



# Aquaculture production, GHG emission and economic growth in Sub-Sahara Africa

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## ABSTRACT

Aquaculture is a major source of protein in Sub-Saharan Africa (SSA), a region experiencing rapid population growth, changing lifestyles and preferences, and increased health awareness. However, the industry is still underdeveloped and is of a subsistence nature. Climate change has impacted aquaculture production (AQUAP) in SSA because of greenhouse gas (GHG) emissions. However, AQUAP activities also results in GHG emissions. In SSA, the causal effect of GHG emissions and AQUAP has not yet been empirically established and quantified. The objective of the study was to determine the relationship between GHG emissions and AQUAP in SSA. The parsimonious vector autoregressive (VAR) model was used in the study, with annual time series data of Gross Domestic Product (GDP), meat production (MP), GHG emissions, and AQUAP from 1970 to 2020. The findings demonstrate that AQUAP in SSA was suppressed until 2006 when it suddenly increased. Western and Central Africa have dominated AQUAP in SSA. GHG emissions were dropping sporadically until 1991 when they began to rise gradually. In both the long and short run, GHG emissions had a negative influence on AQUAP, while AQUAP had an asymmetric impact on GHG emissions. AQUAP impacts GDP positively in both the long and short run, and GHG emissions had an asymmetric impact on GDP. In conclusion, GHG emissions negatively affect AQUAP. In addition, AQUAP reduced GHG emissions in the short run but however increased it in the long run. This indicates the infancy of the sector in SSA, the initial phase of the Environmental Kuznets Curves (EKC). Furthermore, GDP is positively affected by both GHG emissions and AQUAP. This also cements the initial stages of the EKC, with economic development also powered by GHG emissions, with also the positive contribution of AQUAP to economic growth. Overall, the study concludes of initial economic, and aquaculture sectoral development powered by GHG emissions. However, this is also leading to increased emissions. The study recommends upscaling AQUAP in SSA given its infancy, huge economic potential, sustainability and low GHG emission potential but should be grounded on environmentally sustainable practices.

**Table 1**  
Acronyms.

ADF	Augmented Dickey-Fuller
AIC	Akaike Information Criterion
AQUAP	Aquaculture production
ARDL	Autoregressive Distributed Lag
ARDL-VECM	Autoregressive Distributed Lag—Error Correction Model
AU	African Union
CH <sub>4</sub>	Methane
CO <sub>2</sub>	Carbon Dioxide
FAO	Food and Agriculture Organization
EKC	Environmental Kuznet Curve

(continued on next page)

**Table 1 (continued)**

ADF	Augmented Dickey-Fuller
GDP	Gross Domestic Product
GHG	Green House Gas
MP	Meat Production
NAPA	National Adaptation Programmes of Action
NEPAD	New Partnership for Africa's Development
NO <sub>2</sub>	Nitrogen Dioxide
SIC	Schwarz information criterion
SSA	Sub-Saharan Africa
US	United States
VAR	Vector Autoregressive

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## 1. Introduction

Aquaculture involves the science of cultivating both marine and freshwater organisms in a controlled environment, with production influenced by economic, technological, biological and environmental factors (Jang and Yamazaki, 2020, Kaleem and Sabi, 2021). Since 1980, aquaculture has been the fastest growing global food-producing sector at 8.6% (Oyebola and Olutande, 2019), and Africa has exhibited the fastest regional growth at 7% (Nadarajah and Flaaten, 2017). On the African continent, aquaculture is highly underdeveloped, and small-holder-specific, having direct impact on food security and ecosystem services while also acting as an indirect driver of the economy (Macleod et al., 2020, Kaunda and Chimatiro, 2015). Due to the fact that the focus in Africa is on food security rather than economic growth, aquaculture production (AQUAP) has largely remained small and part-time, and produce has been consumed directly, bartered or sold locally, playing a minor role in Gross Domestic Product (GDP) and economic growth (Babatunde et al., 2021, Gabriel et al., 2007, Changadeya et al., 2003). Sub-Saharan Africa (SSA) has a less than 1% contribution to global AQUAP (Munguti et al., 2014). This has been due to underutilisation of aquaculture resources. Kenya, for example, only uses 0.014% of its 1.4 million hectares suitable for aquaculture farming. However, a report by World Bank (2015) indicates that production in SSA as high as 5% of global production has been realised.

Weak technical advice, policies, production systems, species, marketing, fish nutrition and lack of good quality seed have delayed SSAs AQUAP expansion (Moyo and Rapatsa, 2021). Furthermore, there has been an overreliance on imports of fish seed and fish ingredients (e.g. premix, vitamins and fishmeal) (Partelow et al., 2021). In addition, growth has been hampered by factors such as aquaculture's novelty, lack of credit and entrepreneurial skills and the generally poor economic conditions in many SSA countries (Changadeya et al., 2003). Aquaculture has also been affected by climate-related stressors such as decreased rainfall, increase in rainfall variability and temperature as well as decreased pH and ocean acidification which has reduced fish abundance, productivity, distribution and size (Tran et al., 2021; Sanon et al., 2020; Bjørndal and Tusvik, 2020). For instance, in the tropics, catch potential will decrease by 40% however, in high latitude areas, it is expected to increase by between 30–70%. This is the result of warmer water species that are likely to migrate to colder areas with a reduction in cold water species. However, the net effect is still uncertain (Bjørndal and Tusvik, 2020).

Recently, there has been a push to improve African AQUAP (Moyo and Rapatsa, 2021; Chan et al., 2021). The 2004 Sirte Summit paved way for the African Unions (AU) New Partnership for Africa's Development (NEPAD) in 2005 to promote aquaculture production and management (African Union/NEPAD, 2014). This has led to some improvements in AQUAP across the African continent. For example, Nigeria and Uganda are the leading countries in SSA in terms of AQUAP, accounting for 34% of national fisheries output and contributing 4.5% and 3% of national GDPs, respectively (Adeleke et al., 2021). Even though South Africa has one of the largest economies in SSA, AQUAP has performed poorly, accounting for less than 1% of GDP and 4% of agricultural GDP (SADC-EU EPA, 2017; AgriSETA 2019; Ngarava et al., 2023). Between 1960–2018, Nigeria, Uganda and Ghana dominated AQUAP in SSA (Table 2).

Aquaculture was introduced in Africa in the 1940s and 1950s to improve rural livelihoods and as a risk management strategy against crop failure (Brummett et al., 2008). There are two hundred million people who depend on fish as a regular protein source in Africa. For instance, in half of the African countries, fish account for 36% of the animal protein (African Union/NEPAD, 2014). In addition, aquaculture has the potential to provide year-round employment (across the value chain) as well as job opportunities and long-term economic growth. For example, Chan et al. (Chan et al., 2021) estimated that employment in Africa's aquaculture will increase from 20.7 million in 2030 to 21.6 million in 2050.

**Table 2**

Aquaculture production in tonnes of selected countries in SSA between 1960 and 2018.

	Minimum	Maximum	Mean	Std. Deviation
Nigeria	2 005.00	316 727.00	59 224.86	98 313.38
Uganda	31.00	118 051.20	33 771.82	45 766.55
Ghana	4.00	76 630.00	7 768.64	16 811.43
Madagascar	4.00	28 335.00	7 001.55	7 434.10
Zambia	3.00	24 300.00	6 211.05	7 073.65
Tanzania	8.00	19 602.00	4 072.05	4 945.07
South Africa	6.00	8 094.27	3 493.15	2 615.21
Kenya	150.00	24 498.00	3 469.19	6 784.65
Zimbabwe	2.00	10 600.00	2 343.55	3 571.13
Sudan	10.00	10 000.00	2 230.17	2 794.41

**Source:** Calculated from World Bank (Jang and Yamazaki, 2020).

By 2050, the fish food system will employ 2.4% of Africa's projected total population (Chan et al., 2021). According to Kaunda and Chimatiro (2015) the aquaculture sector currently contributes US\$3 billion annually, employing 12.3 million (12.3%) of Africa's working population with women accounting for 27.3% (Kaunda and Chimatiro, 2015). Half of the employment is in fisheries while 42% are in processing and 8% are in production (African Union/NEPAD, 2014). Changes in AQUAP are likely to have a significant impact on SSA's economy (Bjørndal and Tusvik, 2020).

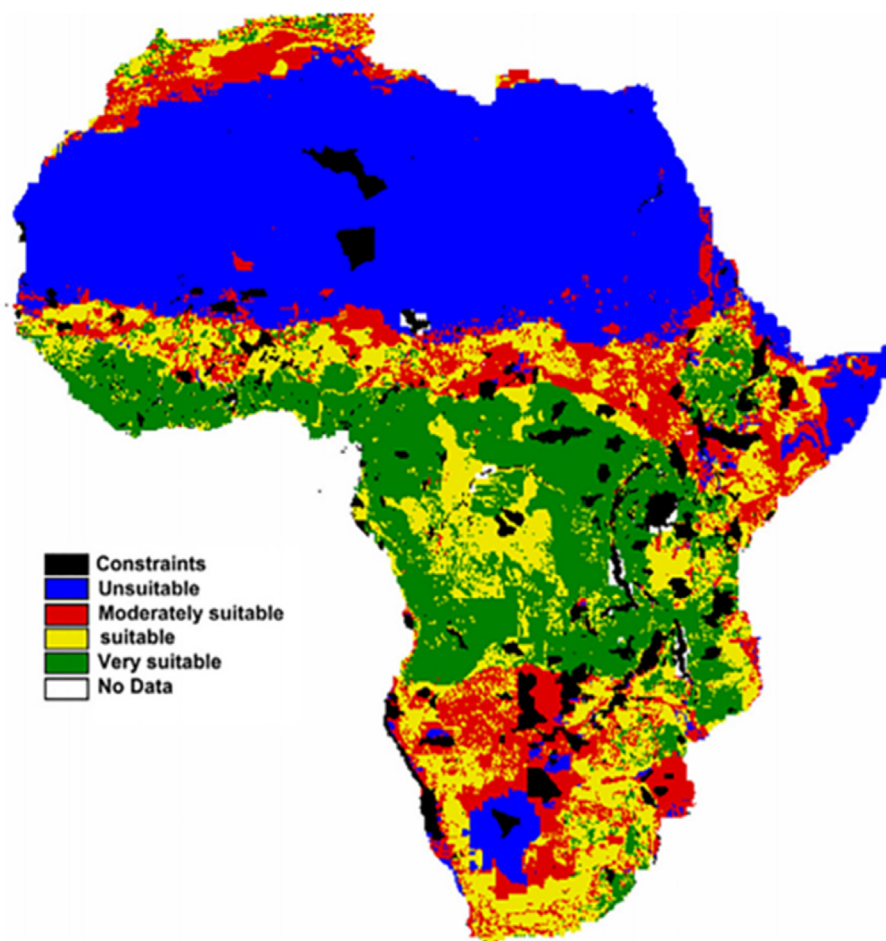
Economic and population growth has increased the demand for fish in SSA with the population expected to be 2 billion by 2050 (Kinkela et al., 2019). This has been augmented by changes in consumer lifestyles and preferences, as well as appreciating the health benefits of consuming fish. However, growth in AQUAP has not kept pace with the increase in demand, even though there is great potential in SSA which has the land and suitable water environment (Fig. 1) (Gabriel et al., 2007; Moyo and Rapatsa, 2021; Tran et al., 2019).

Sub-Saharan Africa (SSA) needs to increase AQUAP because there is room for expansion and to meet projected global food demand (Bohnes et al., 2022). However, this increases environmental concerns such as GHG emissions (Macleod et al., 2020; Kurniawan et al., 2021; MacLeod et al., 2019). For instance, fish faecal matter and feeding residue produce carbon dioxide (CO<sub>2</sub>)-rich organic matter. Nitrous oxide (N<sub>2</sub>O) is also released from protein-rich residual feed and fish excretory products, and the resulting methane (CH<sub>4</sub>) is ejected into the atmosphere as gas ebullition (Raul et al., 2020; Yang et al., 2020). Anthropogenic activities in the agriculture sector are responsible for 23% of atmospheric GHGs, of which approximately 7% come from aquaculture. For example, fertilizers which leach from cropland agriculture; feed manufacture; on-farm energy in pumping water and other fuel consumption; processing and distribution to and from the farm; fish farm waste management; and fluorinated gases which are leaked from cooling systems on-farm and post-farm (Fig. 2) (MacLeod et al., 2019; Henriksson et al., 2014). According to Hu et al. (2012) and Zhou et al. (2021), concern about aquatic N<sub>2</sub>O emission is growing (from 0.15 Tg in 2009 to 0.60 Tg in 2030) because there is a predicted increase in future demand for aquaculture products as the wild fish are reaching their peak plateaus.

According to Oyebola and Olutande (2019), aquaculture has climate change adaptation potential over and above its poverty reduction and food security attributes. It is also however among the most affected by climate change (African Union/NEPAD, 2014). This has negative implications for aquaculture producers whose livelihoods will be affected through income losses, food insecurity and health risks. Food production and GHG emission studies must focus on the proportionate contribution of the aquaculture sector to GHG emissions as well as being a mitigatory strategy, as it is a viable sector for emission reduction due to its intricacies with aquaculture ecosystems (Oyebola and Olutande, 2019; Onada and Ogunola, 2016). Oyebola and Olutande (2019) argue that promotion of AQUAP has come at a cost, for example the increased pro-

**Fig. 1.** Suitability of SSA for small scale aquaculture production.

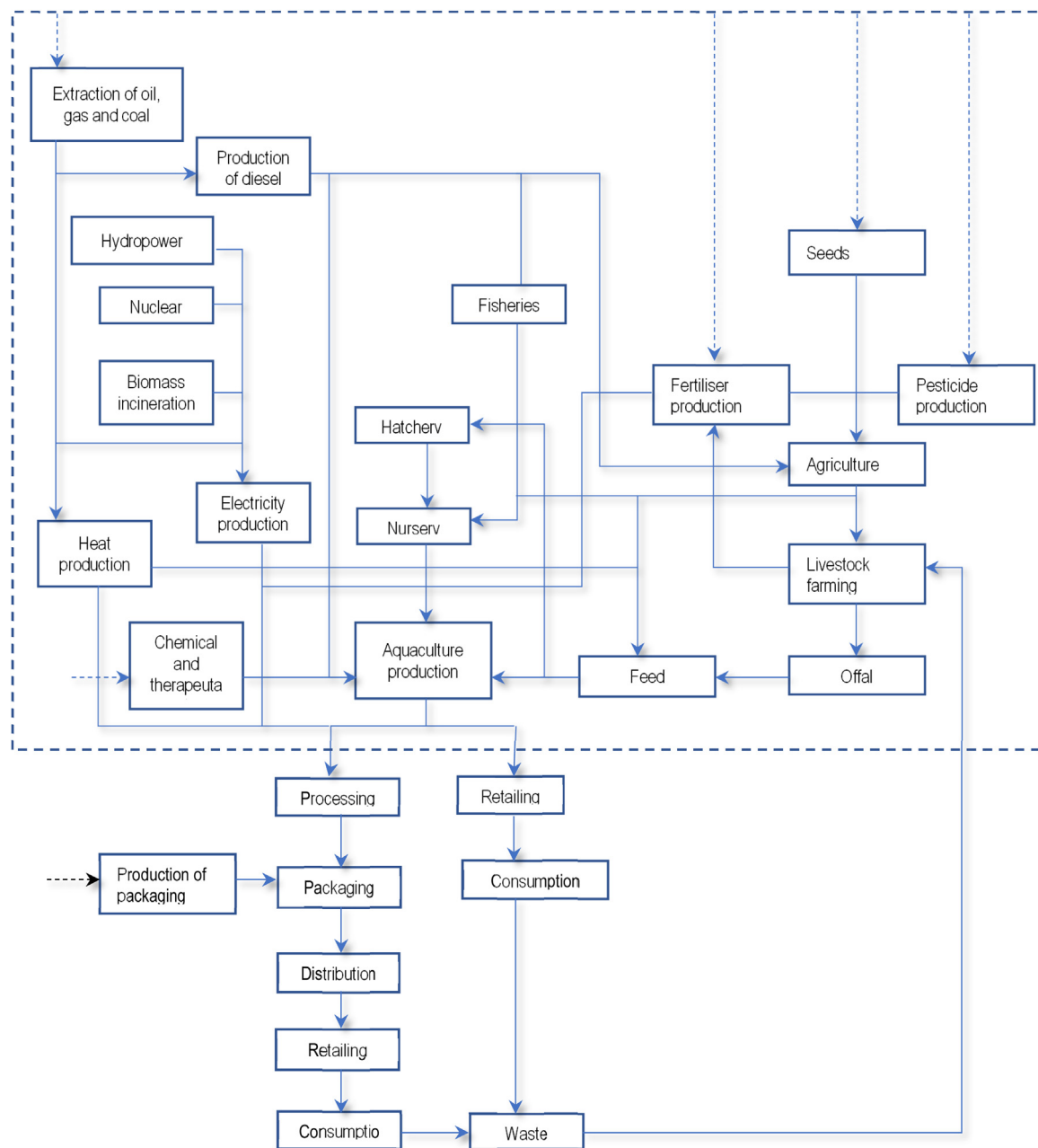
Source: Moyo and Rapatsa (Jang and Yamazaki, 2020)



duction of fishmeal which are animal product based and thus contribute to GHG emission through livestock production. Instances of mangrove clearing have also reduced carbon sinks thereby increasing the persistence of atmospheric GHG. Jiang et al. (2022) further assert that aquaculture production has very low environmental sustainability. However, such arguments have not been quantified, necessitating the current study. Even though various studies have focused on environmental sustainability of AQUAP through emergy analysis (Williamson et al., 2015; Wang et al., 2015), life cycle assessments (Medeiros et al., 2017), ecological and carbon footprint (Madin and Macreadie, 2015) and indicator analysis (Valenti et al., 2018) very few have been carried out in SSA and have quantified the relationship between production and GHG emissions. There is need to understand the contribution of AQUAP to GHG emissions (Macleod et al., 2020) and unmask its environmental sustainability.

As a result, a balance must be struck between reducing environmental impact while also increasing AQUAP (Adegbeye et al., 2019). Understanding the economics of climate change is essential in advising policy and decision-makers in effective aquaculture adaptation and mitigation strategy development. Lack of policy coherence between GHG emissions, AQUAP and economic development has been one of the challenges identified in boosting the sector (African Union/NEPAD, 2014). According to Tran et al. (2021) relationship between aquaculture and GHG emissions is bi-directional, tending to affect each other. There is a need to understand the contribution of aquaculture to GHG emissions so that the real trade-offs with food security and economic development can be determined, and vice-versa: there is need to understand the contribution of GHG emissions to aquaculture. The study sought to ascertain the empirical relationship between SSAs GHG emissions and

AQUAP. Even though reviews conclude that SSA GHG emissions are insignificant compared to global aquaculture, Macleod et al. (2020) propose that this should not be the grounds for complacency because due to the depleted capacity to adapt, the region is highly vulnerable to impacts of climate change, as it is located mainly in the tropics. There is a need to make necessary production practice adjustments to minimize the emissions of GHGs in order to achieve sustainable growth in SSAs AQUAP (Maulu et al., 2021). A study by Kwakwa et al. (2020) employing numerous statistical tools (modified ordinary least squares, Autoregressive Distributed Lag (ARDL) model, Environmental Kuznets Curve (EKC) hypothesis, variance decomposition and impulse response analysis) assessed the relationship between aquaculture and carbon emissions in Egypt and found that aquaculture positively affects carbon emissions. The results showed that in the long run, an increase in AQUAP increased carbon emissions. This is through the utilisation of high-carbon emitting equipment such as aeration machinery, refrigeration, diesel-fuelled generators, boats and transportation, where the demand for more equipment will increase production from manufacturing companies (Maulu et al., 2021; Kwakwa and Adusah-Poku, 2020). This was augmented by Ngarava et al.'s (2023) study in South Africa through an Autoregressive Distributed Lag—Error Correction Model (ARDL-VECM) showing that there indeed was a relationship between GHG emissions and AQUAP. The current study divests from previous studies that have taken more localised and national approaches such as Kwakwa et al. (2020) and Ngarava et al.'s (2023), and focuses on the SSA region, likely to influence regional policy. Even though Macleod et al. (2020) provided a global perspective by quantifying GHG emissions from AQUAP, the study only considered one year and did not track any longitudinal changes. Furthermore, the study was only



**Fig. 2.** Pathway through which GHG emission can impact aquaculture production (dotted line represents the boundary in primary food production, with anything outside indicating the value chain beyond production. The dotted arrows emanate from the value chain beyond production).

**Source:** Henriksson et al. (Jang and Yamazaki, 2020) and MacLeod et al. (Kaleem and Sabi, 2021)

descriptive and did not attempt any statistical enquiry. This was also the same limitation to Chen et al. (2023) who conducted a bibliometric analysis of literature on global GHG emissions from AQUAP and Ahmed et al. (2019) who conducted a review of the AQUAP environmental concerns. To the authors' knowledge, there are very limited studies, which have used the parsimonious autoregressive method to assess the relationship between AQUAP and GHG emissions that was used in the current study as explained in the analytical framework section.

The lack of environmentally friendly procedures that allow development with the least impact on the environment is one of the factors affecting economic growth and aquaculture intensification in SSA (Bohnes et al., 2022). Because SSA aquaculture relies heavily on feed imports, indirect GHG emissions are generated as a result of the long food supply chain, such as feed transportation from overseas (Moyo and

Rapatsa, 2021). Sub-Saharan Africa (SSA) is also suffering in foreign markets due to the inefficiency of domestic guidelines for the quality and safety of aquaculture products (Muringai et al., 2022). According to Kaunda and Chimatiro (2015) there is a need to harness the potential wealth that is obtainable from aquaculture in SSA as the sector contributes to employment and food security, and potentially to economic growth if well implemented and managed. However, environmental concerns about GHG emissions seem to stifle this objective. The current study aims to feed into SSA's AQUAP policy space where issues concerning, or lack thereof, conservation and sustainable use of aquaculture resources, sustainable smallholder contribution to socio-economic benefits, food security and poverty alleviation, awareness creation on the significance of the sector on the continent and promoting governance and management for sustainable production. This is significant



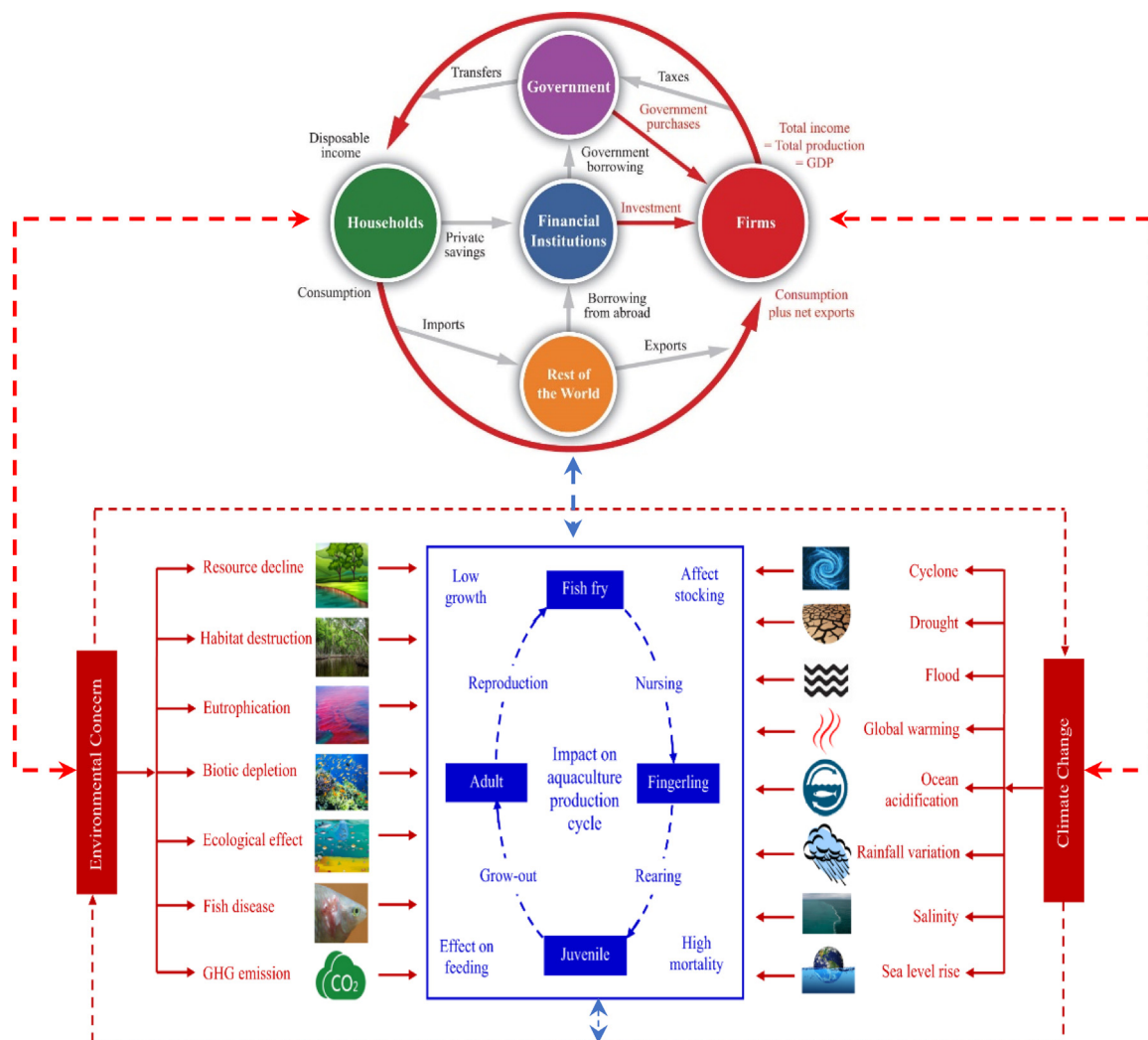


Fig. 3. Conceptual framework.

Source: Adapted from Ahmed et al. (Jang and Yamazaki, 2020)

given that aquaculture has not been extensively considered in the profiles of SSA countries' National Adaptation Programmes of Action (NAPAs) (African Union/NEPAD, 2014).

## 2. Material and methods

### 2.1. Conceptual framework

The study adopted a conceptual framework developed by Ahmed et al. (2019) (Fig. 3). AQUAP is susceptible to environmental concerns and climate change. Environmental concerns such as GHG emissions have been attributed to AQUAP, which has also been affected by GHG emissions. According to Ahmed et al. (2019) aquafeeds contribute the largest GHG emissions in aquaculture from the supply chain. Clearing mangroves for coastal aquaculture has also released significant amounts of GHG emissions. However, increase in GHG emissions have increased the impact of climate change on AQUAP through increased temperature from global warming, salinity, sea level rise and other climate extremes. The negative effect that GHG emissions and climate change have on AQUAP indirectly affects the GDP by influencing output, consumption, and trade. GHG emissions and climate change also have a direct effect on GDP. The study theorizes that there is a longitudinal bi-directional relationship between GHG emissions, AQUAP and GDP. The framework as proposed by

Ahmed et al. (2019) allows the contextualisation of the current study by offering a pathway through which GHG emissions and AQUAP affect each other and how this overall affects the wider economy. From Fig. 3, it can be theorised that GHG emissions as an environmental concern doubly affects the wider SSA economy and AQUAP. AQUAP on the other hand has direct relationship with economic development and offers a consequential loop to environmental concerns, chief among them GHG emissions. AQUAP substitutes such as livestock animal protein sources can provide alternatives, but this also has an environmental cost, through GHG emissions and affects the wider economy as well as AQUAP. The study then seeks to stamp out any such relationships between AQUAP, GHG emissions, economic development, and livestock MP.

### 2.2. Study design

The study used a longitudinal time series design and the parsimonious vector autoregressive (VAR) model as used by Ngarava (2021). Time series designs have a temporal perspective in detecting, analysing, and explaining phenomena. They allow futuristic planning by uncovering past patterns and relationships. The VAR has advantages of capturing real-world behaviour systematically, forecasting and accounting for dynamics of time series data. A parsimonious VAR allows the capture of many patterns without introducing other parameters that require es-

timation, and it does not require every variable into the equation or be in the same order (Dekle et al., 2002).

### 2.3. Analytical framework

In the study, the AQUAP subsystem originates from its internal shocks, which simultaneously and multi-directionally influence itself and other subsystems (i.e. GHG emissions, MP and GDP) (Ngarava, 2021). Over time, this multi-dimensional influence is repeated (Yan et al., 2020). The multivariate vector autoregressive (VAR) model is represented as:

$$Y_t = \gamma + A_1 \cdot Y_{t-1} + \dots + A_q \cdot Y_{t-q} + \mu_t$$

where  $Y_t$  is an  $M \times 1$  vector of endogenous variables,  $q$  is a lag order,  $\gamma$  is a constant terms vector,  $A_1 \dots A_q$  are  $M \times M$  matrices of parameters, and  $\mu_t$  representing an  $M \times 1$  column vector of random error. The VAR model below was constructed using the dynamic relationship between AQUAP, GHG emissions, GDP, and MP:

$$\ln AQUAP_t = \rho + \sum_i^m \beta_i \ln AQUAP_{t-i} + \sum_j^m \tau_j \ln GHG_{t-j} + \sum_k^m \varphi_k \ln GDP_{t-k} + \sum_l^m \theta_l \ln MP_{t-l} + \mu_{1t}$$

$$\ln GHG_t = \pi + \sum_i^m \beta_i \ln AQUAP_{t-i} + \sum_j^m \tau_j \ln GHG_{t-j} + \sum_k^m \varphi_k \ln GDP_{t-k} + \sum_l^m \theta_l \ln MP_{t-l} + \mu_{2t}$$

$$\ln GDP_t = \sigma + \sum_i^m \beta_i \ln AQUAP_{t-i} + \sum_j^m \tau_j \ln GHG_{t-j} + \sum_k^m \varphi_k \ln GDP_{t-k} + \sum_l^m \theta_l \ln MP_{t-l} + \mu_{3t}$$

$$\ln MP_t = \alpha + \sum_i^m \beta_i \ln AQUAP_{t-i} + \sum_j^m \tau_j \ln GHG_{t-j} + \sum_k^m \varphi_k \ln GDP_{t-k} + \sum_l^m \theta_l \ln MP_{t-l} + \mu_{4t}$$

where *AQUAP* - aquaculture production; *GHG* - greenhouse gas emission; *GDP* - gross domestic product; *MP* - meat production;  $m$  - the optimal lag length;  $\rho, \pi, \sigma, \alpha$  - intercepts;  $\beta_i, \tau_j, \varphi_k, \theta_l$  - short-run dynamic coefficients of the model's adjustment to long run equilibrium; and  $\mu_{1t}$  - equation residuals (also known as shocks, innovations or impulses). Meat production (MP) was included in the analysis as it offers a substitute protein source for AQUAP but also has a large bearing on GHG emissions and GDP. The variables in the VAR model are endogenous and rely on their lagged values. The initial stage in estimating the VAR model involved testing for stationarity using the Augmented Dickey-Fuller (ADF) test. Stationarity was tested to check whether the properties of the variables do not change with time. Stationarity is also an assumption requirement in VAR modelling (Singh and Majumdar, 2013). This was followed by determining the number of lags using the Akaike Information Criterion (AIC). Lag determination determines the time between two time series periods. The Cholesky decomposition was used to obtain the impulse response function. The impulse response function depicts the relationship to a stimulus. Diagnostic tests of heteroscedasticity, multi-collinearity and normality were performed using the VAR Residual Heteroscedasticity Tests, VAR Residual Serial Correlation LM test and the Jarque-Bera test for normality, respectively. In the parsimonious VAR model, System Residual Portmanteau Tests for Autocorrelations

and System Residual Normality Tests were used to test for collinearity and normality, respectively. Heteroscedasticity refers to a large variance of the error term, with multicollinearity measuring the intercorrelations and normality is concerned with more frequent distribution near a mean value. The data used in the study was annual time series spanning from 1970 to 2020. Per capita data was used by dividing the current value of the variables by the population. The AQUAP, GHG emission and GDP secondary data were obtained from the World Bank 2022a, b, c), while the MP data were obtained from FAOSTAT (FAOSTAT, 2022). Natural logarithms of the variables were used to mitigate large fluctuations and heteroscedasticity in the data. The data was analysed using E-views 10.

## 3. Results

### 3.1. Descriptive results

The average AQUAP output in the 50 years spanning 1970–2020 in SSA was 137 207 tons, with a maximum of 620 291 tons and a minimum of 4 243 tons observed during the period (Table 3). The average GHG emissions were two million kilotons, with a maximum of three million kilotons and a minimum of one million kilotons observed during the period. Gross Domestic Product (GDP) and MP had averages of US\$671 billion and eight million tons, respectively.

Figure 4 shows that there was a sharp increase in AQUAP from 2006 to 2017. The GHG emissions however were haphazard from the 1970s to 1991, when there was a steady increase thereafter.

AQUAP was minuscule from 1960 to 1990, (Fig. 5), however, from 2002, AQUAP from Central and Western Africa has been increasing at a faster rate than in Eastern and Southern Africa.

### 3.2. Empirical results

The stationarity tests for AQUAP, GHG emissions, GDP and MP are shown in Table 4. All the variables were non-stationary at variables but

**Table 3**

Aquaculture production, GHG emissions, GDP, meat production and population in SSA between 1970 and 2020.

	Aquaculture production (metric tonnes)	Total greenhouse gas emission (kt of CO2 equivalent)	GDP (US\$ current) (billion)	Total meat production (tonnes)	Population (million)
Minimum	4 243.00	1 236 220.00	62.99	3 976 176.00	290.53
Maximum	620 290.63	3 230 505.84	1 835.24	138 97 214.00	1 136.05
Mean	137 207.48	2 093 947.49	671.27	7 697 078.02	626.14
Std. Deviation	203 704.23	530 426.87	600.09	3 043 154.75	248.74
Skewness	1.544	0.191	0.936	0.700	0.462
Kurtosis	0.882	-0.700	-0.778	-0.781	-0.944

**Source:** Calculated from FAOSTAT (Jang and Yamazaki, 2020) and World Bank (Kaleem and Sabi, 2021, Oyeola and Olutande, 2019, Nadarajah and Flaaten, 2017, Macleod et al., 2020).

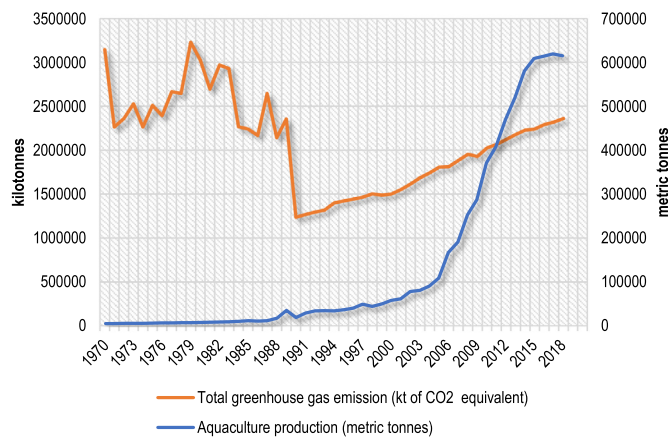
**Table 4**  
Unit root tests and optimal lag selection for aquaculture production, GHG emission, GDP and meat production.

		$\ln AQUAP$	Prob	$\ln GHG$	Prob	$\ln GDP$	Prob	$\ln MP$	Prob
		<i>t</i> -Statistic		<i>t</i> -Statistic		<i>t</i> -Statistic		<i>t</i> -Statistic	
At level									
ADF test statistic		0.466	0.984	-1.286	0.629	-2.323	0.169	-2.022	0.277
Critical values	1% level	-3.578		-3.578		-3.571		-3.568	
	5% level	-2.925		-2.925		-2.922		-2.921	
	10% level	-2.600		-2.600		-2.599		-2.599	
At level									
ADF test statistic		-9.038	0.000	-9.091		-3.851	0.005	-8.047	0.000
Critical values	1% level	-3.578		-3.578		-3.571		-3.568	
	5% level	-2.925		-2.925		-2.922		-2.921	
	10% level	-2.600		-2.600		-2.599		-2.599	
Optimal lag structure									
Lag		AIC	SIC	AIC	SIC	AIC	SIC	AIC	SIC
0		3.320	3.360	1.456	1.497	1.392	1.432	-2.811	-2.796
1		-0.427	-0.346	-1.263	-1.182*	-1.693	-1.614	-4.338*	-4.308*
2		-0.477*	-0.356*	-1.276*	-1.154	-1.909*	-1.790*	-4.311	-4.266
3		-0.447	-0.285	-1.268	-1.106	-1.883	-1.724	-4.299	-4.239
4		-0.402	-0.199	-1.242	-1.039	-1.841	-1.642	-4.262	-4.187
5		-0.439	-0.196	-1.199	-0.956	-1.797	-1.559	-4.243	-4.154

ADF-Augmented Dickey-Fuller.

AIC-Akaike information criterion.

SIC-Schwarz information criterion.

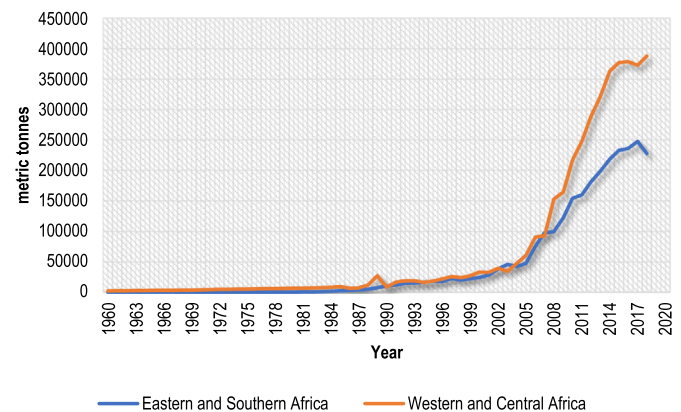


**Fig. 4.** Aquaculture production and GHG emissions in SSA from 1970 to 2018.  
**Source:** World Bank (Jang and Yamazaki, 2020, Kaleem and Sabi, 2021)

were however stationary at first difference. This indicates that the statistical properties of the time series variables (i.e., mean and variance) were initially varying (as depicted by their trends) but after differencing, they were constant, and thus independent of the time they were observed. Thus, bias was reduced by the first difference. The optimal lags that were used in the study were two based on the Akaike Information Criterion (AIC). It therefore shows that variables in the model were based on the past 2-year value.

Table 5 shows that the significant values in the unrestricted VAR were too low (25%), hence necessitating the use of a parsimonious VAR after eliminating multi-collinear variables. In the model, the Wald test was used to remove insignificant variables, and the significant values increased. In the parsimonious VAR model results,  $\ln AQUAP$  could be predicted by  $\ln AQUAP(-1)$ ,  $\ln GHG(-1)$  and  $\ln GHG(-2)$  at the 1% level as well as  $\ln GDP(-1)$  at the 5% level. The  $\ln GHG$  in the parsimonious model was projected by  $\ln AQUAP(-1)$ ,  $\ln AQUAP(-2)$  and  $\ln GHG(-1)$  at the 1% level.  $\ln GHG(-2)$ ,  $\ln GDP(-1)$ ,  $\ln GDP(-2)$  and  $\ln MP(-1)$  at the 1% level predicted  $\ln GDP$ .<sup>1</sup> The parsimonious model

<sup>1</sup> The percentages reflect the degree of accuracy/confidence in obtaining the identified results. At 5% level means the probability of error is 5%, therefore



**Fig. 5.** Aquaculture production in Central, Eastern, Southern and Western Africa from 1960 to 2018.

**Source:** World Bank (Jang and Yamazaki, 2020)

of  $\ln MP$  was predicted by  $\ln AQUAP(-1)$  and  $\ln GHG(-1)$  at the 1% level as well as  $\ln MP(-1)$  at the 5% level.

Table 5 shows that the previous year's  $AQUAP$  increased the current by 86.9%, while the previous year's  $GHG$  decreases the current  $AQUAP$  by 54.6%. This shows that  $AQUAP$  is strongly endogenous as it has a high influence on itself. This is even though the previous 2 year's level of  $GHG$  increases current  $AQUAP$  by 36.7%, and the previous year's  $GDP$  increases it by 20.6%. Table 5 also shows that the previous year's  $GHG$  and the previous 2 year's  $AQUAP$  increase current  $GHG$  by 98.2% and 29.8% while the previous  $AQUAP$  reduce the current  $GHG$  by 28.8%. These results also indicate that  $GHG$  is strongly endogenous as it has a high influence on itself. It is also observed that the previous 2 year's level of  $GHG$  reduce the current  $GDP$  by 21.2%, while the previous year's level of  $AQUAP$  and  $GHG$  increase the current  $MP$  by 4.1% and 14.2%, respectively.

we are 95% confident that the results reflected are correct. Likewise for the 1% level, we are 99% confident that this is the reflection of the results.

**Table 5**Vector autoregressive model for aquaculture production, GHG emission, GDP and meat production<sup>a</sup>.

	Unrestricted VAR				Parsimonious VAR			
	ln <i>AQUAP</i>	ln <i>GHG</i>	ln <i>GDP</i>	ln <i>MP</i>	ln <i>AQUAP</i>	ln <i>GHG</i>	ln <i>GDP</i>	ln <i>MP</i>
ln <i>AQUAP</i> (-1)	0.720***	-0.257**	0.060	0.050***	0.869***	-0.288***		0.041***
ln <i>AQUAP</i> (-2)	0.199	0.186	-0.018	-0.0005		0.298***		
ln <i>GHG</i> (-1)	-0.421	0.760***	0.113	0.150***	-0.546***	0.982***		0.142***
ln <i>GHG</i> (-2)	0.375	-0.094	-0.220	0.035	0.367*		-0.212***	
ln <i>GDP</i> (-1)	0.424	0.216	1.329***	-0.034	0.206**		1.364***	
ln <i>GDP</i> (-2)	-0.231	-0.238	-0.525***	0.039			-0.541***	
ln <i>MP</i> (-1)	-1.163	0.780	0.8201	0.173			1.300***	0.242**
ln <i>MP</i> (-2)	0.501	0.623	0.101	-0.134				
Constant	-5.147	3.732	5.169**	-2.739**	-3.556**		5.721***	-2.143***
Summary statistics								
R-squared	0.985	0.959	0.979	0.9356	0.984	0.955	0.978	0.924
Adj. R-squared	0.982	0.950	0.974	0.922	0.982	0.953	0.976	0.919
Durbin Watson stat					2.081	2.383	2.183	1.946
Model summary								
Log likelihood	256.325							
Akaike information criterion	-9.376							
Schwarz criterion	-7.958							

Sig. at \*\*\*1%.

\*\* 5% and \*10%.Previous year (-1).Previous two years (-2).

<sup>a</sup> See Appendix A for the standard errors and t-statistics.**Table 6**

Summary results of the parsimonious VAR, variance decomposition and impulse response function.

	ln <i>AQUAP</i>	ln <i>GHG</i>	ln <i>GDP</i>	ln <i>MP</i>
Parsimonious vector autoregressive				
	ü <i>AQUAP</i> (-1) increases <i>AQUAP</i>	ü <i>AQUAP</i> (-2) increases <i>GHG</i>	ü <i>GHG</i> (-2) reduces <i>GDP</i>	ü <i>AQUAP</i> (-1) increases <i>MP</i>
	ü <i>GHG</i> (-1) decreases <i>AQUAP</i>	ü <i>AQUAP</i> (-1) reduces <i>GHG</i>		ü <i>GHG</i> (-1) increases <i>MP</i>
	ü <i>GHG</i> (-2) increases <i>AQUAP</i>	ü <i>GHG</i> (-1) increases <i>GHG</i>		
	ü <i>GDP</i> (-1) increases <i>AQUAP</i>	ü <i>GDP</i> (-1) increases <i>GHG</i>		
Variance decomposition				
	ü <i>AQUAP</i> is strongly endogenous	ü <i>AQUAP</i> is weakly exogenous in the long run	ü <i>AQUAP</i> is weakly exogenous in the long run	
	ü <i>GHG</i> and <i>GDP</i> are weakly exogenous in the long run	ü <i>GHG</i> is strongly endogenous	ü <i>GHG</i> is strongly exogenous in the short run	
Impulse response function				
	ü <i>GHG</i> has negative impact on <i>AQUAP</i> in the short and long run	ü <i>AQUAP</i> has asymmetric impact on <i>GHG</i> in both the short and long run	ü <i>AQUAP</i> has positive impact on <i>GDP</i> in both the short and long run	ü <i>AQUAP</i> has positive impact on <i>MP</i> in both the short and long run
	ü <i>GDP</i> has asymmetric impact on <i>AQUAP</i> in both short and long run	ü <i>GDP</i> has asymmetric impact on <i>GHG</i> in both short and long run	ü <i>GHG</i> has asymmetric impact on <i>GDP</i> in the short and long run	ü <i>GHG</i> has positive impact on <i>MP</i> in the short and long run
	ü <i>MP</i> has negative impact on <i>AQUAP</i> in both the short and long run	ü <i>MP</i> had positive impact on <i>GHG</i> in both the short and long run	ü <i>MP</i> had positive impact on <i>GDP</i> in both the short and long run	ü <i>GDP</i> has positive impact on <i>MP</i> in both short and long run

The diagnostic tests for the unrestricted VAR model show that the model was less ideal because of the heteroscedasticity, non-normality, and serial correlations. However, the parsimonious diagnostic tests highlight normality and non-correlation (see Appendix B and C).

The variance decomposition shows that for a 10-year forecast, in the short to long run, more than 60% of the forecast error variance in *AQUAP* is influenced by itself, with a steady increase in the influence of *GHG* and *GDP* (Fig. 6a). It is also shown that in the short to long run, *GHG* influences itself, with diminishing influence from *AQUAP* (Fig. 6b). *AQUAP* does have an increased influence on the error variance of *GDP* in the long run (Fig. 6c), while in the short to long run, both *AQUAP* and *GHG* have a constant influence on *MP* (Fig. 6d). The impulse response function results are shown in Appendix D.

The results obtained from the study are summarised in Table 6.

#### 4. Discussion

The results show that there were two distinct periods of *AQUAP* in SSA. Pre-2006, there was suppressed production, which abruptly increased from 2006 onward. Kaunda and Chimatiro (2015) attribute this increase to the shift in *AQUAP* from smallholder food security orientated to a large-scale industry with the potential in improving economic development through food security, trade and employment creation. In the period 1970–1991, there was significant government support, research and development as well as significant donor support in Africa's *AQUAP*, with some countries such as South Africa, Zambia and Nigeria experiencing commercialisation (Kaunda and Chimatiro, 2015). During the period 1991–2006, donor support was replaced by the commercial sector. The period since 2006 has coincided with a focus on aquacul-



## Variance Decomposition using Cholesky (d.f. adjusted) Factors

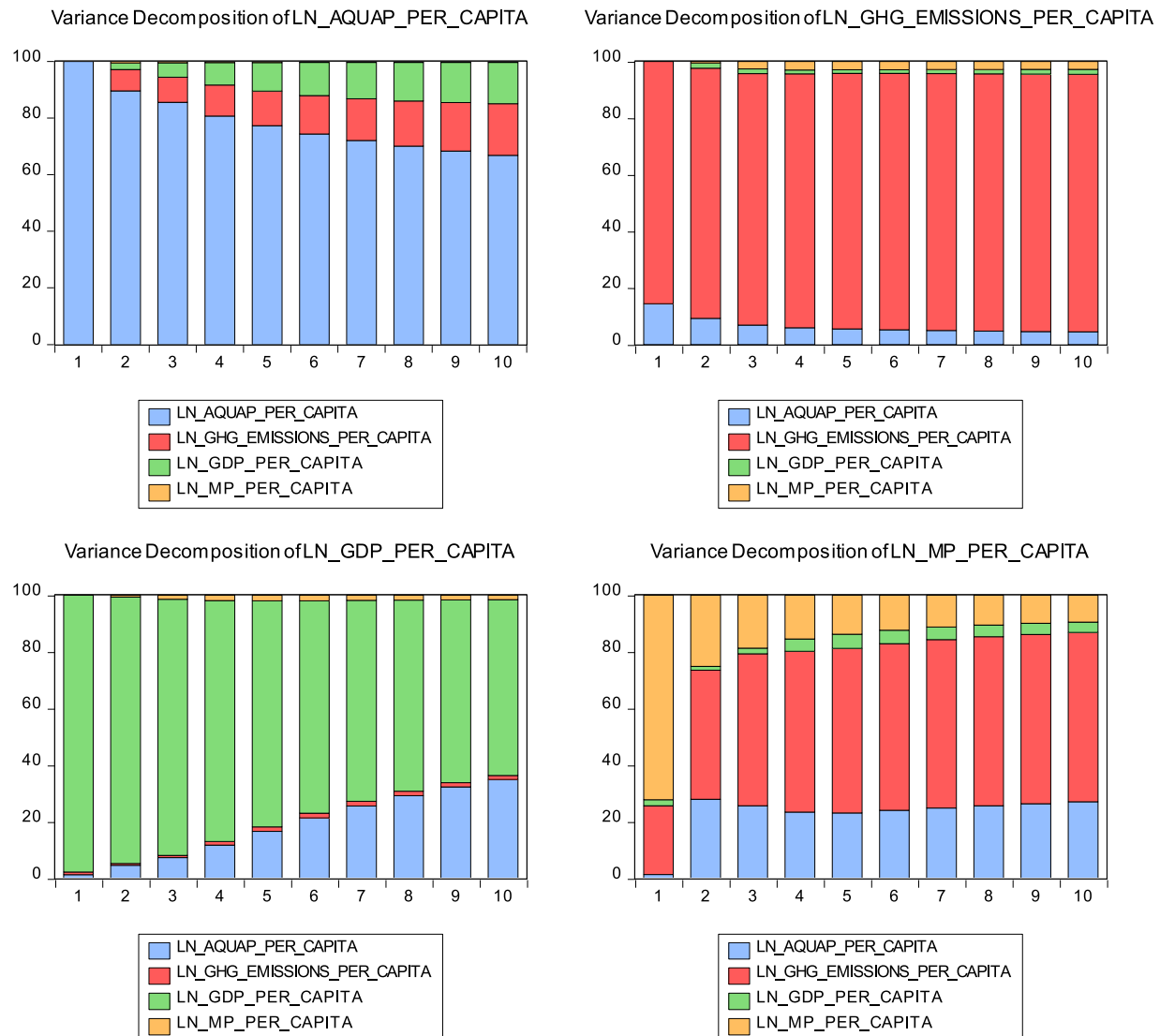


Fig. 6. Variance decomposition showing forecasts measured in percentages (y-axis) per year (x-axis) of aquaculture production, GHG emission, GDP and meat production.

ture and fisheries development through political will, especially after the AU-NEPAD Fish for All Summit (Kaunda and Chimatiro, 2015).

AQUAP in SSA has been dominated by Western and Central Africa. This can be attributed to increasing large-scale investments and fish production in Ghana, Uganda, Nigeria and Egypt resulting in increasing production (Cai et al., 2017; FAO 2018). This was attributed to the expansion of the small-medium scale private sector (Adeleke et al., 2021; Satia, 2011). Other authors reported a lack of quality fish species and seed that are well-suited for pond production in Eastern and Southern Africa compared to Western and Central Africa. For instance, Harohau et al. (2020a, b) reported that in the Solomon Islands, there is a disparity in production and its suitability. Similarly, Hasimuna et al. (2019) reported that similar to other developing countries, the quality of fish seed significantly constrains Zambia's aquaculture. Another factor is that fish farming is not a traditional practice in Eastern and Southern Africa; most people lack knowledge of the economic potential of aquaculture, and many view it as a form of subsistence means of survival and not commercial. Overall, awareness and interest were raised by the Food and Agriculture Organisation (FAO) Special Program for Aquaculture Development in Africa (SPADA) and

the 2005 NEPAD Summit paved way for aquaculture growth in Central and Western Africa. This was augmented by an increase in foreign direct investment (FDI), expertise and public support (Adeleke et al., 2021; Satia, 2011).

GHG emissions in SSA were haphazardly decreasing until 1991 when there was a gradual increase thereafter. According to Ntinyari and Gweyi-Onyango (2021), there was a 17% increase in GHG emissions between 1990 and 2005 globally, and increased in SSA due to changes in modern land-use adopted by the region. In Ghana, for instance, between 1990 and 2011, forestry, agriculture and other land-use changes resulted in a 20% increase in GHG emissions (Israel et al., 2020). This has resulted in the conversion of forests to cropland (thus reducing carbon sinks), increased animal population, land clearing, increased crop production and enhanced fertiliser application, all associated with enhanced GHG emissions.

The parsimonious VAR results showed that AQUAP was increased by the previous period's production, GDP and GHG emissions' previous two periods. However, the GHG emissions' immediate previous period tended to decrease AQUAP. The results further showed that AQUAP was strongly endogenous (having a strong influence on itself), while

GHG emissions and GDP were weakly exogenous in the long run. In addition, GHG emissions and MP had a negative impact on AQUAP in both the long and short run, while GDP had an asymmetric impact. An IPCC report indicated that aquaculture will be affected by GHG emissions in both the short and long run, a result of limited access to water, feeds and decreased productivity (Mbow et al., 2008). In China, Xu et al. (2022) also found that GHG emissions had an impact of AQUAP. This was mainly driven by emissions from feed materials and N<sub>2</sub>O production. Their study however proposed that this could be minimized through varying the species that were produced as there were differences in their GHG emissions. Robb et al. (2017) also found that aquaculture feed was the main emitter of GHGs. The contribution of SSA to GHG emissions is minimal since aquaculture in SSA is not yet intensified compared to a global scale. GHG global emissions from AQUAP rise with the increase in production. SSA region produced 557 tonnes for four aquaculture groups in 2017 with relative GHG emission of 1.576 tonnes of CO<sub>2</sub> (Macleod et al., 2020). The aquaculture industry in SSA is growing and the GHG emission is linked to this growth. For example, Zambia experienced an alarm in AQUAP for large-scale ponds from 2009 to 2014 (Kaminski et al., 2018). Coincidentally, this occurs during the period when GHG in SSA was experiencing constant growth between 2006 and 2018. UN, (2022) advocate for sustainable improvement in aquaculture production and as well as improving producer resilience and adaptive capacity to counter the effect of GHG emissions induced climate change.

The results also showed that GHG emissions were increased by the previous period's amount and GDP as well as the previous two periods' AQUAP. However, the previous period's AQUAP reduces GHG emissions. GHG emissions were strongly endogenous to itself, while AQUAP was weakly exogenous in the long run. Meat production (MP) had a positive impact while AQUAP and GDP both had an asymmetric impact on GHG emissions. This shows that MP had a causal effect on GHG emissions while AQUAP and GDP had both an increase and decrease on GHG emission. Yuan et al. (2019) showed that AQUAP in China significantly increased the GHG emitted. This was corroborated by Ahmed et al. (2019), attributing the increases in GHG emissions to changes in land use. The haphazard decrease in GHG emissions before 1991 can be explained by false starts in AQUAP. According to Fakoya et al. (2009) there is a mismatch between technologies introduced by the developed countries to the practical needs of SSA. Post 1991 the increase in GHG corresponds with an increase in aquaculture (Fig. 4). The increase in AQUAP along the value chain could be the reason GHGs increased. Satia (2011) reported that the increase in AQUAP during the same period in Kenya was due to the enhanced participation and activities of the private sector.

In addition, the GHG emissions' previous two periods reduce GDP. GHG emission is strongly exogenous on GDP in the short run while AQUAP is weakly exogenous in the long run. AQUAP has a positive impact on GDP while GHG emissions have an asymmetric impact in the long and short run. These results corroborate the Environmental Kuznets Curve (EKC) theory of increased GHG emissions sustaining economic growth initially and then concerted efforts to reduce them further perpetuate economic growth. Studies in China corroborate the findings of a relationship between GHG emissions and economic growth (Xu et al., 2022). A study by Kwakwa and Adusah-Poku (2020) in Egypt found that an increase in AQUAP increased carbon emissions in the long run. This is through the utilisation of high-carbon emitting equipment, where the demand for more equipment will increase production from manufacturing companies.

The results further indicated that in the previous period, GHG emissions and AQUAP increase MP. AQUAP and GHG emissions had a positive impact on MP in both the long and short run. Though unexpected, such a relationship is explainable through the complementarities that can be observed between meat and fish production. Macleod et al. (2019) highlighted the dependence of manufactured feed production on meat and bone meal. However, Kristofersson and Ander-

son (2006) also indicated that fishmeal was also critical for use in animal and AQUAP. In SSA, the findings are augmented by the fact that both aquaculture and terrestrial livestock production are complemented to provide food security for smallholder households (Obiero et al., 2019). Simdi and Seker (2021) found that livestock production had a causal relationship with GHG emissions. In this instance, livestock production increased GHG emissions. However, enhanced GHG emissions through stock feed manufacturing can also have a positive impact on MP. According to Sonesson et al. (2009) GHG emissions from stock feed production constitute between 35%–80% of total GHG emissions from MP. Livestock stock feed production also constitutes 33% of croplands, with their associated GHG emissions (FAO, 2012). Thus, stock feed production and its associated GHG emissions can have a positive effect on MP.

## 5. Conclusion

This study outlined the relationship between GHG emission and AQUAP in SSA. The parsimonious VAR model used in this study produced relationships with accuracy levels that are commensurate with the needs of most stakeholders interested in aquaculture development. The model can be considered reliable because it performed well in both unrestricted and better in the parsimonious situation. Forecast techniques such as variance decomposition and impulse response function were used to predict the future relationship between these variables. The data that was used in the study was longitudinal time series from 1970 to 2020. The results show two distinct growth periods in SSAs AQUAP, which has been dominated by Ghana, Uganda, Nigeria, and Egypt. Furthermore, in both the long and short run, GHG emissions had a negative impact on AQUAP. It was also observed that AQUAP had an asymmetric impact on GHG emissions in both the long and short run. In both the long and short run, AQUAP had a positive impact, while GHG emissions had an asymmetric impact on GDP.

In conclusion, aquaculture has been increasing in SSA due to expansion and industrialization in the sector, especially in Western and Central Africa. This has been backed by donor, government and private sector support and an expansion of the small-medium private sector. Modernization and land use changes have resulted in the increase of GHG emissions in SSA. It is further concluded that an upward trend in AQUAP was dependant upon the immediate previous levels of AQUAP and GDP, as well as 2-year previous level of GHG emissions. However, the immediate previous level of GHG emission resulted in a downward trend in AQUAP. Increase in GHG emission will increase the AQUAP in the long term. Thus, AQUAP is negatively affected by GHG emissions. The effects of GHG emissions on AQUAP in SSA can be explained by the initial phases of EKC, where a long-term increase in GHG emission will result in expansion of the AQUAP sector due to increased energy utilization which is currently in the form of fossil fuel. However, in the immediate term, GHG emissions are likely to negatively affect AQUAP through acidification, water pollution, species redistribution, climate extremes and salinity, amongst others.

It can also be further concluded that an upward trend in GHG emission was dependant upon its immediate previous levels and GDP, as well as 2-year previous level of AQUAP. However, the immediate previous level of AQUAP resulted in a downward trend in GHG emissions. The effect of AQUAP on GHG emission has been the result of production practices and value chain behaviours. This is through shifting from a sustainable small-scale production system in the short run to commercialised and industrialised systems in the long run, which increases GHG emissions. Both GHG emissions and AQUAP play significant roles in economic development. Increase in AQUAP will increase the GHG emissions in the long term. This also reinforces the EKC initial stage where in the long term, due to the expansion of the AQUAP sector, there will be increased GHG emissions.

Overall, the paper depicts the significance of balancing AQUAP's environmental sustainability with economic growth. The effect of GHG emissions on economic development shows that SSA is still in the devel-

opment stage and heavily requires GHG emissions for its development in the intermediate future. Investing in cleaner technologies and encouraging sustainable production practices can have the dual effect of economic growth and circumventing environmental degradation. This can be through the promotion of climate smart aquaculture as it responds to the growing demand in a sustainable manner. The study also recommends introducing climate resilient species that can aid in combating the effect of GHG emissions of AQUAP. However, this should take into consideration the ecological balance as invasive species might overrun the indigenous ones. Integrated aquaculture-livestock-crop production systems for smallholder producers can be promoted as well as provide policy guidelines on GHG emission in AQUAP which are lacking. The findings show that the VAR model has enormous potential for predicting relationships between aquaculture, GHG emissions, and economic growth. Exploring different techniques that can be used to maximize aquaculture development can help SSA progress in aquaculture by providing information on relationships between indicators/ variables that influence aquaculture in various locations. The study further recommends upscaling AQUAP in SSA given its infancy, huge economic potential, sustainability and low GHG emission potential. There should be expansion and promotion of aquaculture especially in Eastern and Southern Africa which lack knowledge and economic benefits of the sector. This can mimic the FDI, expertise and public support as observed in Central and Western Africa. Further enquiry into the reinforcing effects of AQUAP and GHG emission can concentrate on a cost-benefit or cost effectiveness analysis of recommended emission reduction strategies. Another point of entry is conducting studies that partitions the value chain and pinpoint where there is high emission and where further mitigation strategies can be targeted. A study that augments the Water-Energy-Food Nexus in sustainable AQUAP can highlight GHG emissions from a sectoral view which can add into the knowledge of how GHG emissions affect AQUAP.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

The authors do not have permission to share data.

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### Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.envc.2023.100737](https://doi.org/10.1016/j.envc.2023.100737).

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