.

Thus, the cross-sectional lag ranges from 0 to 3. Where $p_y = 0$, and $p_x = 3$

3.7. Proportional Change Coefficients

Since Equations (3) and (4) are written in natural log, the regression coefficients are interpreted using elasticity. However, the dependent variables (farm-gate methane and nitrous oxide emissions) are reported yearly [78]. Hence, it is required that the emissions elasticity is converted to proportional change coefficients of emissions with the help of the preceding formula [79]:

$$\text{Proportional change in Emissions} = \exp\left(\delta \hat{\alpha}\right) \quad (17)$$

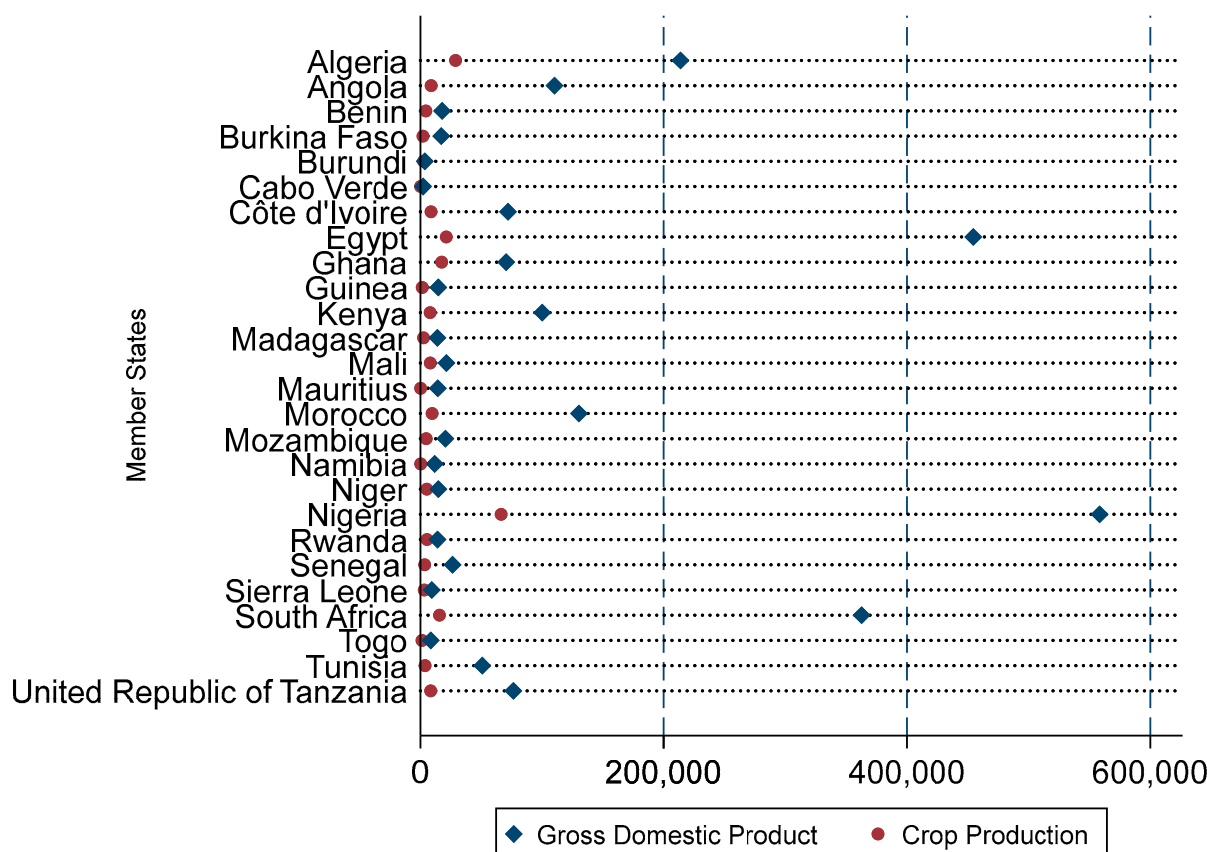
where $\exp$ represents exponent, $\delta = \ln([100 + m]/100)$, The predicted regression coefficient (α) represents the predicted rise in emissions, and the change's size is denoted by m .

3.8. Data on Key Variables in the Primary Regression Models

The study sampled the RTB member states because crop production plays a significant role in their growth. Figure 3 shows that in the selected RTB member states crop production is a major contributor to GDP because crop production values are closer to GDP on the far left end of the horizontal line. However, a few member states, like South Africa, Côte d'Ivoire, and Nigeria, have values closer to the right, probably because they have more robust extractive, industrial, or service sectors, which raise GDP above crop production. Notwithstanding, crop production still has a role to play in these RTB member states if we net out the contribution of the extractive industries, especially oil and precious minerals such as diamond and gold.

Furthermore, some of these member states belong to more than one RTB due to overlapping membership. For instance, the United Republic of Tanzania belongs to RTBs such as the SADC, and EAC. In addition, there are also RTBs whose membership extends beyond regional boundaries, like the Common Market for East and Southern Africa (COMESA). Therefore, it is difficult to study these member states and RTBs because of their overlapping membership, which makes it impossible for panel data declaration and estimation in Stata. To unpack the complexity and ease model estimation, we exclude the RTBs with a deeper cross-regional geographical scope. As such, we drop RTBs like COMESA. Thus, we select

the AMU, EAC, ECOWAS, and SADC RTBs in the north, east, west, and southern regions, respectively. These four selected RTBs comprise forty-four (44) member states: five (5) from AMU, eight (8) from EAC, fifteen (15) from ECOWAS, and sixteen (16) from SADC. In addition, we exclude member states with overlapping membership to avoid duplication (Tanzania), giving us a total of forty-two (42) member states. Twelve (12) member states are then included based on data availability on common (crops produced cereals, vegetables, roots and tubers, and fruits), rural population, and technology. Thus, our final sample consisted of thirty (30) member states, which represent approximately 70 percent of the RTB member states (see Table 1).



The share of crop production to gross domestic product (in US\$ million)

Figure 3. The share of crop production to the member state's GDP in US\$ million as of 2023. Source: Constructed by the Author.

Table 1. Member states of the regional trading blocs studied.

S/n	Economic Community of West African States	South African Development Community	East African Community	The Maghreb
1	Benin	Angola	Burundi	Algeria
2	Burkina Faso	Eswatini	Kenya	Egypt
3	Cabo Verde	Lesotho	Rwanda	Morocco
4	Côte d'Ivoire	Madagascar	Tanzania	Tunisia
5	Ghana	Mauritius	Uganda	
6	Guinea	Mozambique		
7	Liberia	Namibia		
8	Mali	South Africa		
9	Niger			
10	Nigeria			
11	Senegal			
12	Sierra Leone			
13	Togo			

Source: Constructed by the Author.

3.9. Selection of Key Variables in the Primary Regression Models

Carbon dioxide equivalent emissions can broadly reflect emissions from crops, livestock, and forestry divisions. However, for a detailed analysis, the study focuses on the crop sub-sector's contribution to emissions. This is because crop production faces increased pressure due to the rising world population and the attainment of food security; crop emission intensity becomes critical, as it may be associated with higher emissions. In this regard, crop emissions can result from upstream, downstream, and farm-gate levels. However, the predominant CO₂ equivalent emissions at the farm-gate level, which account for the direct contribution of crops to emissions, are methane and nitrous oxide emissions [3], as revealed by studies such as [4,25,29,80]. Thus, we employ methane and nitrous oxide emissions as our dependent variables.

Crops have faced increased pressure due to the population's growing demand for food, which requires crop intensity and yield to increase by 80 percent [10,11]. The increase in cropping intensity and yield will arguably lead to higher agricultural emissions. The 10 major crops grown in Africa are maize, sorghum, cassava, millet, rice, groundnuts, cowpeas, wheat, beans, and vegetables. The production of these crops is expected to increase from 36.5 percent to 127.6 percent, with a corresponding increase in emissions from 0.5 to 5.2 percent from 2020 to 2050 [5]. Thus, by categorizing these crops into different food groups, such as cereals, roots and tubers, vegetables and fruits, crop contribution to emissions can be quantified as of 2022 and use the results to proffer measures to reduce emissions below the projected 5.2 percent in 2050. In addition, fruit production is included to capture how the African continent's drive to achieve nutrition security actually impacts emissions. Extant studies have examined the contribution of fruits [30,80], vegetables [7,27], roots and tubers [23,29], and cereal crops [22,25] to emissions, respectively. The control variables, such as population and technology, have also been employed by authors such as [81,82] to determine their effect on emissions. As such, these variables were used as independent variables to determine their effect on CH₄ and N₂O emissions at the farm-gate level in the RTBs member states in Africa. Data on the variables for the sampled RTB member states are collected from the Food and Agriculture Organization Statistical database [20] for the period 1990 to 2022. The description of the variable is presented in Table 2.

Table 2. Variable Description.

Variable	Description	Data Source	Measurement	Reference
Methane	Emissions from agricultural activities such as burning residues and the cultivation of rice and other crops.	FAOSTAT	Kilotons	[4,25]
Nitrous oxide	Emissions from agricultural activities, such as irrigation and land use change.			[29,80]
Cereal	The primary output of all cereals at the farm-gate.		Metric tons	[22,25]
Root and tuber	The total output of roots and tubers at the farm-gate.			[23,29]
Vegetable	The primary output of vegetables at the farm-gate.			[7,27]
Fruit	The primary output of all fruits at the farm-gate.			[30,80]
Rural population	The total number of people that reside in the rural area per year		Per thousand people.	[81]

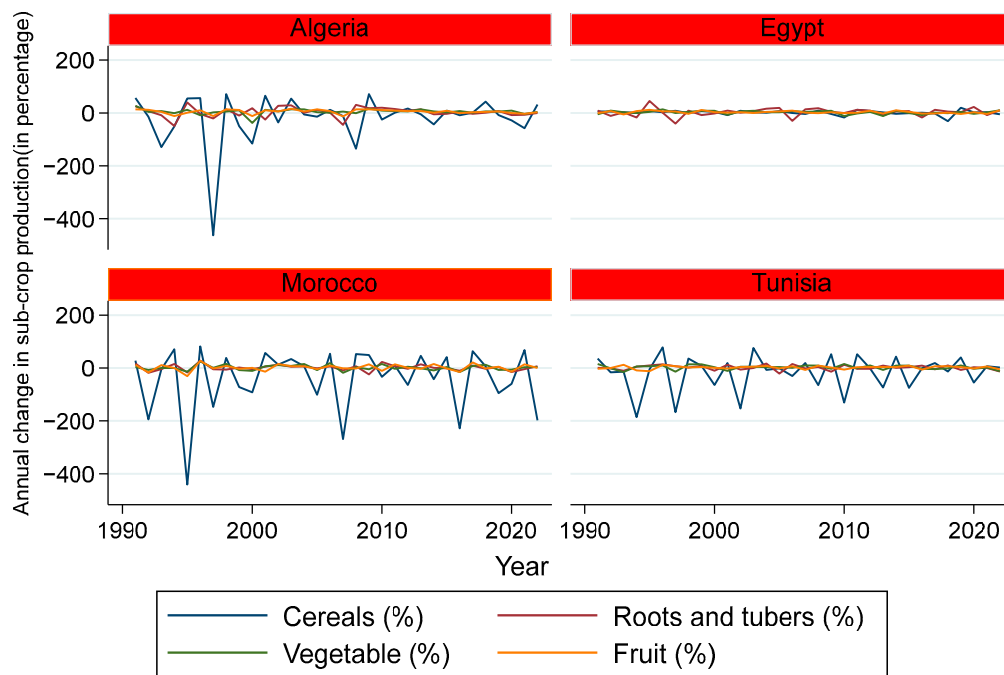
Table 2. Cont.

Variable	Description	Data Source	Measurement	Reference
Technology	It encompasses the government expenditure, credit, development flows, and foreign direct investment in the agricultural sector.		US\$ million	[82]
Area harvested	Harvested crop area		Per hectare	[56]
Cereal emission intensity	Emissions per cereal production.		Kilogram CO ₂ eq/kilogram	[57]
Irrigation	Area of land with irrigation capabilities		Per thousand hectares	[83]

Source: Computed by the Author.

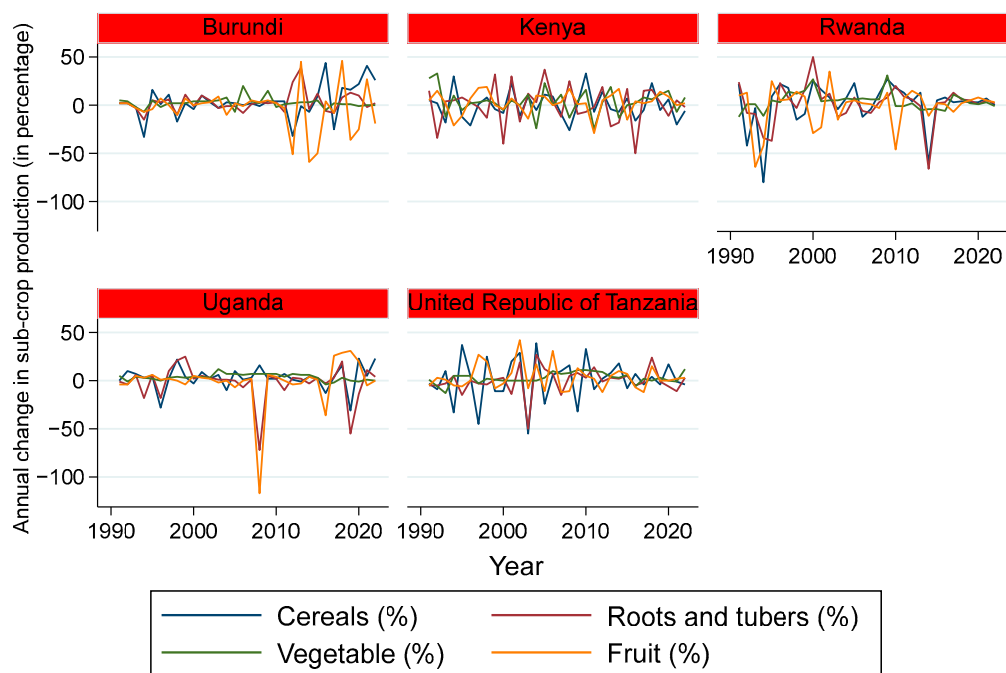
3.10. Trend Analyses of Key Variables in the Primary Regression Models

From Figure 4A, given that roots and tubers are comparatively stationary, the member states of the AMU bloc show stable, moderate growth paths for fruits and cereals. This is because of the Mediterranean environment and irrigation-driven practices that support crop choice and yield stability in the AMU. The absence of notable shifts in the growth of roots and tubers indicates that these crops are not significantly impacting climate change in the AMU. However, vegetable growth is volatile probably due to seasonality. EAC countries continue to grow a variety of crops, with cereals, vegetables, roots and tubers, and fruits showing an increasing trend. This is because this region uses numerous farming techniques and the emphasizes the adaptability of its agricultural policies to achieve a smooth and comprehensive growth [84]. The general upward trend indicates adaptable agricultural practices and efficient production; however, fluctuations in cereal and fruit production show vulnerabilities to year-to-year climatic conditions (Figure 4B). ECOWAS member states have seen substantial increases in cereals, roots, and tubers. However, the trends show that several ECOWAS member states, notably Niger, Senegal, and Sierra Leone experience frequent shocks, which may be attributed to changes in input prices, significant climate variability, and shifting governmental policies [85]. Furthermore, there has not been an enormous spike in fruits and vegetables, implying that although the cultivation of vegetables is frequently performed on a smaller scale, it capitalizes on controlled environments that protect against changes in the climate, such as irrigation systems [86] (Figure 4C). The predominant trend in SADC bloc is resilience, especially in terms of cereal output, which aligns with Southern Africa's greater extent of agricultural modernization and state support. However, the bloc lags in cereal growth. Fruits, vegetables, roots, and tubers also show a positive trend, suggesting continued progress in crop sectors. Although climate or structural shocks are undoubtedly the cause of the sporadic variability in member states like Eswatini, Mauritius, and Mozambique, SADC member states have portrayed consistent trends over the years [87,88] (Figure 4D).



Graphs by Arab Maghreb Union Regional Trading Bloc

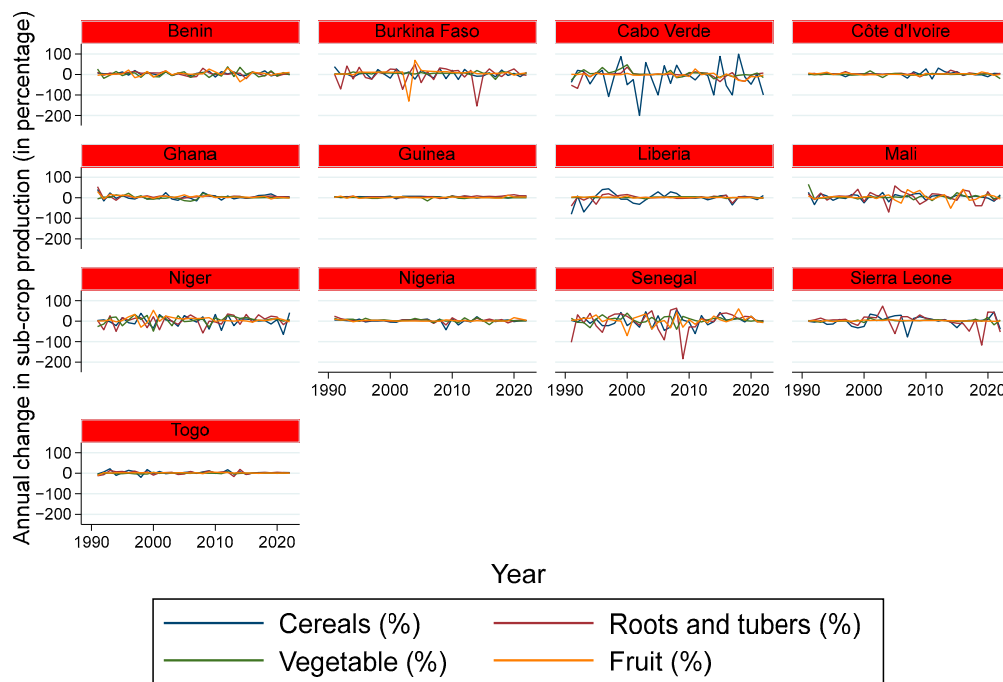
(A)



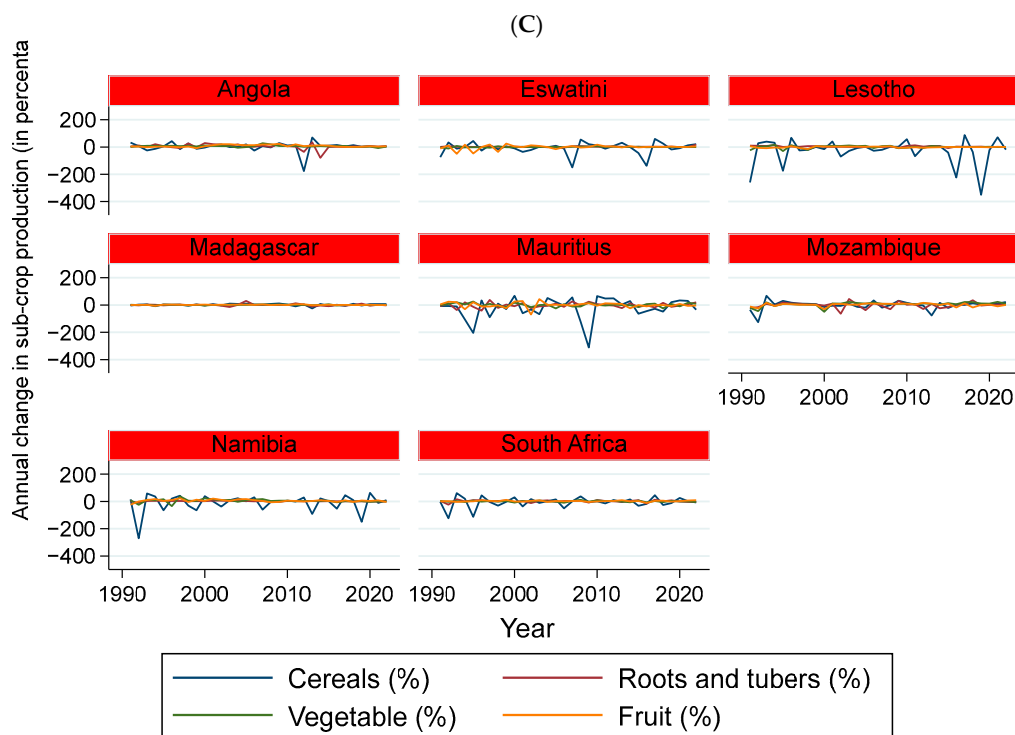
Graphs by East African Community Regional Trading Bloc

(B)

Figure 4. *Cont.*



Graphs by Economic Community of West African States Regional Trading Bloc



Graphs by Southern African Development Community Regional Trading Bloc

(D)

Figure 4. Panel (A)—Arab Maghreb Union Member States. Panel (B)—East African Community Member States. Panel (C)—Economic Community of West African States Members. Panel (D)—South African Development Community Member States. (A–D) Shows the percentage change in crop production in each regional trading bloc member state. Every member is displayed by a small panel that illustrates the annual percentage growth for cereals, roots and tubers, vegetables, and fruits from 1990 to 2022. Source: Constructed by the Author.

3.11. Growth in Methane and Nitrous Oxide Emissions

Figure 5A shows that over the past three decades, CH₄ and N₂O emissions have grown modestly throughout member states of the AMU. Large irrigation and more mechanized agriculture systems are contributors to this resilience. With minimal variation for each GHG, the emissions patterns in AMU countries point to persistent progress in input handling and possibly more uniform implementation of environmental regulations [89]. A slightly distinct perspective is given by the EAC. In this bloc, CH₄ and N₂O emission trends show slight consistent increases, especially in Kenya and Tanzania. These trends underscore the region's diverse and intensive farming methods. Importantly, more reliance on small-scale farming may account for Burundi and Rwanda's reduced emission rates [90]. These patterns highlight how crucial crop management and extension services are in determining the scale and variability of GHG rise throughout EAC in the long run (Figure 5B). The emissions narrative is more volatile in the ECOWAS. The magnitude and intensity of the agricultural sector shifted, access to agricultural inputs fluctuated, and large-scale climatic changes have contributed to the sporadic rises and falls in member states like Ghana and Nigeria. Smaller member states like Benin, Sierra Leone, and Togo, show consistent but slower rises. The significant influence of environmental pollution on emission trends across ECOWAS member states shows the importance of policy coordination across crop management and climate adaptation options [91] (Figure 5C). Notwithstanding notable differences between the region's more productive and less productive economies, the SADC bloc represents the African perspective. South Africa stands apart in that its emission trajectory is completely flat and consistent, which indicates its innovative rules and regulations and mechanized agricultural practices [92,93]. CH₄ and N₂O emissions shifted marginally in some SADC member states, such as Lesotho, Madagascar, Mozambique, and Namibia. This is likely linked to fluctuations in rainfall and the interaction between subsistence and commercial farming (Figure 5D).

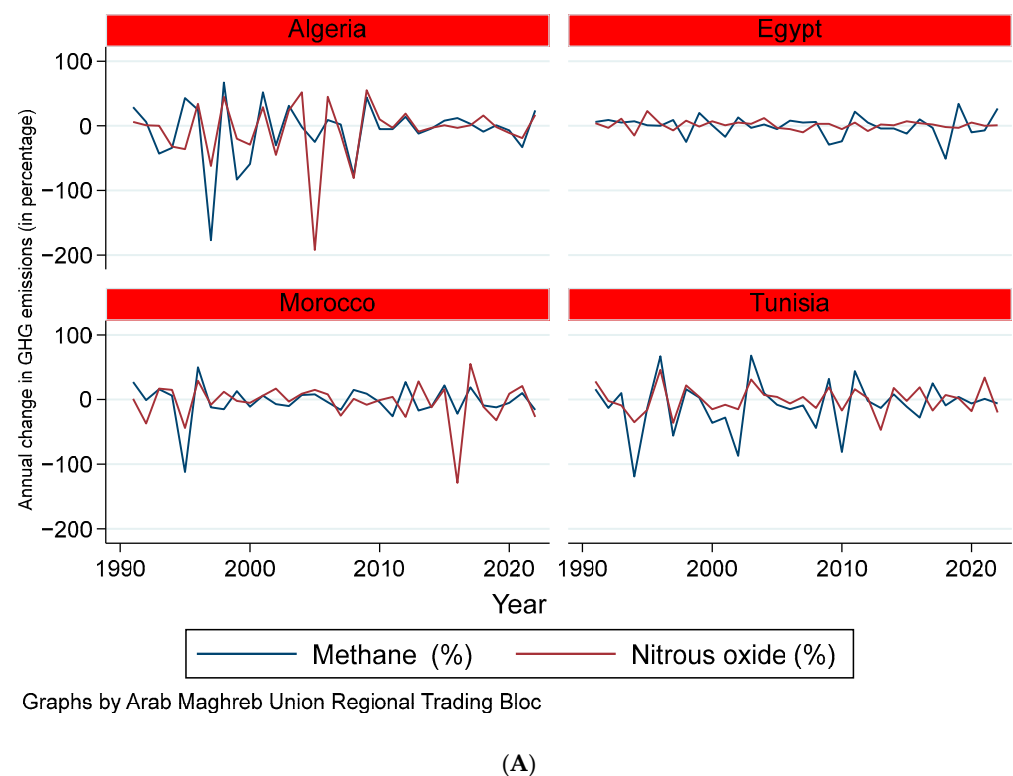
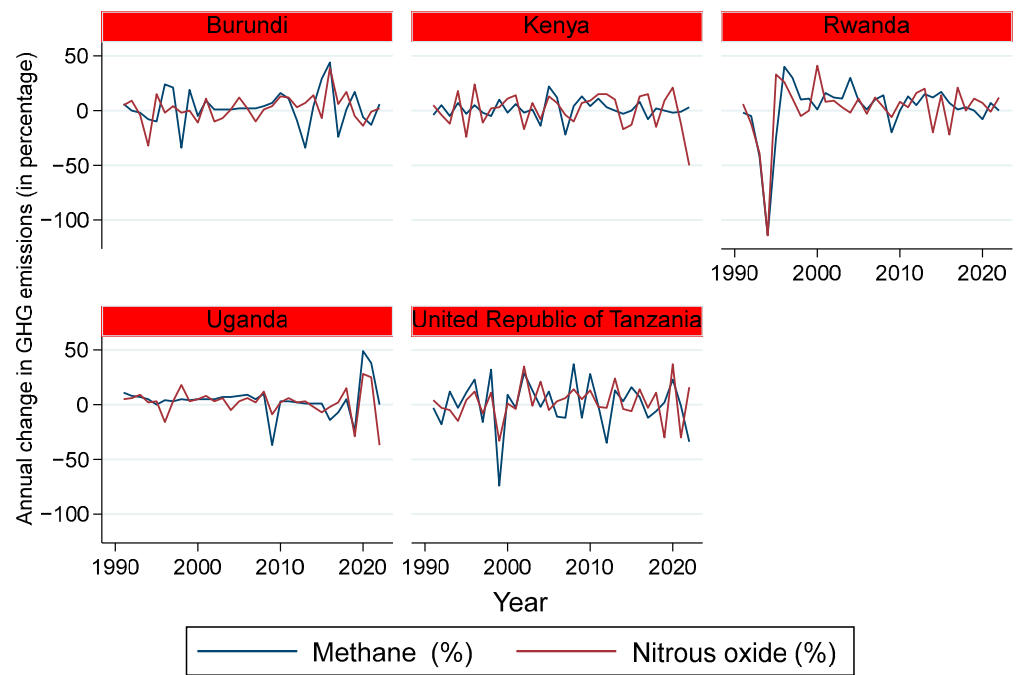
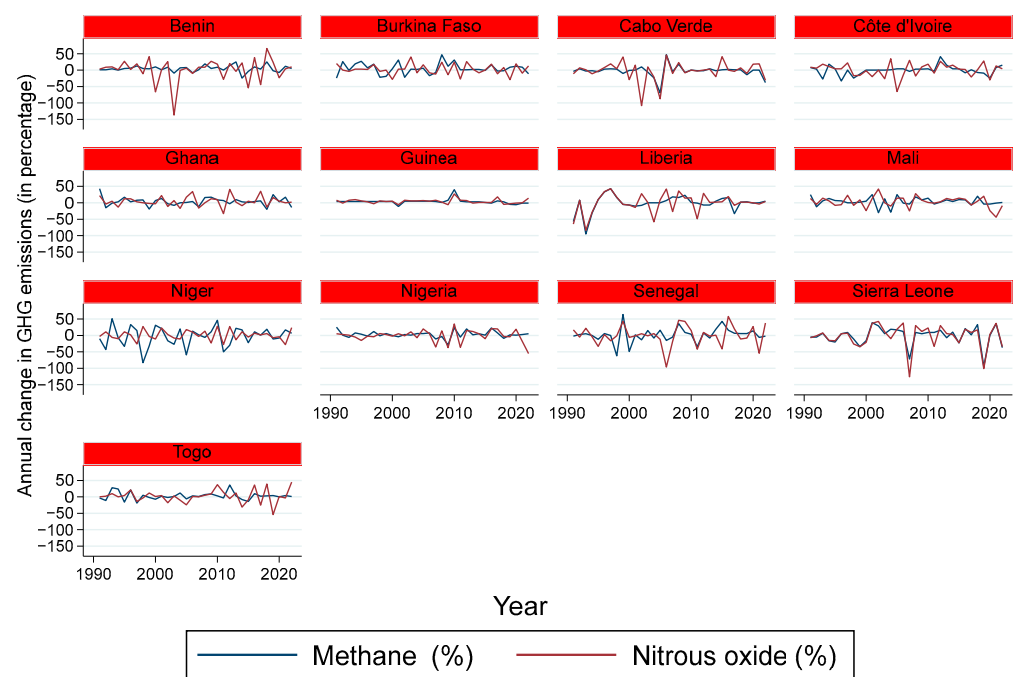


Figure 5. Cont.



Graphs by East African Community Regional Trading Bloc

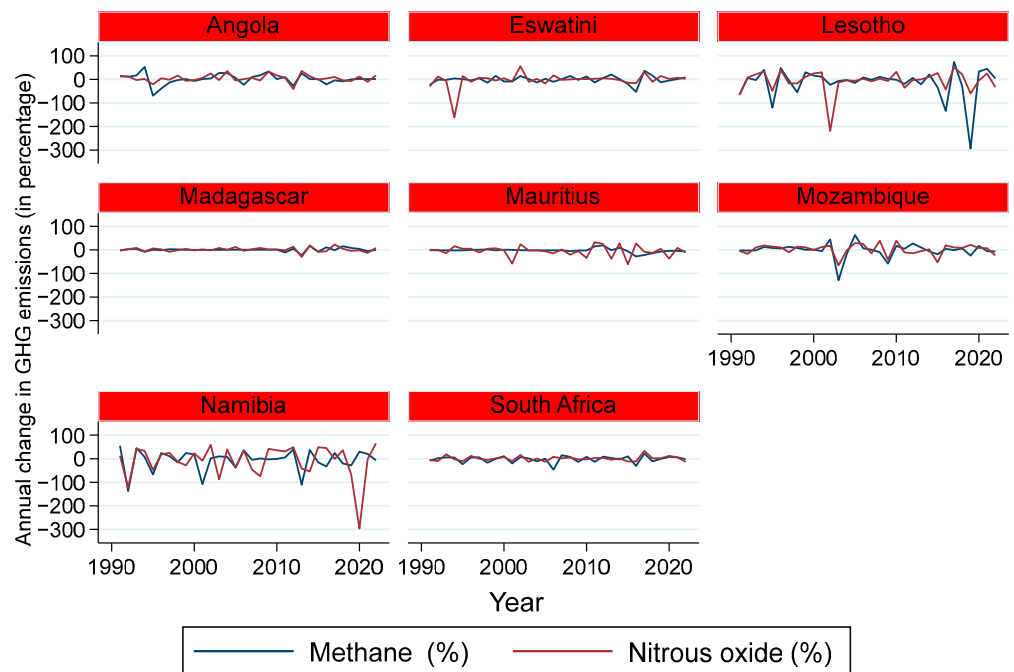
(B)



Graphs by Economic Community of West African States Regional Trading Bloc

(C)

Figure 5. Cont.



Graphs by Southern African Development Community Regional Trading Bloc

(D)

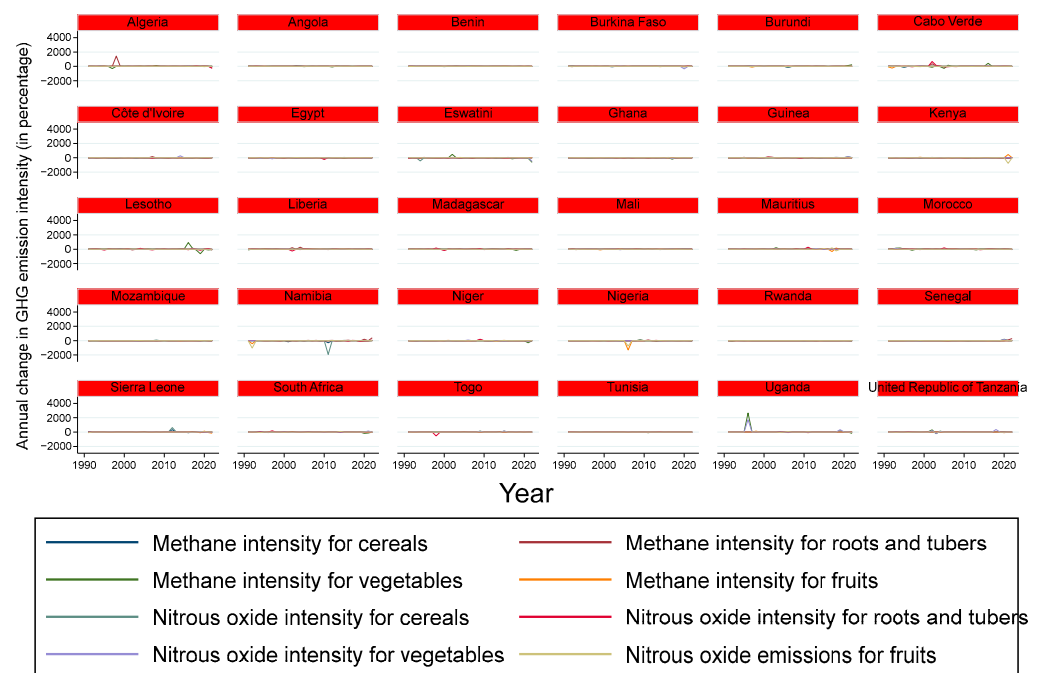
Figure 5. Panel (A)—Arab Maghreb Union Member States. Panel (B)—East African Community Member States. Panel (C)—Economic Community of West African States Members. Panel (D)—South African Development Community Member States. (A–D): The growth trends in N_2O and CH_4 across Africa's RTB member states from 1990 to 2022 are depicted. The trajectory patterns display low to moderate variability, with notable variations in some member states of RTBs. Source: Constructed by the Author.

3.12. Crop Methane and Nitrous Oxide Intensity

Figure 6 depicts several trends and patterns in crop CH_4 and N_2O intensities across the RTBs. The CH_4 and N_2O emission intensities remain low and stable for most member states' crops. Fruits and vegetables generally have the lowest emission intensities with unexpected troughs in Namibia and Nigeria associated with upland and low-intensive farming practices for crop cultivation. There are occasionally notable fluctuations in emission intensity despite the general predictability; these are mostly linked to roots and tubers, and, to a lesser extent, cereals. Lesotho, South Africa, Liberia, Mozambique, and Tanzania are noteworthy examples of these unexpected rises in CH_4 and N_2O emissions per unit of output, which are mainly from member states and seasonal in source. The rises are likely triggered by several interconnected factors, such as productivity volatility, variations in farming practices, sporadic climate variations, and shifts toward more wetland or waterlogged cultivation techniques, especially for cereals [94]. In addition, CH_4 intensity appears to be more volatile than N_2O . This may be due to its greater susceptibility to aerobic conditions prevalent in waterlogged rice and tuber fields [95].

By analyzing specific crop shifts, CH_4 intensity for cereals typically remains low but often jumps drastically in member states with intermittent fluctuations in land use or farming techniques. Similarly, temporal stability is observed in N_2O intensity for cereals, with only a few minor fluctuations. This may indicate that fertilizer management is mostly efficient across a large number of member states, with exceptional inconsistencies. Roots and tubers are especially vulnerable to unexpected fluctuations in CH_4 and N_2O intensities. This phenomenon can frequently be attributed to shifts in the application of organic material, floodplain cultivation, or yield variability triggered by global warming. Fruits and

vegetables, on the other hand, appear to be among the most stable and climate-resilient crops; their relatively low and predictable structures result from cultivation techniques that promote efficient nutrient utilization and reduce the creation of adverse microorganisms [96,97]. Notably, fruit crops provide low-intensity production methods with low GHG emissions. These results imply that management and policy interventions aimed at limiting input-based emission spikes in cereals, roots, and tubers, as well as facilitating a rise in fruit and vegetable farming, can offer effective routes leading to environmentally friendly cultivation in the RTB member states in Africa [98] (see Figure 6).



Graphs by Regional Trading Bloc Member States

Figure 6. The intensity of methane and nitrous oxide emissions from the various crops across the RTBs in Africa is compared. The intensity is the emission per output. Source: Constructed by the Author.

4. Results

4.1. Descriptive Analysis of Key Variables in the Primary Regression Models

Table 3 shows that, on average, the regional trading bloc member states emitted 38.62 kilotons of CH_4 and 2.81 kilotons of N_2O . The key drivers of these emissions are crop production, the size of the rural population, and expenditure on technology. However, the ECOWAS and AMU member states stood out as the major regional trading blocs whose member states are driving these emissions. For instance, while the ECOWAS member states are the major emitter of CH_4 (574.89 kilotons), the AMU member states are the principal emitter of N_2O (42.13 kilotons). The dominance in farm-gate emissions by the ECOWAS member states can be attributed to the ECOWAS engagement in large scale cereal farming with little or no emissions mitigation practices. As a result, ECOWAS produces the highest cereals (48.1 million metric tons), and roots and tubers (123 million metric tons). In addition, the bloc has the largest average rural population (167 million people) engaging in unfriendly environmental agricultural activities such as the burning of crop residues [3]. In the AMU member states, the highest amount of vegetables (25.7 million metric tons) and fruits (32.1 million metric tons) are high-emitters and users of fertilizers (technology). This further explains why the AMU member states spend the largest amount of money on technology (USD 201.35 billion) [99].

Table 3. Summary statistics.

Variable	AMU	EAC	ECOWAS	SADC	Full Sample	Means
	Mean	Mean	Mean	Mean	Mean	Highest Mean Difference (RTB)
Methane (In kilotons)	307.29 (56.90)	10.45 (3.50)	574.89 (228.59)	265.95 (31.36)	38.62 (77.89)	564.44 ^{+,*} (ECOWAS)
Nitrous oxide (In kilotons)	42.13 (7.66)	3.58 (1.31)	23.12 (8.08)	15.53 (29.00)	2.81 (5.54)	38.55 ^{-,*} (AMU)
Cereals (In million metric tons)	41.4 (8.88)	4.47 (1.05)	48.1 (13.2)	20.1 (4.95)	3.80 (5.81)	43.7 ^{+,*} (ECOWAS)
Roots and tubers (In million metric tons)	22.4 (5.16)	7.80 (2.64)	123.0 (45.6)	20.4 (6.58)	5.79 (16.0)	115 ^{+,*} (ECOWAS)
Vegetables (In million metric tons)	25.7 (7.66)	2.73 (0.88)	17.1 (6.44)	4.39 (1.48)	1.66 (3.18)	23.0 ^{-,*} (AMU)
Fruits (In million metric tons)	32.1 (8.64)	7.174 (1.68)	20.9 (6.55)	9.967 (3.82)	2.34 (3.15)	24.9 ^{-,*} (AMU)
Rural population (Per million people)	130.05 (22.28)	45.04 (9.44)	167.23 (26.71)	61.16 (7.68)	13.45 (17.08)	122.19 ^{+,*} (ECOWAS)
Technology (In US\$ billion)	201.35 (126.10)	15.58 (15.67)	8.79 (86.12)	113.26 (92.83)	13.94 (33.77)	185.77 ^{-,*} (AMU)

Source: Computed by the Author Legend: ⁽⁺⁾ positive, and ⁽⁻⁾ negative mean differences, * represents statistical significance, and standard deviations in parentheses. NOTE: Summary statistics for individual member states are in Appendix A Table A1.

An analysis of the individual indicators reveals that the low and similar differences in means between the SADC and the EAC member states in terms of fruit, and vegetable production suggest that these regional trading bloc members share similar agro-ecological conditions, farming practices, and agricultural policies. However, there are differences in the means for cereal production across the regional trading bloc member states. The ECOWAS members have the highest positive mean difference. This signifies variation in terms of the scale of farming, and the intensity of fertilizer usage. There is also a large variation in the rural population across the regional trading bloc members, with the ECOWAS members displaying the highest positive value. The variation in the variables symbolize the disparity in farm-gate CH₄ and N₂O emissions and their drivers across the regional trading bloc member states.

4.2. Diagnostic Tests of Variables in the Primary Regression Models

Multicollinearity represents a high degree of linear intercorrelation between explanatory variables in a multiple regression model and leads to incorrect results of regression analyses. The most common diagnostic tools of multicollinearity is the variance inflation factor (VIF). To check for the presence of multicollinearity, we observe the value of VIF. A VIF value higher than 5 to 10 signifies the presence of multicollinearity [100]. The results in Table 4 show that the mean VIF is 4.98, which is less than 10. This means that there is the absence of severe multicollinearity in the exogenous variables. Thus, validates the assumption of independence of the explanatory variables in (Equation (13)).

Table 4. Test for multicollinearity.

Variable	VIF	1/VIF
<i>ln</i> of rural population	8.8	0.1137
<i>ln</i> of vegetables	6.29	0.1590
<i>ln</i> of fruits	5.55	0.1803
<i>ln</i> of cereals	4.5	0.2220
<i>ln</i> of roots and tubers	3.17	0.3152
<i>ln</i> of technology	1.55	0.6447
Mean VIF	4.98	

Source: Computed by the Author.

In the regression approach, the existence of CD is tested. The [67] test is employed to determine the correlation between the RTB member states because it is suitable for unbalanced panels and more robust than the [101] CD test. The null hypothesis in this test is a weak CD between the RTB member states. From Table 5, the probability values of the variables in the CH₄ and N₂O models are statistically significant at the 1% level. Hence, the null hypothesis of a weak CD is rejected, and confirms the existence of a strong CD across the panels in both equations.

Table 5. Test for cross-sectional dependence.

Variable	CD Test for Methane	Variable	CD Test for Nitrous Oxide
<i>ln</i> of methane	26.349 ^a	<i>ln</i> of nitrous oxide	55.142 ^a
<i>ln</i> of cereals	34.751 ^a	<i>ln</i> of cereals	34.751 ^a
<i>ln</i> of roots and tubers	52.788 ^a	<i>ln</i> of roots and tubers	52.788 ^a
<i>ln</i> of vegetables	55.012 ^a	<i>ln</i> of vegetables	55.012 ^a
<i>ln</i> of fruits	48.092 ^a	<i>ln</i> of fruits	48.092 ^a
<i>ln</i> of rural population	61.085 ^a	<i>ln</i> of rural population	61.085 ^a
<i>ln</i> of technology	80.315 ^a	<i>ln</i> of technology	80.315 ^a

Source: Computed by the Author Legend: ^a significant at 1%.

Since there is a CD, the [69] second-generation unit root test ($Z[t\text{-bar}]$) is used. The test is based on the average of the particular Dickey–Fuller (or Augmented Dickey–Fuller) t-statistics from each panel unit for constant term and trend in level and first difference. According to the null hypothesis, every variable is non-stationary. From Tables 6 and 7, the variables are stationary at the level for the “constant” and “constant and trend.” However, roots and tubers, and technological variables are non-stationary at the level of the “constant.” Similarly, technology also has a unit root at the level of the “constant and trend.” Conclusively, there is mixed integration of order one and zero. However, all variables are integrated to order one for both “constant” and “constant and trend” in the CH₄ and N₂O models.

Furthermore, a test for slope heterogeneity is performed. The test null hypothesis is that the slope coefficients are uniform. The coefficients are statistically significant at the 1% level, rejecting the null hypothesis and declaring the presence of heterogeneous slopes among the panels (Table 8).

For the CH₄ emissions model, Table 9 shows that for the one versus no structural breaks, two versus one structural break, and three versus two structural break hypotheses tested, the t-statistic is below the critical values at 1%, 5%, and 10% levels of statistical

significance. Thus, the null hypotheses cannot be rejected and conclude that there is a stable trend in the data structure. Similarly, data on the N₂O emissions for the first break [F(1/0)] does not detect any statistically significant shift in the data structure. However, the data structure strongly supports the second and third breaks over their respective lags. Thus, over time, there are significant breaks in the N₂O data in 1999, 2006, and 2015. These breaks may be associated with the credit crunch in 2007 and the commitment made by member states to reduce emissions in 2015.

Table 6. Pescadf unit root test for the methane model.

Variables	Constant		Constant and Trend	
	Level	First Difference	Level	First Difference
<i>ln</i> of methane	−7.095 ^a	−16.806 ^a	−5.707 ^a	−14.532 ^a
<i>ln</i> of cereals	−5.751 ^a	−17.52 ^a	−4.699 ^a	−15.825 ^a
<i>ln</i> of roots and tubers	−1.413	−15.427 ^a	−1.893 ^a	−13.645 ^a
<i>ln</i> of vegetables	−2.461 ^a	−12.72 ^a	−0.161 ^a	−7.596 ^a
<i>ln</i> of fruits	−2.675 ^a	−13.738 ^a	−1.85 ^a	−12.591 ^a
<i>ln</i> of rural population	−13.496 ^a	−7.413 ^a	−6.75 ^a	−7.037 ^a
<i>ln</i> of technology	−1.321	−14.068 ^a	1.468	−12.282 ^a

Source: Computed by the Author Legend: ^a significant at 1%.

Table 7. Pescadf unit root test for nitrous oxide model.

Variables	Constant		Constant and Trend	
	Level	First Difference	Level	First Difference
<i>ln</i> of nitrous oxide	−2.991 ^a	−16.515 ^a	−2.326 ^a	−14.148 ^a
<i>ln</i> of cereals	−5.751 ^a	−17.52 ^a	−4.699 ^a	−15.825 ^a
<i>ln</i> of roots and tubers	−1.413	−15.427 ^a	−1.893 ^a	−13.645 ^a
<i>ln</i> of vegetables	−2.461 ^a	−12.72 ^a	−0.161 ^a	−7.596 ^a
<i>ln</i> of fruits	−2.675 ^a	−13.738 ^a	−1.85 ^a	−12.591 ^a
<i>ln</i> of rural population	−13.496 ^a	−7.413 ^a	−6.75 ^a	−7.037 ^a
<i>ln</i> of technology	−1.321	−14.068 ^a	1.468	−12.282 ^a

Source: Computed by the Author Legend: ^a significant at 1%.

Table 8. Slope heterogeneity test for methane and nitrous oxide models.

	Methane	Nitrous Oxide
	Delta	Delta
Adjusted delta	23.768 ^a	16.384 ^a
	27.371 ^a	18.867 ^a

Source: Computed by the Author Legend: ^a significant at 1%.

From the diagnostic tests, the presence of CD, structural/no structural breaks, and heterogeneous slope coefficients were confirmed in Equations (3) and (4). Hence, the CS-ARDL model is employed to address these issues jointly.

Table 9. Bai & Perron test for structural breaks.

	Methane			Nitrous Oxide		
	F(1/0)	F(2/1)	F(3/2)	F(1/0)	F(2/1)	F(3/2)
T—Statistic	1.71	2.26	2.39	2.62	6.97	6.62
1% Critical value	5.69	6.24	6.53	5.69	6.24	6.53
5% Critical value	4.35	4.88	5.2	4.35	4.88	5.2
10% Critical value	3.72	4.32	4.65	3.72	4.32	4.65
Detected number of breaks:	0	0	0	3	3	3

Source: Computed by the Author. F is the F statistic, F(1/0) means no evidence of at least one break; F(2/1) strong evidence of at least two breaks; F(3/2) strong evidence of at least three breaks. Three cases are considered: cereals, roots, and tubers, and fruit, due to the length of the period being less than the number of variables. The lag of the cases is taken into account for the dynamism of the model. The cross-sectional means of the first difference in the lag of the cases are incorporated to account for cross-sectional dependence and the standard error for the robustness of the result: Set trimming to 0.25 for at most 3 breaks.

4.3. Crop Production and Farm-Gate Emissions: Short- and Long-Run Relationships

The study examined the short- and long-run effects of crop production on farm-gate emissions in selected RTB member states in Africa. This objective is achieved by defining crop production as cereals, roots and tubers, vegetables, and fruit production and separating emissions into methane and nitrous oxide emissions. The CS-ARDL model, which is dynamic, controls for CD, slope heterogeneity, serial correlation, structural breaks, and endogeneity [77] is employed to estimate model (16).

4.3.1. Crop Production and Methane Emissions: Short- and Long-Run Relationships

Table 10 shows that all crop products have a positive sign, except roots and tubers. This means that roots and tubers are the only products with the potential to reduce methane emissions at the farm-gate level in the RTB member states. However, cereals and fruit products are the crop products that affect methane emissions in the short and long run. The lag of methane emissions is also significant, validating the specification of a dynamic model. Analytically, cereals have short-run proportional change coefficients of 1.0021 and 1.0033 for the long term. This means that an increase in cereal output will result in 1.0021 and 1.0033 kilotons of CO₂ equivalent rise in farm-gate methane emissions in the short and long run, respectively, on average in a year. Thus, the production of cereals is a significant contributor to farm-gate emissions. In the long-run, its contribution increases by 0.0012 kilotons of CO₂ equivalent emissions, yearly. Likewise, fruit production makes a positive contribution to farm-gate methane emissions in the RTB member states, both in the short and long run. Fruit production has a short-run proportional change coefficient of 1.0019 and a long-run proportional change coefficient of 1.0023. This indicates that fruit production significantly increases farm-gate methane emissions in both the short and long term. Additionally, the increase in farm-gate methane emissions caused by fruit production is exacerbated in the long run by 0.004 kilotons of CO₂ equivalent emissions on average, yearly. This implies that fruit production is a significant contributor to farm-gate methane emissions. The lag of emissions has a co-efficient of 0.8664. This coefficient shows that past emissions are correlated with present emissions, hence the estimated model is dynamic. Further-more, the negative error correction term [ECM (−1)] with a speed of adjustment of 0.866 confirms the presence of a long-run relationship, implying that approximately 87% of disequilibrium in emissions is corrected annually through policies geared towards reducing methane emissions and negative shocks. The F-statistic has a coefficient of 2.78, which means that the model has a good fit.

Table 10. CS-ARDL Crop production and methane emissions results.

Variable	Short-Run Elasticity Coefficient	Short-Run Proportional Change Coefficient	Long-Run Elasticity Coefficient	Long-Run Proportional Change Coefficient
<i>ln</i> of Cereals	0.4746 ^a (−0.0838)	1.0021	0.7739 ^a (−0.2882)	1.0033
<i>ln</i> of Roots and tubers	−0.1425 (−0.1657)	0.9994	−0.162 (−0.1808)	0.9993
<i>ln</i> of Vegetables	0.1651 (−0.1059)	1.0007	0.2923 (−0.2462)	1.0013
<i>ln</i> of Fruits	0.4472 ^a (−0.1394)	1.0019	0.5403 ^a (−0.192)	1.0023
<i>ln</i> of Rural population	−0.1045 (−0.4731)	0.9995	−0.3394 (−0.581)	0.9985
<i>ln</i> of Technology	−0.0152 (−0.0244)	0.9999	−0.0234 (−0.0319)	0.999
Lag of emissions	0.1336 ^a (−0.05)			
Error correction term	−0.8664 ^a (0.4998)			
F-statistic	2.78 ^a			
Number of observation	949			
Number of member states	30			

Source: Computed by the Author Legend: ^a significant at 1%, standard error in parentheses.

4.3.2. Crop Production and Nitrous Oxide Emissions: Short- and Long-Run Relationships

Cereals and the production of fruit have a positive influence on the emissions of nitrous oxide in the short term. However, cereals are the sole contributors that may account for nitrous oxide emissions in the long term (Table 11). The positive signs on the coefficients of cereals and fruits show that they are the crops that drive farm-gate nitrous oxide emissions in the member states of the regional trading blocs. Specifically, an increase in cereal production will result in a 1.0024 and 1.0035 kilotons of CO₂ equivalent emissions increase in nitrous oxide on average in a year in the short and long run, respectively. Table 11 also shows that fruit production has a proportional change coefficient of 1.0025. Thus, a move to increase fruit production by a percentage point will result in an average yearly rise of 1.0025 kiloton of CO₂ equivalent emissions in nitrous oxide in the short run. The error correction term is −0.8422. This depicts a long-run relationship and an 84.22 percent disequilibrium adjustment of nitrous oxide emissions after a shock every year. Moreover, the lag of the emissions coefficient is 0.1578 and statistically significant at the 1% level. This implies that previous years' emissions explain present emissions, hence confirming the use of a dynamic model. The F-statistic coefficient is statistically significant, representing the overall goodness of fit of the nitrous oxide regression model.

Table 11. CS-ARDL Crop production and nitrous oxide emissions results.

Variable	Short-Run Elasticity Coefficient	Short-Run Proportional Change Coefficient	Long-Run Elasticity Coefficient	Long-Run Proportional Change Coefficient
<i>ln</i> of Cereals	0.5229 ^a (−0.1096)	1.0024	0.8115 ^a (−0.2442)	1.0035
<i>ln</i> of Roots and tubers	0.2877 (−0.3431)	1.0012	0.3939 (−0.5061)	1.0017
<i>ln</i> of Vegetables	0.0251 (−0.1343)	1.0001	0.1252 (−0.1647)	1.0005

Table 11. Cont.

Variable	Short-Run Elasticity Coefficient	Short-Run Proportional Change Coefficient	Long-Run Elasticity Coefficient	Long-Run Proportional Change Coefficient
<i>ln</i> of Fruits	0.5784 ^b (−0.2903)	1.0025	0.6375 (−0.5519)	1.0028
<i>ln</i> of Rural population	0.9891 (−1.29)	1.0043	0.6514 (−1.5189)	1.0028
<i>ln</i> of Technology	0.0131 (−0.016)	1.0001	0.0089 (−0.234)	1.0000
Lag of emissions	0.1578 ^a (−0.0439)			
Error correction term	−0.8422 ^a (−0.0439)			
F-statistic	1.44 ^a			
Observation	949			
Member states	30			

Source: Computed by the Author Legend: ^a, significant at 1%, ^b significant at 5%, standard error in parentheses.

4.3.3. Comparative Results of Short- and Long-Run Methane and Nitrous Oxide Models

Cereals are the sole crop categories that give significant positive proportional effects on both methane and nitrous oxide emissions. Their impacts are smaller in quantity but more pronounced over longer periods than over short-term periods. Fruit production's immediate impact on nitrous oxide is relatively substantial but less compared with the methane model results. However, in the long-run fruit production only explains emissions in the methane model (Table 12).

Table 12. Comparative short- and long-run methane and nitrous oxide emission results.

Variable	Methane Emissions		Nitrous Oxide Emissions	
	Short-Run	Long-Run	Short-Run	Long-Run
	Proportional Change Coefficient	Proportional Change Coefficient	Proportional Change Coefficient	Proportional Change Coefficient
<i>ln</i> of cereals	1.0021 ^a	1.0033 ^a	1.0024 ^a	1.003 ^a
<i>ln</i> of roots and tubers	0.9994	0.9993	1.0012	1.0017
<i>ln</i> of vegetables	1.0007	1.0013	1.0001	1.0005
<i>ln</i> of fruits	1.0019 ^a	1.0023 ^a	1.0025 ^b	1.0028
<i>ln</i> of rural population	0.9995	0.9985	1.0043	1.0028
<i>ln</i> of technology	0.9999	0.999	1.0001	1.0000

Source: Computed by the Author Legend: ^a, significant at 1%, ^b, significant at 5%.

4.4. Robustness Checks: Pooled Mean Group

The PMG estimator was proposed by [102]. It is a dynamic model that permits group differences in short-run coefficients and error variances while constraining long-run coefficients to be the same. This estimation technique is robust because cross-sectional units can be pooled and also averaged. Table 13 shows the results of the PMG model. The results suggest that the cereals variable has a positive sign in the short and long run for the methane and nitrous oxide emissions models. These results confirmed the findings presented in Table 10 for cereal production. In addition, the positive fruit production effect

on methane emissions is also confirmed in the long run (Table 10). However, vegetables, the rural population, and technology also have long-run effects on methane emissions.

Table 13. PMG Crop production and methane emissions results.

Variable	Short-Run Elasticity Coefficient	Short-Run Proportional Change Coefficient	Long-Run Elasticity Coefficient	Long-Run Proportional Change Coefficient
<i>ln</i> of Cereals	0.2971 ^a (−0.0634)	1.0013	0.3156 ^a (−0.046)	1.0014
<i>ln</i> of Roots and tubers	0.0548 (−0.0675)	1.0002	−0.0524 (−0.0383)	0.9998
<i>ln</i> of Vegetables	0.1134 (−0.089)	1.0005	−0.0854 ^b (−0.0405)	0.9996
<i>ln</i> of Fruits	0.2068 (−0.1284)	1.0009	0.2171 ^a (−0.0427)	1.0009
<i>ln</i> of Rural population	−3.5268 (−5.5204)	0.9849	1.1926 ^a (−0.1126)	1.0052
<i>ln</i> of Technology	−0.0025 (−0.0096)	1.0000	−0.0240 ^b (−0.0109)	0.9999
Error correction term	−0.3925 ^a (−0.0523)			
Number of observations	949			
Member states	30			

Source: Computed by the Author Legend: ^a significant at 1%, ^b significant at 5%, standard error in parentheses.

Similarly, from Table 14, the short- and long-run effect of cereal production are confirmed in the nitrous oxide emissions model (Table 11). However, technology is a short-run drivers of nitrous oxide emissions, while the rural population and fruit production are long-run drivers.

Table 14. PMG Crop production and nitrous oxide emissions results.

Variable	Short-Run Elasticity Coefficient	Short-Run Proportional Change Coefficient	Long-Run Elasticity Coefficient	Long-Run Proportional Change Coefficient
<i>ln</i> of Cereals	0.2921 ^a (−0.0861)	1.0013	0.4077 ^a (−0.0438)	1.0018
<i>ln</i> of Roots and tubers	0.246 (−0.2246)	1.0011	0.049 (−0.0364)	1.0002
<i>ln</i> of Vegetables	0.1199 (−0.1106)	1.0005	0.0359 (−0.0392)	1.0002
<i>ln</i> of Fruits	0.0376 (−0.1161)	1.0002	0.1683 ^a (−0.028)	1.0007
<i>ln</i> of Rural population	4.9843 (−2.71466)	1.0218	0.7300 ^a (−0.0949)	1.0032
<i>ln</i> of Technology	0.0286 ^a (−0.0103)	1.0001	0.014 (−0.0144)	1.0001
Error correction term	−0.44144 ^a (−0.0586)			

Table 14. Cont.

Variable	Short-Run Elasticity Coefficient	Short-Run Proportional Change Coefficient	Long-Run Elasticity Coefficient	Long-Run Proportional Change Coefficient
Number of observations	949			
Member states	30			

Source: Computed by the Author Legend: ^a significant at 1%, standard error in parentheses.

4.5. Sensitivity Analysis

The “technology” variable is captured in this study to understand the role of agricultural expenditure in explaining emissions. However, the inclusion of various sources of agricultural expenditure into a single measure risks difficulty in its interpretation. To overcome this challenge, a sensitivity analysis is conducted using “irrigation” as a proxy for technology in the CH₄ (model 3) and N₂O (model 4) emission models. The irrigation variable is employed as a proxy for technology in line with the substantial growth in irrigation investment in Africa, to increase the percentage of cultivated land that is fitted for irrigation from 6 percent, thereby closing the yield gap [83,103]. The models (3 and 4) were estimated using the CS-ARDL to validate the results of the technology variable in Tables 10 and 11. The estimated results for both models are presented in Table 15. The level of statistical significance of the irrigation variable is predominantly above 10 percent in the CH₄ and N₂O emissions models in both the short and long run. Thus, the insignificance of the irrigation variable bolsters the primary results, suggesting that technology does not play a role in determining farm-gate CH₄ and N₂O in Africa’s RTB member states’ Nationally Determined Contributions.

Table 15. Sensitivity analysis (Using irrigation as a proxy for technology).

Variable	Methane Model				Nitrous Oxide Model			
	Short-Run Elasticity Coefficient	Proportional Change Coefficient	Long-Run Elasticity Coefficient	Proportional Change Coefficient	Short-Run Elasticity Coefficient	Proportional Change Coefficient	Long-Run Elasticity Coefficient	Proportional Change Coefficient
Irrigation	−0.288 (0.267)	0.9970	−0.380 (0.393)	0.9962	−0.045 (0.447)	0.9996	−0.051 (0.484)	0.9995
Control Variables	Controlled							
F-statistic	2.58 ^a				1.1			
Error correction term	−0.928 ^a (0.048)				−0.998 ^a (0.033)			
Observation					960			
Member states					30			

Source: Computed by the Author Legend: ^a significant at 1%, standard error in parentheses.

4.6. Mediating-Effect Results

4.6.1. Crop Production-Methane Emissions Action Mechanism Results

Crop production can significantly promote farm-gate CH₄ and N₂O emissions. The study selected area harvested and cereal emission intensity as intermediary variables in order to thoroughly examine and validate the crop production action mechanism influencing farm-gate CH₄ and N₂O emissions in Africa’s RTB member states.

Table 16 presents results for crop production, area harvested, and cereal emission intensity in the short and long term [104]. The results also show that crop production has a significantly positive effect on the area harvested due to the expansion of arable land caused by agricultural land use intensification. Furthermore, the area harvested and CH₄ emission coefficients are significantly positive in both the short and long run.

However, the proportional change coefficient of crop production (SR 1.0049 and LR 1.0068) (Where SR is short run and LR, long run) is less than the estimated results (The sum of the statistically significant sub-crops.) (SR 2.0040 and LR 2.0056) in Table 10. This implies that area harvested plays a partial intermediary role in the impact of crop production on farm-gate CH₄ emissions of Africa's RTB members' Nationally Determined Contributions in the short and long run.

Table 16. Results for crop production-methane emissions mechanism test.

Variables	Area Harvested		Cereal Emission Intensity		Methane	
	Short Run	Long Run	Short run	Long Run	Short Run	Long Run
	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient
Crop production	0.488 ^a (0.073) [1.0049]	0.676 ^a (0.074) [1.0068]	−0.090 (0.0883) [0.9991]	−0.147 (0.187) [0.9985]	-	-
Control variables	Controlled					
Lag	−0.304 ^a 0.051		0.383 ^a (0.055)	-	-	-
Error correction term	−0.696 ^a (0.051)		−0.617 ^a (0.055)	-	-	-
F-statistic	9.66 ^a		1.48 ^a	-	-	-
Area harvested	-		-	-	0.834 ^a (0.105) [1.0084]	1.174 ^a (0.167) [1.0118]
Cereal emission intensity	-		-	-	0.058 (0.074) [1.0006]	0.134 (0.092) [1.0013]
Control variables	Controlled					
Lag	-		-		0.181 ^a (0.052)	-
Error correction term	-		-		−0.819 ^a (0.052)	-
F-statistic					9.62 ^a	-
No. of observations	960					
Number of groups	30					

Source: Computed by the Author Legend: ^a significant at 1%, standard error in parentheses, and proportional change coefficient in bracket.

4.6.2. Crop Production-Nitrous Oxide Emissions Action Mechanism Results

Similarly, the study examined the mediating effect of area harvested and cereal emission intensity on the promotion of farm-gate N₂O emissions in Africa's RTB member states. Table 17 presents regression results for crop production and area harvested on the one hand, and area harvested, cereal emission intensity, and farm-gate N₂O emissions on the other hand. The results show that area harvested promotes farm-gate N₂O emissions at a 1 percent level of statistical significance. In parallel, area harvested directly promotes farm-gate N₂O emissions at a statistical significance level of 1 percent. Moreover, the crop production proportional change coefficients (SR 2.0049 and LR 1.0035) in Table 11 are greater than the estimated result in the short run (1.0049) but less than the long run (1.0068) result in Table 17. This indicates that area harvested plays a partial intermediary role in the short run, but a full mediation role in the long run, in the effect of crop production on farm-gate N₂O emissions in Africa's RTB members' Nationally Determined Contributions.

Table 17. Results for crop production- nitrous oxide emissions mechanism test.

Variables	Area Harvested		Cereal Emission Intensity		Nitrous Oxide	
	Short Run	Long Run	Short Run	Long Run	Short Run	Long Run
	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient
Crop production	0.488 ^a 0.073 [1.0049]	0.676 ^a 0.074 [1.0068]	−0.090 (0.0883) [0.9991]	−0.147 (0.187) [0.9985]		
Controlled variables						
Lag	0.304 ^a 0.051		0.383 ^a 0.055			
Error correction term	0.696 ^a 0.051		−0.617 ^a 0.055			
F-statistic	9.66 ^a		1.48 ^a			
Area harvested					0.701 ^a 0.112 [1.0069]	0.882 ^a 0.139 [1.0079]
Cereal emission intensity					0.173 0.073 [1.0042]	0.27 0.124 [1.0051]
Control variables			Controlled			
Lag					0.249 ^a (0.044)	
Error correction term					−0.751 ^a 0.044	
F-Statistic					4.22 ^a	
No. of observations			960			
No. of groups			30			

Source: Computed by the Author Legend: ^a significant at 1%, standard error in parentheses, and proportional change coefficient in bracket.

5. Discussion

Attaining net zero emissions by 2050 requires a reduction in the emission of greenhouse gases. However, results from the cross-sectionally augmented autoregressive distributed lag estimation technique, as well as pooled mean group analyses, consistently show that cereal production promotes farm-gate methane emissions in both the short and long run in Africa's regional trading bloc member states. Specifically, a standard deviation increase in cereal production will result in a rise in farm-gate methane emissions of 1.0021 and 1.0033 kilotons of carbon dioxide equivalent year^{−1} on average in the short and long run, respectively. This is because the underlying drivers of methane emissions, such as agronomic and biogeochemical mechanisms, respond immediately to managerial strategies and continuously develop over time [5,105].

The short-run effect of cereals, especially rice, on farm-gate methane emissions is indicative of Africa's expanding irrigated and lowland rice cultivation, leading to an increase in methane due to the swift response of methanogens to increases in flooded rice fields and intensity. This effect is exacerbated in the long-run by the continuous cultivation of cereals in waterlogged farmlands, the production of agricultural byproducts such as rice straw, incomplete combustion of burnt remnants, and the burning of crop residues, which accumulate soil organic matter and lock in emissions-intensive irrigation systems [105–107]. This finding aligns with [4,25], which suggested that crop production contributes directly to methane emissions through the use of conventional flooding methods. This finding is also consistent with the results of [108–110], which showed that increasing grain production

leads to increased agricultural emissions due to the expensive coupling interruption of decoupling activities and the adoption of inefficient agricultural practices.

Similarly, cereals also drive nitrous oxide emissions in Africa's regional trading bloc member states. This is because of their significant positive proportional change value. Hence, a move by Africa's regional trading bloc member states to increase cereal production by a standard deviation will lead to a 1.0024 and 1.0035 kilotons of CO₂ equivalent yr⁻¹ on average rise in farm-gate nitrous oxide emissions in the short- and long-run, respectively. The increase in nitrous oxide emissions is higher in the long-run because of the intensification and expansion of cereal production, which generally require additional application of nitrogen fertilizer in the cultivated areas. And the retaining conditions that encourage nitrous oxide-producing microbial processes, which result in an increase in farm-gate nitrous oxide emissions [111].

The underlying mechanism for the short-run results is that Africa's yields are low; thus, intensifying cereal farming to close the yield gap requires a higher rate of application per hectare of synthetic fertilizer, manure, or both. Consequently, with moist soils, the new nitrogen is quickly converted by soil bacteria, which drives fertilizer-induced farm-gate nitrous oxide emissions [112]. In the long-run, even when current-year fertilizer does not increase, "legacy nitrogen" tends to promote nitrification–denitrification and high nitrous oxide emissions because recurrent fertilizer uses and retained residues generate soil nitrogen stocks. Therefore, with additional nitrous oxide-emitting areas on top of previously intensified land, increasing grains in fresh cropland increases the fertilized field, which increases emissions [111,113,114]. The result supports the findings of [4,22,26], which revealed that cereals such as rice, wheat, and maize in mixed order are significant drivers of nitrous oxide emissions in mono-cropping, intercropping, early, late, and double-cropping. Furthermore, this study finding aligns with [115], who stated that differences in temperature requirements for crops grown accounted for the accumulation of more nitrous oxide emissions by cereals compared to legumes. However, [116] findings suggested that nitrous oxide emissions were reduced through the correct selection of cereal varieties and sustainable agricultural practices.

In addition to cereals, fruit production is identified as a long-run driver of methane emissions. It has a positive long-run proportional change coefficient, indicating that higher fruit output results in a 1.0023 kilotons of CO₂ equivalent increase in farm-gate methane emissions on average per year. This is likely because in the long term, continuous covering with mulch, leaves, droppings, and root turnover causes perennial orchards to accumulate large quantities of soil and waste carbon, thus creating a developing basal reservoir that may generate methane if soils are moist or inadequately aerated [117,118]. The study results in [30] confirmed that fruit production can deplete water resources as a result of shifting demand for crops that require adequate water, such as avocado. In summary, cereals drive both methane and nitrous oxide emissions over time, while fruits mainly affect methane emissions. Policymakers in agriculture, climate, and trade should consider these relationships when developing strategies to increase output, promote trade, and mitigate these emissions.

Comparative analyses of the methane and nitrous oxide emission models revealed that cereal and fruit production drives farm-gate methane and nitrous oxide emissions in the regional trading bloc member states. Cereals are notorious for emitting both methane and nitrous oxide in the short and long term. However, the effect of cereals on nitrous oxide emissions is more pronounced than on methane emissions. This result is not striking because the increase in the area under cereal cultivation and application of fertilizer are strongly associated with rises in nitrous oxide emissions across the regional trading bloc's member states. On the contrary, agricultural activities such as rice cultivation or

occasionally flooded crop fields cause less significant methane emissions. Refs. [110,119] supported these findings by demonstrating that agriculture-related nitrous oxide emissions are strongly driven by cereal cultivation and fertilizer use, even though methane emissions tend to be more closely linked with cereals through shifts in land use or organic management. In addition, fruit production drives methane, but not nitrous oxide emissions, in the long run. This is because, in contrast to temporary nitrous oxide emission spikes from seasonal crop cultivation, fruit farming promotes long-term soil microbial accumulation that generates methane under permanent cover, thus increasing methane over time without a proportionate increase in nitrous oxide emissions [120].

Regarding mediation, it is believed that cropland expansion and production systems may be linked through which crop production can affect farm-gate methane and nitrous oxide emissions. Thus, by taking the area harvested and cereal emission intensity as proxies for cropland expansion and production systems, respectively, the action mechanisms were investigated. The results suggest that the effect of crop production on farm-gate CH₄ emissions of Africa's RTB members' Nationally Determined Contributions in the short and long term is somewhat mediated by harvested area. Additionally, the impact of crop production on farm-gate N₂O emissions in Africa's RTB members' Nationally Determined Contributions is partially mediated by the area harvested in the short term but fully mediated in the long term.

6. Conclusions

The study employed the STIRPAT model, which considers multiple drivers of emissions and is more appropriate in determining causal short- and long-run effects of crop production on farm-gate emissions in the regional trading bloc member states in Africa. The study focused primarily on the root causes of agricultural emissions by zooming into the different sub-components of the crop sector, such as cereals, roots and tubers, and fruits, and linking them to emissions (methane and nitrous oxide) at the farm-gate level. Furthermore, the robust CS-ARDL technique was employed to ensure the reliability of the study findings. The results revealed that cereal production increases farm-gate methane and nitrous oxide emissions in Africa's regional trading bloc member states' Nationally Determined Contributions in the short and long run. The increase is between the range of 1.0021 and 1.0033 kilotons for methane and 1.0024 and 1.0035 kilotons for nitrous oxide emissions per year. Thus, cereal production has a more adverse effect on nitrous oxide than methane emissions. In addition, fruit production increases farm-gate methane emissions, in Africa's regional trading bloc member states' Nationally Determined Contributions by an average yearly rise of 1.0023 kilotons in the long run. With respect to mediation, cropland expansion (proxied by area harvested) plays a partial intermediary role in the impact of crop production on farm-gate methane and nitrous oxide emissions in the short run and methane emissions in the long run. However, it assumes a full mediation role in the long run in the effect of crop production on farm-gate N₂O emissions in Africa's RTB members' Nationally Determined Contributions.

Based on the empirical findings, several recommendations are made. First, there is a need to have a targeted use of nitrogen fertilizer and crop rotations to reduce cereal-related nitrous oxide and methane emissions. Second, promote the use of a drip irrigation system for fruit to reduce long-term methane emissions, and third, advocate for the scaling up of secured subsidies and incorporation of the other recommendations into the African Union's Agenda 2063 and in Africa's RTB member states' Nationally Determined Contributions.

Notwithstanding, this study has limitations. Notably, since the crop sub-sector is a fraction of the agricultural sector, other sub-sectors like livestock and forestry that also have the potential to drive farm-gate emissions should be studied for a comprehensive analysis

of farm-gate emissions in the agricultural sector. However, they are excluded because the focus of this study is to provide a detailed investigation that is manageable, robust, and free from excessive complexities. Thus, this study lays the foundation for future research in the livestock and forestry sub-sectors. Again, aside from farm-gate emissions, we have pre- and post-crop production emissions, which we do not account for; hence, it also serves as a potential area for future research. Lastly, the reliability of the findings may be limited due to the use of data from the FAOSTAT database despite the flaws associated with its collection, computation, and related uncertainties.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Showing summary statistics for member states.

RTB	Methane	Nitrous Oxide	Cereals	Roots & Tubers	Vegetables	Fruits	Population	Technology
Arab Maghreb Union Member States								
Algeria	1.91	2.20	3,379,664.00	2,607,641.00	3,903,938.00	3,739,872.00	12,040.52	908.71
	0.44	0.69	1,406,411.00	1,593,811.00	2,139,947.00	2,097,809.00	487.55	785.53
	0.95	1.05	870,017.00	715,936.00	1,300,588.00	1,242,788.00	11,247.75	−584.33
	2.88	3.45	6,066,239.00	5,020,249.00	7,986,966.00	7,071,434.00	12,718.63	2584.07
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Egypt	165.89	27.35	20,100,000.00	3,760,665.00	13,600,000.00	11,100,000.00	45,550.75	111,816.00
	23.37	4.54	3,288,880.00	1,745,015.00	3,373,522.00	3,181,650.00	8533.03	71,348.61
	105.15	18.13	13,000,000.00	1,600,411.00	7,459,974.00	5,977,551.00	32,450.63	735.77
	213.82	32.85	24,100,000.00	7,712,031.00	18,800,000.00	16,000,000.00	60,691.93	237,047.70
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Morocco	5.50	6.34	6,476,768.00	1,452,429.00	3,434,894.00	4,305,758.00	13,440.26	60,297.24
	0.77	1.38	2,974,395.00	353,152.40	847,129.70	1,277,107.00	264.37	40,605.30
	3.39	3.61	1,783,230.00	894,210.10	1,907,077.00	2,337,928.00	12,839.86	183.64
	7.21	9.34	11,700,000.00	1,967,534.00	4,491,362.00	6,618,471.00	13,688.17	126,623.00
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Tunisia	0.80	1.93	1,725,829.00	337,181.80	2,092,994.00	1,679,399.00	3548.36	20,842.69
	0.23	0.40	592,995.90	76,908.41	729,207.20	442,289.30	48.18	10,423.03
	0.32	1.04	550,525.50	199,000.00	1,096,862.00	1,049,565.00	3462.24	101.82
	1.35	2.92	2,896,345.00	465,000.00	3,219,344.00	2,530,206.00	3622.88	43,107.63
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
East African Community Member States								
Burundi	2.33	0.25	384,242.20	2,198,305.00	348,509.80	1,592,571.00	7330.45	364.06
	1.22	0.13	278,550.40	1,070,159.00	115,611.10	312,135.20	1799.81	319.30
	1.06	0.15	224,724.00	1,262,722.00	210,000.00	957,109.60	5075.81	1.26
	5.03	0.55	1,581,835.00	4,419,890.00	498,160.50	2,355,697.00	10,848.08	1493.66
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Kenya	6.48	2.97	3,571,863.00	2,877,909.00	1,959,503.00	2,652,795.00	29,252.15	13,663.48
	1.45	1.05	725,022.50	1,035,765.00	600,950.90	863,644.30	6204.77	13,785.90
	4.70	1.66	2,539,301.00	1,437,978.00	743,080.00	1,400,923.00	19,483.07	72.99
	8.73	5.55	4,881,251.00	4,734,181.00	3,359,488.00	4,468,921.00	39,817.14	54,593.73
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00

Table A1. Cont.

RTB	Methane	Nitrous Oxide	Cereals	Roots & Tubers	Vegetables	Fruits	Population	Technology
East African Community Member States								
Rwanda	1.52	0.34	461,602.60	2,758,519.00	412,058.70	2,672,650.00	7985.94	1548.14
	1.03	0.19	244,435.20	1,037,497.00	216,855.70	438,034.00	1786.13	2075.85
	0.19	0.06	130,072.50	886,071.80	121,412.90	1,549,000.00	5344.91	7.66
	3.17	0.75	932,107.30	4,485,985.00	688,418.30	3,611,200.00	11,247.44	7046.43
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Uganda	8.83	0.99	2,809,803.00	5,777,216.00	884,843.60	7,835,354.00	25,121.42	2800.51
	4.01	0.29	942,322.60	1,671,836.00	382,722.50	2,448,102.00	6620.01	2786.40
	3.92	0.54	1,576,000.00	3,501,000.00	415,500.00	3,451,798.00	15,507.40	−5.62
	21.76	1.88	5,525,000.00	8,765,000.00	1,412,799.00	11,800,000.00	37,099.64	8707.83
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
United Republic of Tanzania	124.49	3.35	6,959,240.00	8,634,589.00	1,806,026.00	3,652,592.00	30,820.69	4679.76
	54.26	1.67	3,043,055.00	2,112,238.00	736,986.40	1,737,320.00	6471.26	4708.99
	53.33	1.45	2,952,900.00	4,862,263.00	1,013,675.00	1,213,738.00	20,651.76	5.61
	226.43	7.20	12,500,000.00	13,200,000.00	3,182,946.00	5,884,175.00	42,177.77	19,276.83
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Economic Community of West Africa States Members								
Benin	3.60	0.76	1,307,770.00	5,107,649.00	398,597.70	348,965.80	4840.86	1254.19
	1.95	0.57	559,093.40	1,890,488.00	181,999.40	169,602.20	971.81	1113.20
	1.47	0.30	545,898.00	2,019,754.00	214,645.00	173,161.40	3261.67	40.58
	7.74	2.30	2,320,756.00	7,952,286.00	744,746.30	676,228.80	6450.30	3840.75
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Burkina Faso	24.57	1.64	3,551,293.00	130,609.80	702,582.70	537,292.60	11,015.93	1800.32
	16.64	0.64	1,081,092.00	72,103.90	387,412.50	467,407.70	2256.69	1809.73
	5.02	0.75	1,517,900.00	37,400.00	229,116.00	69,831.00	7593.83	0.47
	58.71	2.70	5,180,702.00	299,127.00	1,416,382.00	1,429,305.00	15,056.71	6551.88
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Cabo Verde	0.09	0.01	7812.30	13,383.70	29,258.79	14,251.07	195.41	434.14
	0.01	0.00	7383.53	4118.41	14,497.60	2805.70	5.28	577.50
	0.04	0.00	4.00	7665.00	4682.00	6998.93	188.64	0.25
	0.10	0.01	36,439.00	21,263.00	49,973.16	19,007.00	202.82	1619.85
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Côte d'Ivoire	18.03	1.28	1,898,790.00	8,439,046.00	659,303.40	2,317,163.00	10,262.68	3502.64
	5.70	0.40	809,132.40	3,082,855.00	60,097.09	369,014.70	1580.02	2029.81
	11.64	0.66	1,221,428.00	4,685,380.00	569,753.70	1,569,720.00	7440.95	51.43
	28.40	2.14	3,308,600.00	14,800,000.00	774,260.60	3,155,808.00	13,017.21	8534.65
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Ghana	13.52	1.24	2,440,180.00	19,100,000.00	628,941.70	3,804,305.00	11,441.48	5472.18
	5.78	0.79	1,063,430.00	8,996,124.00	141,073.70	1,767,052.00	1242.96	5165.18
	4.63	0.43	843,800.00	4,409,038.00	376,972.00	923,900.00	9297.56	17.89
	27.95	2.85	5,136,565.00	38,200,000.00	801,831.50	6,397,830.00	132,50.62	12,706.64
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Guinea	117.14	0.90	2,525,157.00	1,644,864.00	523,224.00	1,157,566.00	6757.86	191.58
	60.08	0.43	1,084,393.00	904,542.00	35,209.19	188,701.80	1262.81	344.63
	48.79	0.36	1,061,616.00	797,775.00	440,139.00	856,803.00	4348.02	−101.04
	210.11	1.70	4,745,053.00	4,313,086.00	566,956.10	1,614,579.00	9022.71	1606.98
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Liberia	2.36	0.15	202,201.80	524,923.60	95,278.76	173,197.30	1786.78	19926.22
	0.94	0.08	85,830.44	144,054.10	19,784.49	33,465.90	515.13	27,234.66
	0.64	0.03	50,000.00	232,616.20	70,996.00	106,779.00	865.31	34.98
	4.18	0.27	335,180.00	769,796.30	125,356.50	217,563.00	2517.04	83,520.52
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Mali	38.44	2.43	5,033,452.00	453,662.60	1234188.00	1,116,921.00	8967.91	1584.89
	18.00	1.44	3,010,112.00	380,888.90	555,779.00	729,994.00	1622.21	1750.40
	14.52	0.78	1,771,419.00	51,296.00	296,290.00	392,951.00	6490.90	5.73
	72.73	5.86	10,500,000.00	1,452,527.00	2,597,052.00	2,576,204.00	11,739.44	7679.90
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Niger	2.37	1.50	3,778,998.00	331,297.20	1,250,303.00	336,543.60	12,683.56	1130.32
	0.59	0.45	1,416,583.00	278,992.10	1,050,195.00	243,196.40	4475.57	1183.05
	1.47	0.84	1,850,285.00	118,320.00	249,554.90	43,800.00	6781.41	40.81
	3.69	2.29	6,100,262.00	1,103,733.00	3,605,640.00	762,360.20	21,584.00	4599.48
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Nigeria	306.24	11.54	24,000,000.00	83,500,000.00	10,700,000.00	10,200,000.00	85,076.73	48,374.03
	108.44	3.37	3,808,570.00	28,800,000.00	3,836,856.00	2,359,821.00	10,149.39	47,687.52
	147.93	8.03	17,700,000.00	33,600,000.00	4,168,000.00	6,382,000.00	66,993.86	1002.50
	524.14	21.07	30,300,000.00	136,000,000.00	16,400,000.00	16,900,000.00	100,786.30	150,428.20
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00

Table A1. Cont.

RTB	Methane	Nitrous Oxide	Cereals	Roots & Tubers	Vegetables	Fruits	Population	Technology
Economic Community of West Africa States Members								
Niger	2.37	1.50	3,778,998.00	331,297.20	1,250,303.00	336,543.60	12,683.56	1130.32
	0.59	0.45	1,416,583.00	278,992.10	1,050,195.00	243,196.40	4475.57	1183.05
	1.47	0.84	1,850,285.00	118,320.00	249,554.90	43,800.00	6781.41	40.81
	3.69	2.29	6,100,262.00	1,103,733.00	3,605,640.00	762,360.20	21,584.00	4599.48
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Senegal	11.22	0.79	1,593,330.00	441,460.10	436,945.00	586,966.30	6801.55	3171.29
	7.98	0.45	861,180.00	506,957.20	323,109.50	516,698.20	1390.93	2647.76
	3.41	0.26	730,335.00	41,762.52	69,661.00	167,637.00	4616.79	57.85
	29.66	1.97	3,663,690.00	1,688,559.00	1,048,198.00	1,997,619.00	9231.74	10,463.86
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Sierra Leone	35.25	0.43	831,425.90	1,703,635.00	279,722.50	214,152.90	3617.96	170.63
	14.89	0.22	431,829.10	1,342,271.00	87,725.94	48,840.27	680.68	228.78
	12.30	0.11	222,472.00	224,400.00	180,000.00	152,985.00	2797.80	−7.46
	78.39	0.94	2,131,723.00	4,038,764.00	479,186.00	282,814.10	4704.51	968.71
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Togo	2.06	0.47	946,571.40	1,514,481.00	144,587.50	55,243.69	3778.37	919.57
	0.76	0.19	307,205.00	390,027.10	5667.20	9354.61	696.56	948.42
	0.91	0.29	464,877.00	840,495.50	130,698.40	41,660.19	2704.30	22.72
	3.33	1.09	1,439,850.00	2,244,231.00	158,700.00	68,459.46	4927.84	3053.12
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
South African Development Community Member States								
Angola	7.19	0.75	1,218,094.00	8,470,025.00	1,008,288.00	2,349,265.00	9078.95	28,557.11
	3.49	0.52	969,838.10	4,782,581.00	638,038.50	2,089,799.00	1123.50	29,812.68
	2.68	0.22	248,500.00	1,798,899.00	250,000.00	405,000.00	7650.44	−334.50
	13.00	1.74	3,179,113.00	18,300,000.00	2,016,573.00	6,120,250.00	11,168.04	106,077.00
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Eswatini	0.28	0.14	92,247.19	61,337.73	11,885.88	125,597.10	891.97	67.35
	0.04	0.04	28,131.74	12,613.61	941.32	24,748.44	129.07	54.09
	0.19	0.06	27,540.66	43,917.00	10,500.00	73,787.10	687.36	−61.25
	0.37	0.21	152,068.00	94,364.16	13,345.90	162,715.60	1121.10	154.91
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Lesotho	0.34	0.08	127,164.00	96,997.26	27,664.90	16,010.38	1528.87	332.81
	0.10	0.03	64,141.44	26,693.76	5322.99	1412.73	73.75	329.04
	0.09	0.04	25,678.06	45,093.00	18,000.00	13,000.00	1379.92	−0.81
	0.51	0.19	257,418.00	134,962.10	35,000.00	19,000.00	1667.71	1234.29
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Madagascar	226.41	1.32	3,647,026.00	3,899,903.00	394,242.00	1,031,850.00	13,197.81	368.21
	27.27	0.29	914,651.20	6,301,12.10	51,151.28	188,307.30	2698.24	365.36
	181.73	0.98	2,497,184.00	2,960,139.00	330,300.00	767,800.00	8865.35	9.49
	299.33	1.90	5,159,721.00	5,183,376.00	470,948.30	1,289,990.00	17,539.78	1349.60
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Mauritius	0.12	0.20	797.12	17387.83	70759.96	18964.32	698.89	1992.22
	0.02	0.05	609.11	3161.57	12,109.77	6331.79	50.07	1680.12
	0.07	0.11	112.00	11,654.00	44,860.04	8370.00	592.34	14.78
	0.16	0.28	2284.00	23,317.00	93811.71	31,958.00	756.76	4496.45
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Mozambique	21.16	1.09	1,610,493.00	5,582,967.00	529,814.50	565,793.10	15,181.41	3954.45
	7.96	0.53	613,783.80	1,269,572.00	553,516.30	253,428.90	3433.20	3487.00
	9.84	0.36	244,554.10	3,365,024.00	115,282.00	280,400.00	9935.74	23.40
	33.61	2.18	2,832,309.00	7,482,694.00	2,224,968.00	1,019,695.00	21,121.58	10,952.81
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
Namibia	0.08	0.13	114,871.40	306,863.50	39,039.43	37,611.89	1244.32	4406.66
	0.02	0.16	34,827.81	66,667.26	22,936.58	20,785.69	77.47	3499.01
	0.05	0.02	31,031.00	195,000.00	8000.00	7998.06	1023.44	29.57
	0.13	0.68	186,008.30	392,075.90	67,982.48	71,123.62	1299.61	13,785.07
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00
South Africa	10.38	11.81	13,300,000.00	1,974,537.00	2,303,409.00	5,821,977.00	19,334.56	73,580.81
	2.08	1.80	3,257,667.00	459,713.80	294,933.30	1,346,182.00	439.12	59,399.63
	7.20	9.25	5,056,342.00	1,125,028.00	1,892,468.00	3,815,637.00	18,015.16	−78.46
	14.61	17.10	19,600,000.00	2,763,924.00	2,724,794.00	8,772,836.00	19,800.02	182,594.30
	33.00	33.00	33.00	33.00	33.00	33.00	33.00	33.00

Where mean, standard deviation, minimum, maximum, and number of RTB member states are in vertical order in that manner. Source: Computed by the Author.

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