Three essays on the economic impacts of climate change and water scarcity in the Nile River Basin

Edeo Mude Kalo

This thesis is presented in fulfilment of the requirements for the degree of

Doctor of Philosophy

Department of Economics

University of Strathclyde

July 2025

This thesis is dedicated to my mother, Fatima Lenjiro, and iconic artist Hachalu Hundessa Bonsa, who have both profoundly impacted my journey with their memories and legacies.

Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree. The copyright of this thesis belongs to the author under the terms of the United Kingdom Copyright Acts as qualified by University of Strathclyde Regulation 3.50. Due acknowledgement must always be made of the use of any material contained in, or derived from, this thesis.

Edeo Mude Kalo

July 2025

Acknowledgements

I am deeply grateful to almighty Allah, who is merciful and kind enough to give soul, physical ability and knowledge to finish this study. His divine guidance has been the cornerstone of my academic journey, instilling in me the strength and wisdom to overcome challenges. I would like to express sincere thanks to my supervisor, Dr. Grant Allan, for his exceptional guidance, encouragement, and unwavering support throughout this journey. His insightful feedback and expertise have been invaluable in completing this work. Without his support, it would be impossible. His role in my academic journey is genuinely significant, and I deeply appreciate his contributions. Dr. Marco Alfano's support would be invaluable, particularly in the initial stages of my study, especially for chapter one. His guidance has been instrumental in this accomplishment. Also, I would like to express great appreciation to Dr. Kevin Connolly for his crucial support during the analysis of third chapter, especially regarding the use of the CGE model. His constructive feedback and suggestions were pivotal in carrying out the study. I would like to thank the entire economic department, including the teaching and administration staff. Many of you might be taught, advised, or supported me during my studies. Moreover, I thank Fiona McIntosh, who supported my entry into the MSc program and encouraged me to pursue a PhD.

I am deeply grateful for the specific support and opportunities offered by Strathclyde University and the Fraser of Allander Institute. Their financial support, research facilities, and the platform they provided for my personal growth and knowledge enrichment have been invaluable to my academic journey.

I thank Restore Birmingham, who helped me journey into the academy and life settling in the UK. The support during my family reunion process and after the arrival of my family was special. I give special thanks to Jeremy Thomson, whose introduction to Dr Ali Ahmad, a Warwick University lecturer, was a pivotal moment in my academic journey. Dr. Ali's mentoring significantly transformed my academic experience. His unwavering support has given me self-confidence and determination, contributing to my professional growth in the UK. I am deeply grateful for the combined support from Restore Birmingham; your assistance and motivation have significantly impacted my life, and I sincerely thank you for everything you have done to help me achieve this success.

Finally, I want to express my deepest, boundless gratitude to my beloved family, especially my wife, Fatuma Gango. Her incredible support and sacrifices have been the cornerstone of my academic success. Her devotion, affection, and inspiration are invaluable to me, and I could not have reached this point without her solid support. Their love and encouragement have been a constant source of strength, making this journey not just mine, but ours. Thank you to my close friends in England and member of our community in Scotland, who have consistently inquired about my progress in studies and life. You have been an essential part of my journey toward completing my studies.

Abstract

This thesis applies economic theories to analyse the effects of climate change on food prices, measure virtual water content in international trade, and examine the implications of climate-induced agricultural productivity loss in the Nile River Basin (NRB) economy. It begins by examining the impact of trade anticipation on domestic food prices in East Africa, with a focus on staple foods. A trader anticipation model is proposed to analyse short-run price responses to weather shocks, emphasising the importance of traders' expectations of future harvests influenced by weather updates. The study finds that weather shocks have a significant influence on food price volatility, and policy interventions, such as export restrictions, can help mitigate price spikes in the short run. However, weather events still exert a powerful effect on food prices, highlighting the need to account for traders' anticipatory behaviours.

Building on the analysis of food prices, the research then explores the virtual water content in international trade to identify an alternative water source for the NRB. Using a multi-regional input-output framework with a water-extended model, it assesses the domestic and global water footprint of the NRB region. The findings indicate that the NRB region was a net exporter of virtual water, despite facing severe water scarcity issues, while Europe, Asia, and North America were net importers. The analysis indicates that most NRB countries have shown low water dependency, which improved in 2015 compared to 2007 due to various factors, including export restrictions during the global food crisis. This improvement can be attributed to the adoption of virtual water dependency trends, which helped mitigate the impact of water scarcity. However, high water self-dependency for domestic consumption and export signifies over-exploitation of water resources, posing challenges for sustainable water management. The study highlights the importance of developing more effective water-sourcing strategies and fostering international cooperation to ensure water security in the NRB region.

Finally, the thesis examines the effect of climate change-induced agricultural productivity loss on Egypt's economy using a CGE model. The findings suggest that agricultural productivity losses could have a significant impact on total output, value-added, household consumption, and employment in the long run. Agriculture, the most affected sector, has experienced a decline in production, resulting in a decrease in GDP and household income. Disruptions in agriculture have spillover effects across the economy, resulting in substantial welfare losses and increased unemployment. The study highlights the agricultural sector's vulnerability to climate change and the consequent socio-economic impacts. It emphasises the need for a national adaptation plan to mitigate climate risks, with a primary focus on water resources. Such a plan should include measures to enhance agricultural resilience, improve water use efficiency, and support affected communities to ensure economic stability and food security.

This thesis underscores the pressing need for targeted policy interventions and future research to mitigate the impacts of climate change on food prices, water resource availability, and economic stability in the NRB. The findings are pivotal for informing policymakers and academic researchers about fundamental areas of intervention and research gaps related to NRB regional climate resilience.

Table of contents

List of figures

List of tables

Chapter 1

Thesis Overview

1.1 Introduction

This thesis comprises a set of interconnected essays that explore the exposure of the economies of the Nile River Basin (NRB) countries to climate change. It focuses specifically on price volatility, virtual water flows, and the economic effects of agricultural productivity loss. These essays provide a comprehensive analysis, building on the existing academic literature for the NRB and incorporating considerable climate change scenarios.

The NRB region was chosen for this study due to my extensive research and personal experiences in an area that has been profoundly affected by climate change. The NRB is a critical African region facing severe challenges such as price volatility, erratic rainfall patterns, water shortages, and rising temperatures (Awange, 2021). These issues have made the NRB one of the most vulnerable regions to the impacts of climate change. My long-term engagement with the region has provided me with a deep understanding of the complexities and features of these challenges. The NRB's unique environmental and socio-economic conditions make it an ideal case study for examining the broader implications of climate change on food prices, water resource management, and economic stability. Egypt was chosen for the case study because it is a downstream nation of the Nile River Basin and relies heavily on water from upstream countries. This makes it particularly vulnerable to climate change-induced water shortages, which can impact its national economy. This dependency means that all climate change effects in the region, such as water shortages, are acutely reflected in Egypt. The country's reliance on the Nile for its water needs makes it a critical example of how climate change impacts can cascade through the region, affecting economic stability and resource availability. By focusing on Egypt, this thesis aims to provide valuable insights into the broader implications of climate change on downstream nations and support the development of strategies to mitigate these effects.

Initially, an econometric panel approach was employed to assess the extent to which weather shocks impact food prices, specifically through a mechanism referred to as "trader anticipation." This conceptual framework posits that traders adjust prices based on expected changes in supply resulting from adverse weather events, thereby transmitting climatic variability into market outcomes (Robinson et al., 2024). Understanding this channel is critical for comprehending short-term price volatility and market behaviour in climate-sensitive economies (Schlenker, 2024).

The examination of weather shocks on food prices through trader behaviour and export restrictions provides a foundational insight into the broader economic dynamics of the Nile River Basin (NRB). The selected Eastern African countries face complex and interconnected challenges that stem from both environmental variability and structural economic dependencies (Bailey, 2015). This component of the study examines how climatic events impact food markets and trade responses, thereby identifying key vulnerabilities within the regional agri-food system. The six countries considered in this analysis are not only geographically interconnected by the NRB but also share overlapping dependencies on water resources and agriculture, making them particularly susceptible to climatic and hydrological shocks (Robles et al., 2009).

Building on this foundation, the subsequent analysis shifts focus to the concept of virtual water trade, which refers to the indirect transfer of water through the trade of water-intensive products (Aulerich et al., 2014). A multi-regional input-output (MRIO) model is utilised to quantify the extent of virtual water embedded in international trade flows among NRB countries, alongside an assessment of their respective water scarcity levels. This approach enables a nuanced understanding of how trade can serve as a mechanism for redistributing water stress, potentially enhancing regional resilience as a strategy. The findings underscore the importance of trade policy in mitigating the effects of water scarcity and in supporting sustainable resource management across national boundaries (Elshennawy et al., 2016).

Finally, the investigation turns to a country-specific case study of Egypt, employing a multi-sectoral Computable CGE model. This model is a widely used tool in economics that allows for the analysis of the effects of various economic policies or shocks on a complex economic system (Willenbockel et al., 2013). In this case, it is used to assess the economic implications of climate-induced productivity loss in the agricultural sector. As a downstream nation heavily reliant on Nile water flows, Egypt is particularly exposed to upstream climatic disturbances and regional water policy decisions (Aerts et al., 2024). The CGE analysis highlights the cascading economic effects of reduced agricultural productivity, with broader implications for food security, macroeconomic stability, and socio-political resilience (Abtew, 2025). These results emphasise the urgent need for integrated climate adaptation and water governance strategies within the NRB.

Collectively, the findings from these three essays provide a comprehensive examination of the interdependencies between climate variability, water resources, and economic outcomes in the Nile River Basin. The thesis contributes to the academic literature on environmental economics and regional trade, while also providing policymakers with actionable insights. Given the urgent need for sustainable development and climate resilience in one of the world's most water-stressed regions, this research highlights the importance of immediate action based on a deeper understanding of the challenges and potential solutions in the NRB.

1.2 Motivation

The motivation behind this thesis is to address the adverse effects of climate change on the economies of NRB countries, with a specific focus on price volatility, virtual water flow, and the economic consequences of water scarcity. The purpose and problem justification of the research are detailed as follows:

Since the financial crisis erupted in the Western economy in 2007/08, East Africa experienced sharp and rapid rises in food prices, continuing even when international market prices fell noticeably by late 2008. This led to acute food shortages for over 50 million East Africans, primarily low-income families who were net purchasers of food (J.Cohen, 2009; Korotayev and Zinkina, 2015). The continuous increase in food prices resulted in domestic violence, conflict, and civil uprisings due to unemployment, poverty, and social injustice (Karla, 2011). The causes of the food price hike are multidimensional, including reduced agricultural production, climate variability, and water scarcity (Easterling et al., 2007). Climate variability and change are anticipated to continue exerting upward pressure on food prices, increasing poverty and malnutrition rates. Therefore, the primary aim of this thesis is to understand the range, intensity, and nature of the domestic factors driving food price volatility in the selected countries within the East African region.

Due to climate change, physical water availability in the NRB region is crucial, as it is exposed to drought and rainfall fluctuation (Melesse and Demissie, 2024). The water problem in Africa is characterised by the mismatch between the spatial distribution of water resources, economic development, and primary factors of production, combined with inadequate water resource management. Sustainable water resource management has been a typical challenge for East and North African countries in arid and semi-arid regions. Fast economic growth, intensive lifestyles, and demand for water resources have become unprecedented, with climate change likely exacerbating the problem (Vorosmarty et al., 2000). Being a net exporter of water-intensive agricultural products from the NRB puts additional pressure on water availability, which is essential for economic activity. The concept of virtual water in international trade has emerged as a crucial subject in water resource management. In the study conducted by Hirwa et al. (2020), it was highlighted that Virtual water flows through trade play a key role in addressing the region's water scarcity. Therefore, the second objective of this thesis is to evaluate the extent of virtual water in international trade, the degree of water scarcity, and its implications. This evaluation aims to empower environmental stakeholders and policymakers to make informed decisions about water allocation and policy direction in international trade.

Finally, the current pressing problem revolves around the climate change-induced impact on the NRB economy, specifically the reduction in agricultural productivity. This issue is of immediate concern for Egypt, given its heavy reliance on the upper Nile riparian [1] for physical water flow. The country's economic activities, particularly in agriculture and industry, are at risk due to the region's vulnerability to climate shocks. Agriculture plays a central role in Egypt's economy, and understanding its vulnerability to climate change is essential for designing effective policy responses. While previous studies have used CGE models to explore similar issues in other regions, several critical gaps remain. For instance, Banerjee et al. (2021) analysed agricultural losses in Latin America and the Caribbean but did not incorporate household-level adaptation strategies, which are highly relevant in a nation's socio-economic landscape. Liu et al. (2020) assessed the sectoral impacts of climate change in China, particularly in water-scarce provinces. Still, their model lacked feedback mechanisms for trade, which limited its ability to capture dynamic economic responses. Similarly, Abeysekara et al. (2024) examined the economic consequences of climate change on South Asian agriculture, finding significant reductions in output and growth. However, their model did not account for regional heterogeneity within South Asia, which constrained its ability to reflect localised climate risks and agricultural vulnerabilities.

Overall, this thesis addresses three key objectives: analysing the impact of weather updates and trader anticipation on food prices, evaluating the extent of virtual water flow in international trade, and examining the effects of climate change-induced agricultural

[1] Upper riparian refers to the upstream countries of the Nile River basin mainly those in the Blue Nile (e.g., Ethiopia) and White Nile (e.g., Uganda, South Sudan) catchments that contribute the majority of the Nile's water flow to downstream nations like Egypt.

productivity loss on the national economy. The findings are pivotal for informing policymakers and academic researchers about fundamental areas of intervention and research gaps related to NRB regional climate resilience.

1.3 Contributions

This thesis examines the adverse effects of climate change on the economies of NRB countries, with a focus on price volatility, virtual water flow, and the economic implications of water scarcity. The research makes significant contributions to the academic literature in several key areas.

The study begins by examining the reasons behind the surge in food prices in the selected countries within the East African region. It explores how weather-induced trader anticipation disrupts agricultural commodity markets, leading to unpredictable price fluctuations for staple foods. Additionally, it examines the role of government policy interventions, such as export restrictions, in mitigating food price spikes. This research fills a gap in the literature by assessing the impact of domestic factors and the effectiveness of policy responses on food price volatility, providing valuable insights for policymakers.

Furthermore, the study enhances understanding of virtual water and its role in addressing water scarcity in developing regions, particularly in Africa. It utilises MRIO analysis to evaluate virtual water content in international trade, uncovering the links between economic activity and water use. By examining virtual water exports and imports, the study shows how these factors influence sustainable water availability and help mitigate water scarcity in regions frequently affected by drought and water stress. The research offers policy recommendations to tackle water challenges exacerbated by climate change, making it highly relevant for environmental stakeholders and policymakers.

Finally, the study empirically analyses the impact of climate change-induced reductions in agricultural productivity on Egypt's economy using a CGE model. It examines how the depletion of natural capital affects key economic indicators, including GDP, employment, exports, and household income and consumption. The study highlights the agricultural sector's vital role in Egypt's economy and demonstrates how reductions in natural capital inputs directly influence broader economic stability. This evidence-based approach provides critical insights for researchers and policymakers, emphasising the need for sustainable environmental management strategies to enhance Egypt's economic resilience.

Chapter 2

The effect of Weather Shocks on Food Price: A Trader Anticipation and Export Restriction Approach

2.1 Introduction

Food price volatility is a persistent concern for consumers, producers, traders, policymakers, and all other stakeholders in the food value chain. They all have questions about price volatility and are passionate about the future development of food prices. In this study, food price volatility is defined as the concern related to the tendency of Individual crop prices vary (regarding availability and frequency) around their mean value (Marilyne, 2011). Several studies have discussed the factors that contribute to price volatility. For example, the study conducted by Kane et al. (2015). However, these studies primarily focused on the international factors that determine price changes. Agricultural commodity prices are predominantly exposed to domestic risks, such as production, marketing, institutional and financial risks. In some countries, such risks were formerly absorbed by the market regulation and price support policy (Matthews, 2010). The program aims to limit the government's role, including price control, subsidy and stock holding in the market, promote private sector participation, remove economic restrictions, and ensure market-driven price determination (Dennis, 2003). Since then, it has been argued that the adjustment program disregarded domestic commodity price regulations. This has partly affected international commodity pricing. However, there is a need to adjust the price policy to local conditions more effectively by incorporating social objectives and concerns, while also emphasising the improvement of productivity and production itself. However, this policy was reversed by many countries during the economic crisis of 2007/08. During this period, there was a sharp increase in food prices, especially for staple foods such as wheat, maize, rice, and sorghum. This increase significantly affected low-income families, particularly in Africa (Demeke et al., 2008). Several countries have developed price mechanisms to reduce the impact of sudden price surges through policy interventions, such as trade restrictions or export bans and various forms of price control (Gouel, 2013). In this study, we will examine whether these policy changes affect the level of price change in the region. In addition to the policy change, food prices are influenced by both domestic supply and demand-side factors, such as extreme weather events and increasing food demand. Fast-growing economies in developing nations and population pressure are demand-side factors that anticipate price changes. On the supply side, weak investment in the agricultural sector, fluctuation of climatic conditions, and low levels of food inventory are often cited as contributing factors to food price swings. In addition to specific commodity market fundamentals, macro and microeconomic factors are assumed to influence price changes, such as exchange rates, interest rates, and other domestic policy changes. Other researchers have assessed these factors. However, the effect of climate change, specifically through global warming, has not been documented. Hence, this essay focuses on evaluating the uncertainty of climate change impacts on food prices in selected East African countries, including Ethiopia, Kenya, Rwanda, Sudan, Tanzania, and Uganda. While East Africa comprises a broader set of nations, these six have been selected for their significant roles in the region's economy, substantial agricultural sectors, climatic dynamics, significant populations, relative political stability, availability of reliable data, and representation of the region's diverse conditions. This selection provides a robust foundation for analysing the impact of climate dynamics on food price volatility and economic stability. These countries are also part of the Nile River basin, which is a key focus of this research.

The rise in food prices in 2008, price peaks in 2011 and 2012, and the subsequent continuous increase in developing countries are the main reasons for the growing interest in studying this area. Many studies have concluded that higher food prices result from shifts in demand and supply factors. Some of the factors related to demand include high energy prices, increased demand for biofuels, and the ongoing growth of the world population at the rate of 1.14% (Worldometers, 2019). On the supply side, many researchers have concluded that declining grain stocks, reduced investment in the agricultural sector, and deteriorating crop yields due to climate change and extreme weather events are decisive factors affecting food supply (Liliane and Charles, 2020). Supporting this view, Deschenes and Greenstone (2007) provides empirical evidence that random fluctuations in weather have a significant impact on agricultural output. Their findings highlight how climate variability—an expected consequence of climate change—can disrupt crop yields, thereby influencing food availability and contributing to price volatility. This reinforces the relevance of climate change as a key driver of food supply instability. For example, there were decreases in farm production of up to 90% during the drought years in some parts of Kenya, Ethiopia and Somalia. As a result of these weather shocks, food prices soared to new peaks (Cenacchi, 2014). This illustrates how the supply side of the commodity market is closely tied to climate factors. Another essential point to consider is the substitution effect among agricultural commodities. A supply shortage of maize can affect the price trend of wheat or other closely related cereal crops, and the substitutability effect of agricultural commodities also contributes to price movement (Trostle et al., 2008). Therefore, the price volatility of one crop also affects the price volatility of other substitute crops. Understanding this interconnection within the agricultural commodity market is crucial when considering price volatility. Generally, there is limited knowledge about the price volatility behaviour of the agricultural commodity market in a dynamic context.

Few studies have been conducted in other parts of the world, and limited research has been conducted in Africa thus far.

This study has examined the standard effect of weather shocks or climate change on the prices of cereal grains at the market level, with a focus on weather-driven supply shocks. Several previous studies have emphasised the empirical influences of weather shocks on crop yield and their impact on biophysical plant growth and labour productivity (Turvey, 2001). Likewise, the commodity price response to the supply shocks has been explored in several studies. The crucial causal link between commodity prices and weather shocks is the effect on crop yield. Therefore, the persistence of such shocks signifies the presence of several channels linking food prices and weather shocks.

First, updated information about weather shocks can create anticipation regarding future harvests, which may simultaneously influence the market prices of the current stock. Second, at the time of harvest, grain prices will converge to their equilibrium prices as the actual harvest meets the supply volume and market demand. With well-informed market agents and adequate financial products, the final market-clearing prices may not be significantly affected, as price adjustments can occur steadily over the entire period between the weather shocks and the final harvest. This speculation increases the annual variance of food prices, spreading the effect of price spikes over several periods.

Additionally, the yield response to marginal changes in climate conditions can vary depending on the inputs used and weather conditions. Hence, one can envision the nonlinear relationship between agricultural prices and weather shocks following the nonlinearity in the production function. Understanding the ultimate link responsible for weather disruptions in agricultural price formation models is particularly useful for studying price shocks at a regional level. Well-designed food security and early warning systems are essential for modelling the consequences of weather shocks on local food prices. As a result, the impact of rainfall and temperature anomalies on food prices can be designed or modelled in numerous dimensions. Modelling the theoretical assumptions and data constraints consistently leads the way toward market agents' reactions to weather disruptions and updates their views on future harvest. Few empirical studies based on economic theory have been conducted to investigate how abnormal weather shocks affect local market prices. Thus, understanding how market agents utilise weather information is crucial for designing efficient policy interventions.

In this work, we explore the role of weather anomalies in shaping agents' anticipations regarding harvests and future availability, as well as their impact on market prices. Agents can observe the current weather situation and its impact on biophysical plant growth, and their prompt actions based on weather predictions for future availability can significantly impact contemporary market prices. Weather shocks can disrupt future supply, causing market agents to adjust prices for past harvests. Therefore, this study is designed based on intra-annual competitive storage models, with a defined scenario of weather news influencing the process of forming expectations depending on sets of weather information updates. The theory of the competitive storage model informs the empirical investigation of the causal relationship between weather shocks and agricultural commodity prices.

2.1.1 Motivation

East Africa experienced sharp and rapid rises in food prices during 2007/08 when the financial crisis hit developed economies (Rapsomanikis et al., 2009). While food prices on international markets fell noticeably by late 2008, domestic food prices in developing countries continued to remain high. Over 850 million of the world's population faced acute food shortage (J.Cohen, 2009). Most of this population consisted of families with low-income earnings who were net food purchasers in developing countries. Consequently, the rise in food prices had a severe impact on the lives of this community.

Furthermore, the continuous increase in food prices led to domestic violence, conflict, and civil uprisings due to unemployment, poverty, and social injustice in several parts of the Middle East and East African countries (Karla, 2011). The causes of the food price hike have become multidimensional, and their influence has varied over time. Some of the cited factors are related to the region's reduction of agricultural production, climate variability, or water scarcity. The trend of lifting subsidies began during the 1980s and 1990s, coinciding with the implementation of structural adjustment reforms in the public sector. Climate variability and change are anticipated to continue exerting upward pressure on food prices, notably in Sub-Saharan Africa (SSA) and Asia, whereby the rates of poverty and malnutrition are rising among the population (Easterling et al., 2007).

Therefore, this essay focused on understanding the range, intensity, and nature of these domestic drivers of food price volatility in low-income countries.

2.1.2 Research Objectives

This study aims to empirically investigate the causal relationship between food price volatility and extreme weather shocks and examine the role of policy actions in mitigating local food price volatility in East Africa. The specific pertinent questions addressed in this paper are:

1. What role does climate variability play in food price hikes?
2. To what extent can export restriction policies contribute to price regulation?

2.1.3 Significance of the Study

The principal causes of high food prices in the developing world have been a concern of citizens and governments since 2007/08. Challenges such as climate change, global economic slowdown, and trade wars among developed economies have presented unique difficulties for the less developed world. These changes have disrupted the agricultural commodity market, leading to either scarcity or unpredictable price surges for staple foods in East African countries.

Additionally, the domestic market faces challenges due to a lack of proper market integration, institutional quality, and regional instability caused by factors such as governance issues and other socio-economic factors. While many research works have been carried out in this area, most of them have emphasized international and financial perspectives. However, recurrent domestic factors contributing to price volatility, such as weather, political instability, institutional quality, and policy actions, have not been thoroughly assessed and documented in scientific studies.

Therefore, this study aimed to evaluate the effect of domestic factors on food price volatility in the East African region and Policy responses. It aims to contribute to the existing literature on the political economy of food prices and provide insights for future policymakers in considering the role of the domestic market in their decision-making processes.

2.2 Literature review

2.2.1 Definition and Measuring of Food Price Volatility

Volatility is the variability of price series around its central value, which is the tendency of individual crop price deviations from a mean value. According to some researchers Dehn et al. (2005), food price volatility is the rate at which the price of a commodity increases or decreases over a set period. Price Volatility can be measured by computing the standard deviation or coefficient of variation over a year to demonstrate the magnitude of commodity price variation.

Additionally, the discussion began with how to accurately estimate or measure price volatility. According to (Huchet, 2011), price volatility can be estimated unconditionally as a coefficient of variation or variation in price return. However, many researchers have criticised the use of unconditional volatility. Gilbert and Morgan suggest using conditional volatility that can be estimated with the help of ARCH [1] and GARCH [2] models for the existence of persistence in price dataset (Gilbert and Morgan, 2010).

2.2.2 Rationale Behind volatility

The theoretical concept of volatility refers to the uncertain movement of a random variable over time. Particularly, volatility in agricultural commodity prices assumes several uncertainties that affect the income security of producers and the welfare status of consumers and also threaten the overall agricultural market performance (FAO et al., 2011). Hence, the volatile prices of agricultural commodities in general, and food prices in particular, are a policy priority that engages the attention of economists and policymakers. Agricultural commodity prices have been guiding and determining the fate and fortune of nations due to the volatility prevailing in the agricultural market (Dasgupta and Chakrabarty, 2009). It has been widely argued in various literature that the origin of food price volatility, among other factors, is predominantly caused by population pressure, climate events, globalisation, and conflict. However, before proceeding with the determination of volatility, it is essential to check the existence of volatility and its pattern using an econometric approach, such as the Autoregressive Conditional Heteroscedasticity (ARCH) and General Autoregressive Conditional Heteroscedasticity (GARCH) models.

Estimating an ARCH and GARCH model in several studies helps as a precondition to presume the existence of food price volatility. This approach involves identifying the predictable price component from the unpredictable one. It enables the variances of the uncertain component to vary over time, as noted in (Bollerslev, 1986).

A common ARCH/GARCH (1, 1) Model can be specified as follows:

[1] An ARCH (Autoregressive Conditional Heteroskedasticity) model is a statistical model used to analyse historical volatility in financial data to predict future volatility. This model is useful in time series analysis, as it accounts for periods of varying volatility, allowing for more accurate modelling of data with changing variance over time.

[2] The GARCH (Generalised Autoregressive Conditional Heteroskedasticity) model is an extension of the ARCH model that also accounts for variance in the error term. It is widely used in time series analysis to model and predict financial volatility, as it accommodates more complex dynamics in the variance process over time.

$Y_{it} = \alpha_0 + \beta_1 Y_{it-1} + \beta_2 Y_{it-2} + \varepsilon_{it}$

Where Y_{it} is the spot food price of i^{th} country at t^{th} period which ranges from 1,2,3. . . . N.

The variance of the random error is given by $\sigma^2_{i,t} = \omega + \ \alpha_i \varepsilon^2_{i,t-1} + \beta_i \sigma^2_{i,t-1}$

The conditional variance equation specified under equation (2) is a function of three terms the mean (ω), the ARCH term (ϵ^2_{t-1}) - the square residual from the mean equation and the GARCH term (σ^2_{t-1}) - the last period variance. This model incorporates internal shocks (ARCH and GARCH terms) and several external factors, including the recent period of food price volatility. The presence of (1, 1) lags in these (ARCH and GARCH) terms indicates variability in the original data, and the sum of these two coefficients suggests the level of volatility in food prices. The nearer the sum of these two coefficients to one, the greater the tendency of persistent volatility in food prices. If the aggregation of these coefficients exceeds one, it indicates the existence of a unit root in the data series.

The model should have two preconditions. First, there should be a tendency towards low-price volatility, followed by a period of low volatility, and then a tendency towards high-price volatility, followed by a period of high volatility; this phenomenon is known as clustering volatility. Second, the model should have an ARCH effect; the last period's squared residual should be correlated with variance.

2.2.3 Trend of Food Price Volatility in Developing Countries

During the global food crisis, several researchers raised the issue of food price volatility. Those studies focused on whether international price volatility has been transmitted to domestic prices and whether it has increased beyond the existing trends.

Research organised by (Lukas et al., 2017) has analysed the drivers of food price volatility in developing countries. A dynamic panel approach was used to control for country-fixed effects, and a system generalised method of moments (GMM) model was employed to account for the persistence of clustered volatility. The finding underlined the importance of global price volatility, international trade transaction costs, and anti-cyclical trade policy, where net-importer countries were more severely affected by international volatility. This research has also highlighted the importance of international market co-integration and the factors that determine price movements in the global market. However, regional market co-integration will reduce dependence on the international market, which may have an impact on reducing domestic food price volatility, a factor this researcher did not address. Therefore, a noticeable research gap exists regarding the significance of market integration of food prices at the domestic level.

Bowen and Nelson have recently examined the impact of climate shocks on food price stability and international trade, with a particular focus on the supply side. This research aimed to determine whether food imports increase or decrease domestic food prices and analyse whether the foreign climate-induced production shock can be transmitted through trade and influence the domestic food price volatility of net-importer countries. Additionally, the study investigated the importance of stockholding in destabilising domestic prices in importing countries. The research outcome indicated that increasing the ratio of imports and stockholding to consumption had an inverse effect on intra-annual price variability. In contrast, climate-induced supply shocks increased price variability (Bowen, 2019).

The International Institute of Tropical Agriculture assessed the effect of climate variability on food price volatility, emphasising household income and food security in Ethiopia and Ghana. An agent-based modelling approach was applied to highlight adaptive and coping strategies for weather and price variability. The simulation results of this study signify that the climate and food price variability negatively affect the household income and food security of both countries (Tesfamicheal et al., 2017).

The relationship between conflict, food price, and the climate was evaluated using a crop simulation model. The disaggregated data of 113 African markets were used to investigate the association between the three variables. The simulation output indicates a positive correlation between food prices and violence, i.e., a rise in food prices escalates the rate of conflict, and the existence of conflict leads to a surge in food prices. Additionally, the dry weather condition was also correlated with the prevalence of conflict, and a decrease in rainfall intensity has an indirect consequence on conflict through its effect on food prices (Clionadh et al., 2015). The findings of this research suggested that the inverse relationship between climate and conflict can be alleviated through the implementation of effective price management at a domestic level. Furthermore, it proposes that a stabilised and reliable food price alongside an accessible and safe market could reduce the influence of both conflict and climate change. However, other stability factors, such as institutional quality, were not adequately addressed, and this will be incorporated into this paper.

2.2.4 Policy Response to Food Price Volatility in Developing Countries

It is essential for developing countries to understand the unexpected fluctuations in food prices within their domestic markets and how to respond with effective policy interventions. If policy-makers are fully aware of the impact of domestic indicators on food prices, they might develop a policy plan and mechanism to steer the market in the right direction.

Several types of research have been conducted on food price volatility since 2007, while most of this research focused on the nature, content, and causes of international food price variations (FAO et al., 2011). Little has been done to address the impact of policy direction or policy response on food price fluctuations. Understanding the relative power, nature, and influences of government responses towards food price volatility could help improve the current experience or knowledge of commodity marketing policy in future confrontations against this challenge.

Empirical research conducted by Christophe and Gouel has assessed the effect of domestic price stabilisation policies in developing nations. This research attempted to analyse a domestic policy intervention that helps to stabilise the domestic price. It has been assumed that due to the limitations of the food price stabilisation policy, the problem is becoming widespread in developing countries. Even though these kinds of policy interventions contradict the principle of market liberalisation, public policy intervention, particularly for a nation with a largely impoverished population, is essential to have a policy instrument for price stabilisation to alleviate malnutrition and hunger (Gouel, 2013). The researcher mainly criticises the existing interventions, such as the safety net and food market liberalisation policies promoted by donors. These policy tools lack credibility as they exclude private actors, and, in turn, they require the government to design a policy that increases trust in public-private partnerships in the world market. This study emphasises the international market and the fact that domestic policy formulation should coincide with global trade policy.

Policy research undertaken by the World Trade Organisation (WTO) [3] has assessed the relationship between export policy and food prices. The study investigated whether regional trade restriction policies can further exacerbate the global food price spike. This study utilizes monthly trade information from 125 countries, encompassing 29 food commodities, between 2008-10. The findings show that international trade restriction positively correlates with stable food prices. Notably, countries that heavily export commodities are more reactive to global food policy direction and implement such policies accordingly. Finally, a regression estimate shows that a 1% surge in international trade restriction could provoke, on average, a 1.1% increase in global food prices (Giordani et al., 2012).

A recent study on the political economy of food price policy in developing countries has concluded that the domestic policy response to food price volatility will heavily depend on the extent of price transmission from the global market to the domestic market. So, the degree of price transmission can influence exceptional and policy action by the national government towards domestic food price variability (Andersen, 2015). Hence, this research also emphasises the international factors that cause fluctuations in domestic food prices. In contrast, the domestic factors that required policy action were neglected in the study. Therefore, as indicated earlier, most researchers overlook the domestic factors' influence on price volatility.

[3] WTO is the only international organisation dealing with the rules of trade between nations

2.2.5 Food Price Volatility and Weather Shocks

The economic literature has documented the relationship between agricultural commodity supply and climate change through both production Naylor et al. (2001) and pricing (Ubilava, 2013). The larger body of this literature highlights how the ENSO events, especially El Nino [4], adversely affect crop yield, leading to increased commodity prices. Recently, numerous studies have highlighted that agricultural commodity markets have experienced high volatility, particularly in the developing world. Following the 2008 financial crisis, food price volatility has become a significant area of contention within the political and economic debate, and climate variability was one of the factors linked to the price dynamics (Oyiga, 2011).

Agricultural commodity markets have consistently been unstable throughout history, even during seasons with less extreme weather variability (Parkash, 2011). According to FAO et al. (2011), research on cereal and oilseed prices using historical data has documented that the price volatility of these agricultural commodities has continued to increase over the past 50 years, compared to other agricultural commodities (FAO et al., 2011). However, other recent academic literature has raised reservations about the evidence of increasing food price volatility (Minot, 2014). However, it's generally believed that agricultural price volatility has its own characteristics, history, causes, and mitigation mechanisms that change over time and are presumed to address them (Gerard, 2011). It has a unique character that makes it difficult for market participants due to the anticipation of future price risk related to weather uncertainty (Chavas et al., 2014). The Episode of substantial food price volatility significantly threatens food security in the developing world. The impact of food price volatility on consumers is negative, with a more severe effect on the poor, who spend over 80% of their income on food. An economic shock that significantly affects real income has not only exacerbated malnutrition but also highlighted the poverty traps, as both human and physical capital are gradually

[4] El Niño and the Southern Oscillation, also known as ENSO, is a periodic fluctuation (i.e., every 2–7 years) in sea surface temperature (El Niño) and the air pressure of the overlying atmosphere across the equatorial Pacific Ocean

destroyed. Price volatility causes economic uncertainty, which may result in a reduction in investment and significant income fluctuations for those who highly depend on agricultural commodities for their livelihoods. Therefore, price volatility can discourage investment and innovation in sectors like agriculture, which have more uncertain returns (Tadesse et al., 2014). An experience with the direct intervention of food market stabilisation was sometimes problematic, presumably because the policy response from individual countries influences international prices, which are even more volatile. Improving information on global market dynamics from climate effects could reduce the occurrence of risk and avert the adverse impact of high price volatility (Parkash, 2011).

The economic literature has documented the relationship between climate change and the agricultural commodity market, particularly in relation to ENSO events, such as the El Niño shock, which can occur in a specific region or continent. Indeed, those researchers have given attention to the effect of climate variability on production and pricing aspects of agriculture. Specifically, a stream of research has been carried out by analysing the impact of ENSO events on crop production, which in highlighting the economic impact through pricing Handler (1990); Keppenne (1995); Letson and McCullough (2001) have given an emphasis to the socioeconomic relationship between ENSO events and Soybean price and have reached a different conclusion. The first author identifies the effect of ENSO events on soybean prices, while the latter researchers have not discovered the direct relationship between them. Several other related studies have been conducted at different places, for instance, Dilley (1997) has assessed the economic damage of ENSO events on local maize yield variation in Mexico and rice and corn production in Indonesia (Naylor and Falcon, 2010).

Recently, a literature review on the study of the non-linear relationship between agricultural commodity prices and Climate ENSO events was assessed using a smooth transition vector error correction model. This study has analysed the price ratio between coffee, soybeans, corn, fish-soybean meal, and vegetable prices as a measure of the spatial heterogeneity of the climate ENSO effect at the US country level (Ubilava, 2012). Lastly, a recent study conducted by Iizumi (2014) has highlighted that the national-level crop yield responses are different between two climate ENSO events and between crops (Iizumi, 2014). However, the relationship between climate change and agricultural commodity prices has not been studied and documented. Specifically, the effect of extreme climate events (Rainfall and Temperature variability) on commodity prices has not yet been addressed in academic literature.

Another alternative link between climate shock and food price volatility is through information updates on weather and the intended consequences on future harvests. For instance, weather shocks in a particular region alter a local food supply and affect price formation (Jia and Gotz, 2014). Therefore, agricultural prices are sensitive to weather shock and their ability to mitigate production deficit (Fox et al., 2011). Deschenes and Greenstone (2007) have assessed the disruptive consequence of weather shocks on agriculture using a fixed effect approach, and it's shown that a short-run variation in weather affects consumer price and farm profitability. Also, the weather shock can be analysed through the lens of future price theory (Deschenes and Greenstone, 2007). The future prices reflect a market agent's harvest-time price anticipation and react to production forecast (Adjemian, 2012; McKenzie, 2008). Observing the adverse growing conditions of crops, arbitrageurs with full access to weather information and the future market might sell the commodity in the spot market and start a contract for future purchases. Hence, the spot prices might decline in the short run while future prices rise to absorb rainfall and temperatures as exogenous shocks (Bhanumurthy et al., 2013). Weather news plays a significant role in determining food prices. In the commodity market context, market agents are concerned with weather information and possess advanced knowledge about future production and consumption, which is relevant as forward-looking agents. Hence, access to information has a pivotal role in the agro-food commodity price formation scheme (Aker, 2010).

Following the global food crisis, research on price volatility has increased. A recent study by Kakpo et al. (2022) examines the impact of rainfall shocks on food price seasonality in Niger, revealing that adverse weather conditions exacerbate price volatility, particularly in remote markets. However, the study is limited to a single country. It does not account for trader anticipation or policy interventions, such as export restrictions, which my research integrates to explain non-linear food price responses to weather shocks across the broader region, including the East African region. Most of these studies measured the magnitude of global price volatility and its transmission to domestic prices. The focus of these studies was mainly on the international arena, where domestic factors that cause price variation have been overlooked or ignored. Therefore, this study will highlight the significance of domestic factors in agricultural price volatility.

2.2.6 Theoretical framework of weather news in a competitive storage model

The competitive storage model [5], evaluates the formation of traders' anticipations in the commodity market and has established a simple link between food price spikes and weather fluctuations.

In a typical storage model, the anticipation of future price levels is determined based on the assumption that the current harvest is on hand, along with the net inventory cost from the previous period. When considering harvest, the only variable source of information is the result of previous storage decisions, and traders have no information about future availability, as the future is uncertain. Deaton and Laroque (1996) better accommodates the autocorrelation of the observed price set through refining available information to the agent at a period t by relaxing the theoretical assumption and modelling the autocorrelation function (Deaton and Laroque, 1996). Based on the probability distribution, the next period's harvest probability depends on the current price's fluctuation and the quantity produced at each period, taking into account information on the future supply amount. In this manner, information plays a vital role in calculating expected future prices and deciding on the demand for the current level of inventories. In relation to these, Chambers and Bailey (1996) has introduced a time-dependent version of the equilibrium price

[5] It is an economic model that explains commodity prices due to arbitrage behaviour. It's based on the idea that competitive speculators increase or decrease their stocks in anticipation of arbitrage, considering the cost of carry and expected future prices.

level, where the harvest probability distribution changes across production cycles. Prices are functional to each season cycle, and generally, the model accounts for intra-annual dynamics (Chambers and Bailey, 1996).

The influence of weather-related news is particularly vital during the months of crop growth leading up to harvest and when stocks are low, as markets are fragile. Osborne (2004) has confirmed in his study that some African countries, such as Ethiopia, have shown a more significant proportion of production information is acknowledged before harvests through the observation of rainfall records. With a two-harvest cycle and twelve months, rainfall information augmented the model of price expectation.

To specify the modelling of weather news in the local trades' price expectation design, we should consider the specification presented by Osborne (2004), as shown in *Figure* 2.1 below. Also, we should propose several points from the theory of rational expectations and the biophysical characteristics of a crop production system to inform traders how weather updates drive the anticipation mechanism and expose the short-run sensitivity of the local market to diversified shocks.

Fig. 2.1 The period of Price expectation update process

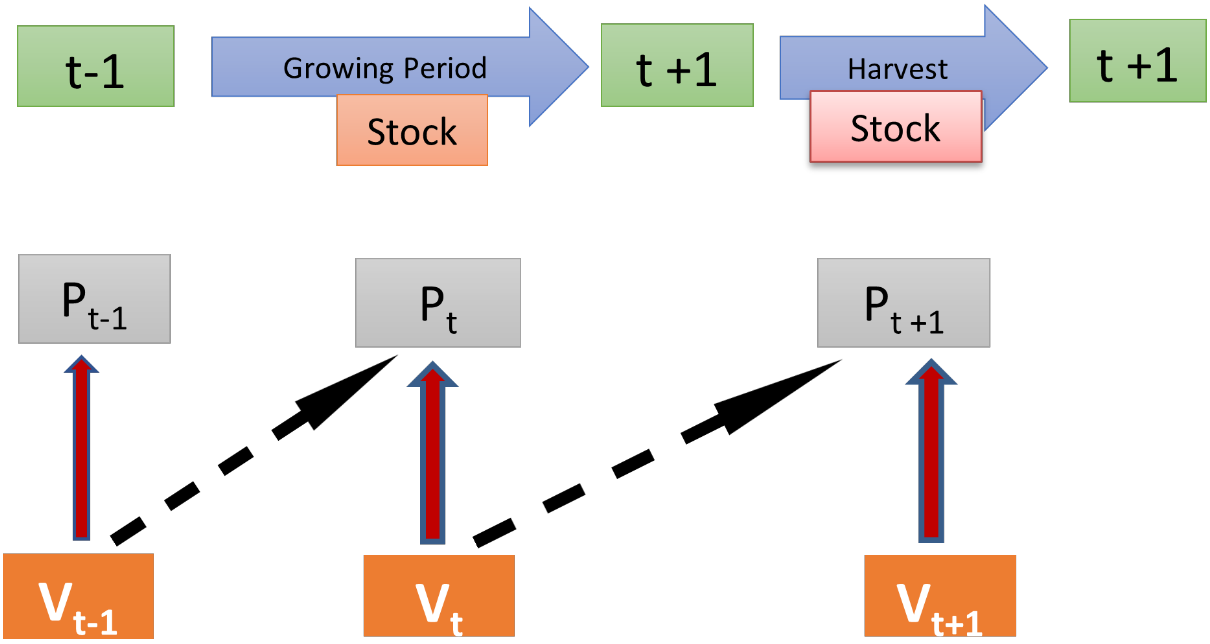


Figure 2.1: Shows the period of the Price expectation update process, highlighting how stocks, prices, and values interact across two distinct periods: $t-1$ and $t+1$. The central Growing Period signifies the phase of production, which significantly impacts future stock and price levels. The arrows illustrate how stocks and values influence prices, capturing the dynamic and cyclical nature of market behaviour in agricultural markets.

A market agent has a forward-looking tendency, based on past realised profits, to maximise expected future profits. The forward-looking behaviour of agents is boundedly rational, as the past information on weather variability in their specific geographic location is used to construct future food availability. Hence, at each production period, the weather changes from the traders' point of view are characterised by the persisting level of weather records at the local meteorological station. As production and marketing trends change over time, the agent's uncertainty or expectation formation may adjust to the current situation and occurrences that the agent has collected throughout their career (Muth, 1991). A common approach to building a relationship between food prices and the weather is to construct an average of the weather data from the last production season in specific production areas observed by the agent, against the current market prices of agricultural commodities. The market agents jointly gathered weather information from local meteorological stations, and national broadcasting media disseminated information on long-run normal conditions.

The expectation of agents is established based on the existing information diffusion system pertinent to agricultural markets. The traders use this information to predict the yield prevailing at harvest time, depending on their knowledge of what is linked with crop growing conditions and weather. Traders have experienced that the direction and magnitude of weather fluctuations affect crop harvests differently. Hence, the study will evaluate a quadratic function to introduce a non-linear forecasting exercise in response to price, mirroring the biophysical link. Therefore, the equilibrium level of price relation to weather would include the non-linearity condition and asymmetric censoring at the turning points. Moreover, the production practice of agricultural commodities accommodates, to some extent, delays in rainfall or the early start of the production season. Hence, the cumulative effect of weather constraints over a season may be more important than the condition of a specific week. Therefore, price expectations are gradually updated based on the extent of partial information established from weather inspections before the harvest supply reaches the market, as introduced by (Osborne, 2004).

In line with Osborne (2004), the reduced form of the price formation model can be expressed as:

$$P_{t+1} \ = F(p_t, S_t, x; \rho, \gamma) + \varepsilon_{m,t} \tag{2.1}$$

2.3 Research Methodology

As a consequence of the global food crisis, several empirical studies have modelled the influence of weather shocks on food prices in different approaches. Anticipation of market agents about future weather updates and crop prospects is one link between Agro-food commodity prices and weather shocks (Summer, 1989). The East African climate is highly heterogeneous throughout the region, exhibiting a diverse range of weather patterns. Annual rainfall varies from a few millimetres in drought-prone areas, such as Sudan, to several hundred millimetres in more favourable rainy areas, like Tanzania and

Uganda. Temperature exhibits similar variability in the region; however, the southern part experiences high variability, whereas the northern parts have low temperature variability.

The major stable food production in the region is predominantly dependent on the intensity of rainfall and surface temperature in a specific district. The duration and intensity of rain also vary from country to country; some countries have a 4-6 month rainfall period while others have a 3-4 month rainfall period. Monsoons typically begin in mid-May and peak in July or August, lasting longer in certain parts of the region. The primary food crop production in the region occurs twice a year, during the main season (May-September) and the sub-season (October-February), and the production length depends on the crops and weather conditions in the specific district (Tariku and Gan, 2018).

2.3.1 Description of the study area

This study has focused on six East African countries, such as Sudan, Ethiopia, Kenya, Rwanda, Tanzania, and Uganda, to determine the effect of weather shocks on food prices and provide insight into the government's policy response to the price surge. All these countries were confronted with high food prices in 2007/08, and the governments reacted to the food surge in several ways. During this period, the world experienced a dramatic increase in food prices, although prices have been decreasing since mid-2009; however, the crisis in East Africa remains high. Therefore, this study has targeted this region to identify the main challenge, emphasising climate change and policy actions.

Interestingly, commodity prices in these countries exhibited a variable pattern compared to global prices when the world price began to decline in the summer of 2008, while East African countries continued to increase during this period. The domestic prices in these countries are less correlated with the world prices. Therefore, the influences that could be developed from world prices are smaller than the regional influence. This region has a unique factor that sets it apart from the global scenario, contributing to the rise in food prices. The countries in the region, which share common resources and face similar challenges, have exhibited similar trends. These challenges include natural disasters, droughts, and political conflicts.

2.3.2 Data and Analytical Parameters

For this study, 20 weather stations and 18 commodity markets were selected as detailed *annexed Figure* A.1 and *Table* A.1. Ethiopia has three commodity markets and six weather stations; Kenya- has four commodity markets and three weather stations; Rwanda - has two commodity markets and two weather stations; Sudan - has four commodity markets and four weather stations; Tanzania - has three commodity markets and three weather stations and Uganda - two commodity market and two weather stations were targeted for the study. Five primary staple foods, including beans, maize, Wheat, Sorghum, and Rice, are the priority crops of this study.

In this study, we utilise monthly average food prices and weather data (rainfall and temperature) to analyse the impact of weather shocks on food price volatility. The primary data sources include:

- **Food Prices Data**: Monthly Price data for each crop under this study, sourced from the Food and Agriculture Organisation (FAO) Commodity Balance Sheet and FAO's Global Information and Early Warning System (GIEWS). The data covers the period between 2005 and 2015, with prices recorded in dollars per ton. Food price data reflects traders' anticipations based on weather updates, significantly influencing price changes. Traders closely monitor weather forecasts, historical data, and real-time updates to predict changes in crop production and adjust their strategies accordingly. By anticipating these changes, traders shape food price dynamics. Integrating weather updates into economic analysis enhances the understanding of price dynamics and improves the accuracy of predictions.
- **Weather Data**: Daily records of rainfall and temperature from the National Oceanic and Atmospheric Administration (NOAA), which are then calculated to

provide monthly average data. These records are collected from weather stations closest to the relevant marketplaces. The data covers the period between 2005 and 2015, with temperatures recorded in degrees Celsius and rainfall in millimetres.

The analytical parameters involve using a cross-country panel model, which is well-suited for less frequent market-level data. The parameters include:

- Dependent Variable: Monthly food prices (in dollars per ton).
- Independent Variables: Monthly average temperature (in degrees Celsius) and rainfall (in millimetres).
- Covariate Variables: Time fixed effect, market fixed effect, country fixed effect, crop fixed effect, and interaction terms.

The data were processed before being implemented into the model. This involved data cleaning to remove any missing or inconsistent entries, ensuring data quality; normalisation to standardise the data and ensure comparability across different units and scales; aggregation to summarise daily weather data into monthly averages; and validation to cross-check data with other sources, ensuring accuracy and reliability. Additionally, several data tests were conducted to ensure robustness, including checks for multicollinearity issues to ensure that independent variables are not highly correlated, tests for heteroskedasticity to ensure consistent variance of errors, and the Variance Inflation Factor (VIF) test to quantify the severity of multicollinearity. The details of these tests and their results are explained in the subsequent sections.

The research focuses on market-level prices to assess the effect of weather shocks on food prices through the trader anticipation transmission mechanism. Market-level analyses are crucial for assessing food price variability and quantifying the impact of weather conditions.

2.3.3 Descriptive Analysis

Before engaging in any regression analysis, it is essential to have confidence in the dataset. It is better to observe what the sample data conveys, identifying whether the data is normally distributed or not, the existence of outliers and other health tests of the dataset. Also, descriptive statistics is a useful tool to provide information on measures of central tendency (mean, median and mode), dispersion (range, variance and standard deviation), and measures of normality – kurtosis (a measure of the degree of sharpness) and skewness (a measure of the degree of asymmetry).

The normality test helps to measure the degree of asymmetry (skewness) of the data series, i.e., whether the distribution is symmetric around its mean or not. The series exhibits a long right tail, indicating positive skewness, with higher values above the sample average. Negative skewness is characterised by an extended left-tail distribution, with lower values occurring below the sample average. Kurtosis measures the peakiness or flatness of the distribution of the series. If a series is mesokurtic, it means a normal distribution with a kurtosis of three. If leptokurtic, it has a positive kurtosis (peaked curve), indicating a higher value above the sample average. The Platykurtic Distribution indicates less variability than the sample average if it has negative kurtosis (a flat curve).

2.3.4 Econometric Analysis

Before running the econometric analysis, the hypothesised explanatory variables were checked for multicollinearity. This problem arises when at least one of the independent variables is a linear combination of the other independent variables. The presence of multicollinearity may cause the estimated regression coefficients to have incorrect signs and smaller t-ratios, resulting in incorrect conclusions.

The variance inflation factor (VIF) techniques were employed to detect the problem of multicollinearity among the continuous variables. According to Gujarati and Porter (2004), VIF can be defined as:

$$VIF(\beta_i) = \left(1 - R_i^2\right)^{-1}$$

Where R_i^2 is the square of the multiple correlation coefficient that results when one explanatory variable (X_i) is regressed against all other explanatory variables. The larger the value of VIF_i, the more "troublesome" or collinear variable Xi is. As a rule of thumb, if the VIF of a variable exceeds 10, a multicollinearity problem exists (Maddala, 1992).

Similarly, the contingency coefficients (CC) were computed for dummy variables from the chi-square (X^2) value to detect the problem of multicollinearity or the degree of association between dummy variables. The dummy variables are said to be collinear if the value of the contingency coefficient is more significant than 0.75 (Healy, 1984).

$$CC = \sqrt{\frac{\chi^2}{N+\chi^2}}$$

Where CC is the contingency coefficient, n is the sample size, and (X^2) is the chi-square value.

In addition, heteroskedasticity [6] is likely to be encountered frequently in econometric data, particularly cross-section data. For regression with cross-sectional data, it is usually safe to assume that the errors are uncorrelated; however, their variances are often not constant across individuals. The reason is that the variation in the dependent variable seldom remains constant when the levels of one or more explanatory variables change (Mukherjee et al., 2013). Therefore, there is a need to test the possible existence of this problem and the test conducted. This study employed the Breush-Pagan test for constant variance to address heteroscedasticity, thereby avoiding false rejection of the hypothesis and an unrealistic confidence interval. The result of the Breush-Pagan test revealed that there was no heteroscedasticity problem in the model delivered in the table under Appendix (A.2 – A.6). All covariate factors, including country, market, and year, as well as their interaction terms, have a significant impact on prices. This suggests that these variables have a significant influence on food prices, and the model provides a good fit for price variability. Also, before running the panel analysis, the Durban-Wu-Hausman test was

[6] It occurs when the variance of the error term is not constant across observations. This can impact the validity of econometric analysis models, such as the panel-time serious data analysis case.

employed to check for endogeneity issues that could arise from uncontrolled confounding variables, which might be correlated with independent variables and the error term. The Hausman test result, with a p-value of 0.0026, below the 0.05 threshold, provides strong evidence that the individual effects in the data are related to the independent variables. This supports the use of the fixed effects model for our analysis, as it effectively accounts for differences between entities that remain constant over time, thereby ensuring the accuracy and reliability of our analysis.

After the data and model tests were carried out, the study proceeded with econometric analysis using a cross-country panel approach. The cross-country panel model[7] has several advantages from an analytical point of view, such as the inclusion of multiple countries in the study, which may increase the number of observations. However, this approach has its disadvantages; most notably, specific country characteristics are not well accounted for, and the estimated representative country sample average coefficient varies significantly across countries (Levine, 1991). Therefore, the results from this study should not be used for specific country recommendations; instead, they reflect the cross-country or regional behaviour of food price volatility.

Two econometric models were employed to analyse the pivotal relationship between weather shocks and food price variability, and the effect of export restrictions on regulating food price variability.

2.3.5 The weather shock and food price variability

Two different approaches were used to estimate the relationship between weather shocks and price variations. First, the effects of contemporaneous and lagged weather variables, which are known to reduce yields and are monitored by traders, were estimated against volatile food prices. Second, attempt to estimate the total price reaction function regressed

[7] A cross-country panel model analyses the behaviour of multiple countries over time using data observed at different periods. Known as longitudinal, cross-sectional time series, or time-series cross-sectional data, this model benefits from high-quality datasets that provide more information than standard cross-sectional data.

with the discrete intervals of weather variables (rainfall and temperature) realisations on prices. Initially, the data were assessed to determine whether they could uncover the asymmetry and non-linearity of weather variations in the price mechanism. Both approaches utilise the time lag between weather shocks that have a subsequent effect on supply shocks to estimate price reactions exclusively due to changes in future price expectations.

In the *first* approach, a set of weather variables and other covariates as fixed effects were regressed on price levels as follows:

$$P_{m,t} = \beta_0 + \beta_1^{'} \overline{w}_{m,t} + \phi_m + \varphi_{c,m} + \Psi_{mn,s} + \gamma_{y,s} + \varepsilon_{m,t} \tag{2.2}$$

Where $p_{r,t}$ is a food price variable in the model reflects trader anticipation behaviour based on weather updates, measured in (\$/tonne), $\overline{w}_{m,t}$ is a series of weather variables for market m. A regression includes a fixed effect for market $\phi_{m,t}$, crop-market $\varphi_{c,m}$, year-state $\gamma_{m,s}$, country-specific monthly seasonal cycle $\Psi_{mn,s}$, and an error term $\varepsilon_{m,t}$. Other variables that are expected to affect food price variability, such as interest rates and storage losses, are excluded from the structural model illustrated in *equation* 2.2 and are assumed to be captured by the market and time-fixed effects. Likewise, idiosyncratic [8] local shocks and government interventions, including recommended price support and other associated decisions, are absorbed by year-state fixed effects. The specific market characteristics that remain constant over time, such as storage facilities and infrastructure, including irrigation technology and soil fertility, can serve as a potential source of omitted variable bias.

The weather data is calculated as a seasonal monthly average, which reflects the extent of rainfall or temperature monitored by traders to inform future price predictions. Market-specific monthly time-series data are formed from 2005 to 2015, and an average pixel value for each cropping season is calculated within the spatial boundaries, in this case, the

[8] unobserved factors that impact the dependent variable—from panel data that changes over time and across units (such as countries, markets, time, etc.)

market. Then, for each weather variable, the weighted average of each season is calculated as follows; $\overline{x} = \frac{X_1+X_2....X_n}{n}$. where x represents the value of the weather record collected from the weather station, and n is the number of months in the cropping season; the length of the cropping month varies within and among countries.

In the *second approach*, the deviation from the long-term average was standardised to a fixed width for temperature and rainfall distribution. To capture the non-linear effects of climate variables on economic outcomes, both temperature and rainfall distributions are discretised into narrow percentile-based bins, each representing 3% of the empirical distribution. This approach enables a high-resolution analysis of how different segments of the climate spectrum impact food prices, particularly in regions where agriculture is susceptible to weather variability. By avoiding broad averaging, this method reveals critical thresholds, such as the tipping points at which insufficient or excessive rainfall begins to disrupt production and significantly increase prices. This binning strategy aligns with methodologies used in recent global studies on climate and economic performance, where economic output is shown to respond asymmetrically across fine-grained intervals of temperature and precipitation (Ingram, 2021). Such detailed discretisation is essential for identifying climate thresholds that may not be visible in coarser models and for informing targeted adaptation strategies in vulnerable regions.

Assuming that the short-run price formation process is influenced by nonlinear functions of observed weather, represented by g(RAIN) for rainfall and m(TMP) for temperature, we rewrite *equation* 2.1 for district d at time t as follows:

$$p_{d,t} = \int g(\text{Rain})\,\Theta(\text{Rain}) + \int m(\text{Temp})\,\Theta(\text{Temp}) + \phi_d + \psi_m + \tau_{y,s} + \eta_{d,t} \qquad (2.3)$$

where Θ(RAIN) and Θ(TMP) represent the distribution of anomalies within our dataset. We discretise the price interval corresponding to rainfall and temperature anomalies into fixed-width bins to estimate the functional forms of $g()$ and $m()$. Within each bin, the relationship between anomalies and prices is jointly estimated according to the *equation* 2.4 below:

$$p_{m,t} = \beta_0 + \sum_{q=1}^{B_{\text{Rain}}} \beta_q^1 \,\text{Rain}_{q,r,t} + \sum_{q=1}^{B_{\text{Temp}}} \beta_q^2 \,\text{Temp}_{q,r,t} + \phi_m + \varphi_{c,m} + \Psi_{mn,s} + \Upsilon_{y,s} + \varepsilon_{m,t} \quad (2.4)$$

Rainfall and temperature are represented as discrete distributions within the dataset, alongside other covariates incorporated as fixed effects. The price intervals corresponding to these weather anomalies are divided into fixed-width bins. Among these bins, the one containing zero, indicating no deviation from normal conditions, is treated as the omitted reference category.

2.3.6 The effect of export restriction on food prices variability

The strategic interaction between weather conditions and export restrictions impacts food price spikes. These two factors are intricately intertwined, resulting in complex dynamics within the global food market.

In addition to directed involvement in buffer stock management (purchasing crops during low prices and selling during high prices) at controlled prices, in developing nations, the government influence the market and its agent's behaviour through discretionary trade policy tools such as export bans, control over export, license etc. Export bans or restrictions has a long history and continue to be prominent policy instrument used for agricultural market regulation in developing nations such as Africa and Asia (Anderson, 2009).

In a developing nation where household food spending accounts for a large proportion, policies are required to regulate food prices (Demeke et al., 2011). In several developing nations, including those in Africa, Asia, and Latin America, temporary export restrictions have been widely employed to regulate food prices during crises. Most of these nations applied export restrictions on major staple crops (Sharma, 2011). This policy intervention was implemented by numerous East African countries, including Ethiopia, Kenya, and Tanzania, which are the target of this research (Porteous, 2017). Hence, this policy instrument will be tested by assuming that these three countries form the treatment group, and the rest form the control group.

Export restrictions on food crops became a prominent strategy during 2007-11 as one of the key drivers of food price and local short-term price regulation mechanisms by nations (Coady et al., 2018). This policy intervention was initially implemented in response to the global food crisis and the sharp increase in staple crop prices observed in several developing countries between 2008 and 2010. A range of trade-restrictive measures, including tariff rates, quotas, and export bans, were employed across different national contexts. This study critically evaluates the effectiveness of export bans as a policy instrument in mitigating food price volatility within the study region, aiming to determine their relevance and impact as a viable policy response to climate-induced market pressures.

To examine whether export restrictions or bans on food exports regulated the food spike that was exacerbated by weather shocks, particularly rainfall shortages, affecting the local food supply. It has been shown that the food price spike, p_{mt}, in the market m and year t.

$$p_{mt} = \alpha_m + \beta_{mn} + \phi_m + \varphi_{c,m} + \gamma_1 \, \text{weather}_{mt} + \gamma_2 \, \text{bans}_{mt} + \gamma_3 \, \text{weather}_{mt} \cdot \text{bans}_{mt} + \varepsilon_{m,t} \tag{2.5}$$

Where α_m is a market fixed effect, $\beta_{mn}$is a month fixed effect, $weather_{mt}$ is the metrological station record of rainfall and temperature enjoyed by the market m and Bans is a dummy variable whether the market m or country ban export of food crop in at time t or not. Additionally, we note the observable value p_{mt}, which represents the continued value of food prices recorded at market m in year t. As a result, *equation* 2.3 was estimated using a fixed-effect linear regression model.

It is expected to see $\gamma_1 < 0$ if rainfall availability does contribute to reducing food prices, as Donaldson (2008) examines how rainfall shortages intensify price hikes through the supply and demand link. The coefficient of export bans γ_2 captures the extent of export restriction associated with reducing food prices. Finally, weather and export restriction interaction term, γ_3 attempt to answer the second main question that has been posed in this chapter: does export restriction mitigate ($\gamma_3 < 0$) or aggravate ($\gamma_3 > 0$) the ill-effect of weather shocks on food price volatility?

2.4 Results and Discussion

This section presents the empirical findings and discussion of the results obtained from descriptive and econometric analyses. This study investigates the short-run effects of weather shocks and government policy interventions on food prices. In general, this section has two major parts. The first part presents the results corresponding to descriptive statistics of important variables included in the models, such as food prices, rainfall, temperature, and export bans related to the food price crisis in East African regions. The second section presents the econometric results that affect food price variation or regulations.

The cropping system within the East African community includes sole cropping, intercropping, mixed cropping, sequential and relay cropping. Land fallow was abandoned a long time ago, and it's no longer practised due to a severe shortage of farmland. The major food crops, such as beans, maize, sorghum, rice, and wheat, have been planted as sole crops twice a year per plot. Hence, in this region, farmers harvest these crops in two production seasons: the main and sub-season. Identifying the cropping calendar helps identify the channel link between food price and weather, as agents determine prices based on weather information. Market agents are forward-looking in their behaviour, with strategic selection based on past weather experience, as rational decision-makers use this to determine the expected future food availability.

These crops differ in terms of the length of the maturity period among the countries under this study. Beans are the shortest-maturing crop in the region, and it takes three to four months for harvest, depending on the variety type and climatic zone. Wheat, maize, sorghum, and rice typically take 5-6 months to mature, depending on soil fertility and rainfall intensity in the respective regions. The following table summarises the seasonal calendar in *figure* 2.2 of East African farming operations for the major staple crops.

Fig. 2.2 Crop Calendar in East Africa

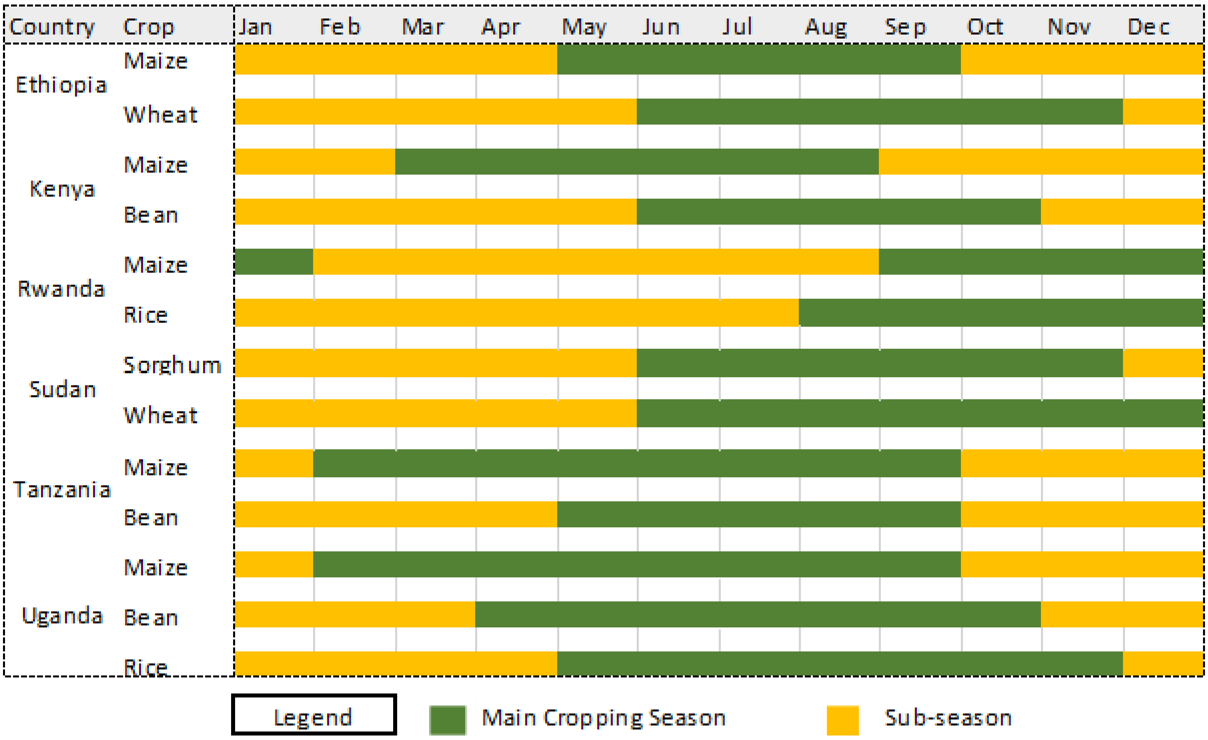


Figure (2.2): Illustrates the crop calendar as a crucial visual aid detailing agricultural cycles for diverse crops across East Africa. Each row corresponds to a different country and depicts the specific crops cultivated in that country each year. Dark green denotes primary cropping seasons, while yellow indicates sub-seasons, facilitating clear comprehension of planting and harvesting periods for each crop.

2.4.1 Food price trends in the region

As indicated in *Figure* 2.3 below, the price of major stable crops (Maize, Wheat, Sorghum, Rice and Beans) has shown an increasing and unstable trend during the study period. As expected, the graph highlighted the price rise during the food crisis in 2007/08 and a sharp surge in 2010/11. The Persistent upward pressure on food prices has been a defining characteristic of the market, particularly for staple crops such as maize, wheat, and rice. Factors including climate variability, fluctuating supply levels, and market anticipation of future shortages primarily drive this volatility. In recent years, unpredictable weather patterns have disrupted agricultural output, influencing traders' expectations and shaping market behaviour. Additionally, external economic shocks and policy interventions, such as export restrictions, have significantly amplified price instability. These combined factors contribute to ongoing price fluctuations, presenting challenges for consumers and policymakers in managing food security and economic stability.

Volatility has been computed for five food prices, both at the national and regional levels, as indicated in the appendix *figure* A.3, and A.4. It is interesting to compare the global food crisis that occurred twice (2007/08 and 2010/11) in the selected period from a developing economy standpoint. On these two occasions, from a global perspective, food price volatility was high and unstable for developing nations, where millions of people faced acute emergencies. This graph confirms a similar result to Daviron et al. (2011), which shows a decline in 2009/10 and then immediately climbs to a high level in the subsequent years. The price variability has demonstrated high and low volatility for an extended period, i.e., low-level volatility remains low for an extended time, and high volatility remains high for a prolonged time. This nature of volatility is termed clustering volatility. It is the tendency of significant price changes in food commodities, which results in persistence in the magnitude of price changes.

Fig. 2.3 Food Price ($/ton) Volatility in East Africa

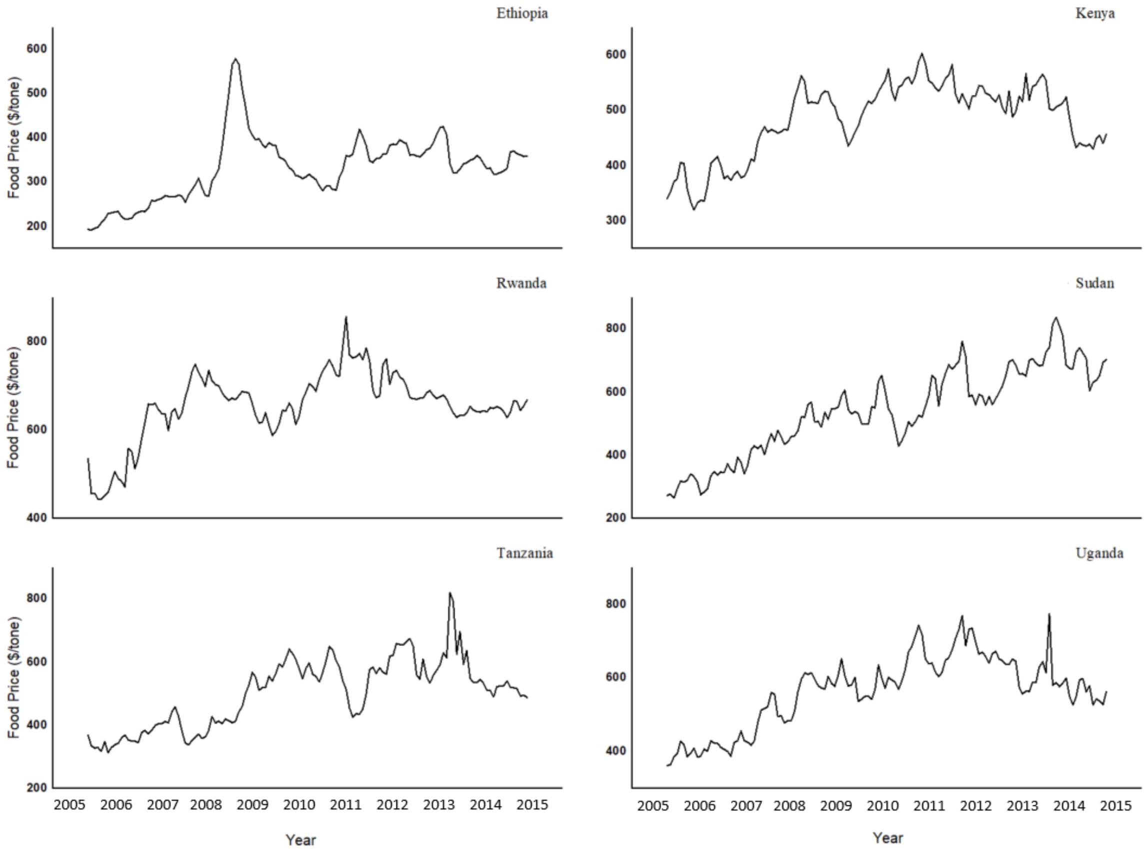


Figure 2.3: Diagram illustrates food price volatility in East Africa from January 2005 to December 2015, showcasing fluctuations in staple crops like maize, wheat, beans, sorghum, and rice. Each country exhibits unique price patterns, and our understanding of the factors influencing these patterns, such as seasonal cycles, market demand, and trader anticipation, is informed by weather updates. Notably, Ethiopia and Kenya show significant price spikes, while Rwanda and Tanzania display more stable trends.

2.4.2 Temperature and Rainfall trends in the region

Temperature variations across East Africa have a significant impact on agricultural productivity and food security. Countries like Sudan and Uganda experience higher average temperatures, ranging from 24.58 °C to 33.85 °C, which can stress crops and reduce yields. Conversely, countries like Ethiopia and Kenya have more moderate temperatures, ranging from 17.49 °C to 21.71 °C, which are generally more favourable for crop growth.

Understanding these temperature patterns is crucial for developing climate-resilient agricultural practices and selecting crop varieties that can withstand extreme temperatures.

Rainfall distribution in East Africa is highly variable, with significant differences between countries and seasons. For instance, Rwanda experiences substantial rainfall, particularly in March and April, with the highest recorded at 180.76 mm in March. In contrast, Uganda and Tanzania have lower rainfall distribution, with some months receiving as little as 2.14 mm. This variability affects water availability for crops, influencing planting and harvesting cycles. Effective water management and irrigation infrastructure are crucial for mitigating the impacts of erratic rainfall and ensuring consistent agricultural productivity (Mubenga-Tshitaka et al., 2023).

The variability in temperature and rainfall has a direct impact on agricultural production in East Africa. Inconsistent rain and extreme temperatures can lead to crop failures and reduced yields. For example, prolonged dry spells during critical growing periods can stress crops, while excessive rainfall can cause flooding and soil erosion. Countries like Ethiopia and Kenya have distinct rainy seasons and are particularly vulnerable to these extremes. Adopting climate-resilient agricultural practices, such as drought-resistant crop varieties and improved irrigation systems, can help stabilise agricultural production and enhance food security (Choi and Eltahir, 2023).

Climate variability also contributes to food price volatility in East Africa. Fluctuations in rainfall and temperature can lead to unpredictable food supply, causing price spikes. For instance, a drought can reduce the availability of staple crops, such as maize and sorghum, leading to higher prices in local markets. Conversely, a bumper harvest due to favourable weather can temporarily lower prices, affecting farmers' incomes (Wossen et al., 2018). Addressing food price volatility requires comprehensive strategies, including investment in agricultural infrastructure, early warning systems, and regional cooperation to ensure a stable food supply and prices.

Both temperature and rainfall are intrinsically linked and profoundly impact agricultural productivity and food price stability in East Africa. The interplay between these climatic factors determines the success of crop yields and food availability. This study highlights how variations in temperature and rainfall across different countries and seasons impact agricultural outcomes.

Fig. 2.4 Average annual Temperature and Rainfall in East Africa

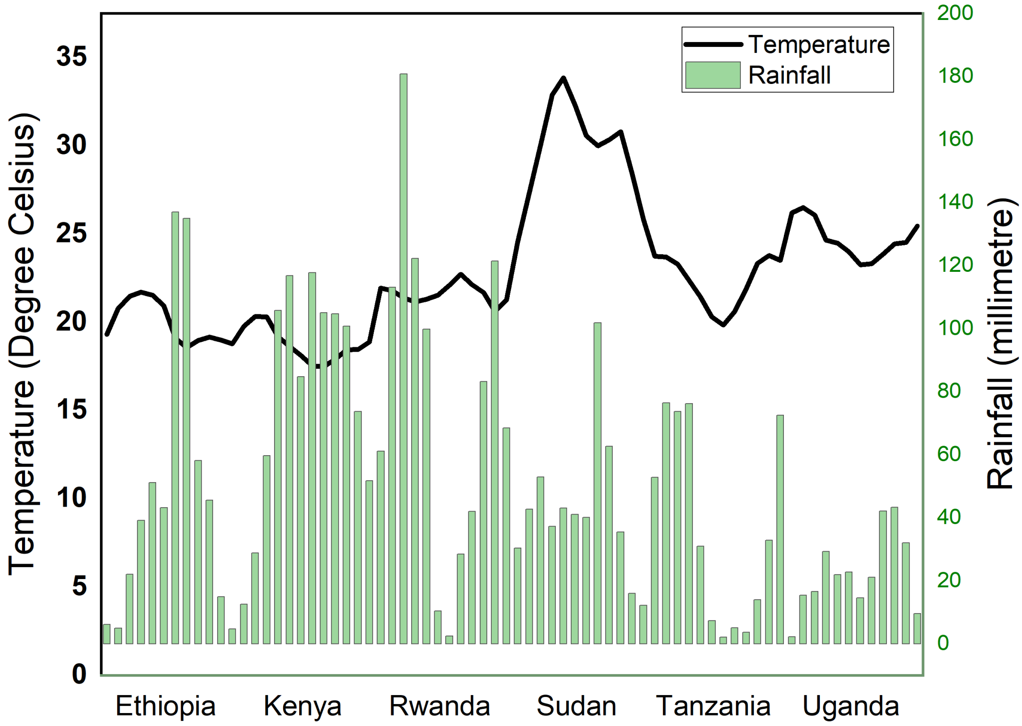


Figure 2.4: This figure illustrates the annual rainfall and temperature patterns across six East African countries. The average annual temperature ranges from 15°C to 35°C, while rainfall varies significantly, from as little as 2mm to 180.76mm. This indicates that rainfall is more irregular and variable than temperature in the region. The graph shows that Uganda and Tanzania receive the least rainfall, whereas Rwanda and Kenya experience relatively higher amounts. Sudan and Tanzania exhibit higher temperatures, while Kenya, Ethiopia, and Rwanda have more moderate averages.

2.4.3 Descriptive analysis

The descriptive statistics of food prices and weather variables are summarised in *Table* 2.1. To begin with, the mean values of food prices are as follows: Beans, $653.60 per ton;

maize, $289.82; rice, $927.30; sorghum, $452.24; and wheat, £532.49. As observed in the table, wheat food prices are the most dispersed, while maize food prices are the least deviated from the sample mean. The price range and the size of the variances of these two extreme crops have confirmed the desperation among observations in this series.

The normality test of the dataset was measured using skewness and kurtosis. The series is commonly skewed if its corresponding value is zero or approximately zero, and Mesokurtic if the value of kurtosis is three. Based on this specification, the skewness value of Beans, maize, rice, and sorghum and temperature is approximately zero, so the food prices of these crops mirror average skewness around the mean, i.e. the sample observations are distributed around the mean, while the skewness value of wheat and rainfall is 1.75 and 11.46, respectively. This value indicates that the wheat price and rainfall distributions have a long right tail (positive skewness), meaning that more observations have higher values above the sample average. Maize and sorghum exhibit mesokurtic shapes, as their kurtosis values are approximately three. In contrast, beans, rice, wheat, and rainfall exhibit leptokurtic shapes, with kurtosis values greater than three.

Table 2.1 Summary statistics of food prices of crops

Variable	**Beans**	**Maize**	**Rice**	**Sorghum**	**Wheat**	**Rainfall**
Mean	653.60	289.82	927.30	452.24	532.49	48.97
Std.Dev.	183.40	91.06	195.16	158.11	250.85	90.41
Min	177.00	105.94	474.29	92.29	159.83	0.00
Max	1481.82	690.30	1974.80	1130.03	1769.35	2696.72
Variance	33637.32	8291.61	38089.14	24999.28	62923.20	8174.55
Skewness	0.44	0.53	0.08	0.32	1.75	11.46
Kurtosis	4.67	3.26	3.93	3.40	6.74	299.93
Obs	1188	1848	528	528	924	5016

2.4.4 Analysis of variance

It is an important tool in economics for comparing several levels (conditions) of two independent variables, involving multiple observations at each level. It is used to examine the effects of the two factors on the continuous dependent variable.

In this analysis, we have one dependent variable (prices) and seven factor variables, including country, market, year, and their interaction. As shown in the table below, this output includes several notable features. The number of observations we can see in this output is 1,188, and the R-squared is 0.77, which indicates that the explanatory variable is explaining a significant portion of the variation in food prices. Specifically, 77% of the variation in food prices is explained by state, market, and time-fixed effects. The analysis of variation outcome structure is divided into different columns: the first column indicates the sources of variation, the second column shows the partial sum of squares, the third column displays the degree of freedom, the fourth column presents the mean sum of squares F-statistics, and the fifth column displays the probability value or level of significance. The last two columns are the most interesting and proceed to the post-test analysis. First, the mean food prices in this region are statistically significantly different across all measurements. The average commodity price is statistically different between two countries, two markets, and two years, and the specific crop is in different markets.

Table 2.2 Anova test of food prices

	Number of obs = 1,188			R-squared = 0.7695	
	Root MSE = 91.9264			Adj R-squared = 0.7488	
Source	Partial SS	df	MS	F	Prob>F
Model	30724942	98	313519.8	37.1	0.0000
Country	1500181	2	750090.7	88.76	0.0000
Market	4170966	6	695161.1	82.26	0.0000
Year	12857281	10	1285728	152.15	0.0000
Country # Year	2688674	20	134433.7	15.91	0.0000
Market # Year	7476173	60	124602.9	14.75	0.0000
Residual	9202561	1089	8450.469		
Total	39927503	1089	33637.32		

2.4.5 Panel Estimation Results

The econometric analysis begins by examining the short-run price reaction to weather shocks, as captured by meteorological stations at the market level, which is calculated using the seasonal average of rainfall and temperature.

In this regression analysis, the effects of marginal changes, as well as coexistent and lagged levels of weather, on food prices have been investigated after controlling for seasonality and the time-invariant behaviour of dependent variables. The regression results indicate an immediate and modest price response to marginal changes due to short-run weather shocks. The magnitude and sign of the level and quadratic coefficients suggest that the reaction function diminishes at the highest extent point of marginal change.

A marginal change in precipitation matters under all circumstances of variation in other covariates, showing a negative sign as a wetter production season is seen by market agents as beneficial for future yield and price reduction. Similarly, the availability of rainfall in the past has also had an adverse effect on food prices, based on information from the most recent harvest.

The reactions to temperature changes in food prices suggest that a rise in temperature increases food prices through traders' anticipation, with the assumption that rising temperatures may lead to drought and production losses in future harvests. This result is consistent across different covariate combinations, and the quadratic term also shows an inverse relationship with food prices.

The results indicate that weather updates have a significant influence on food prices through trader anticipation. Traders closely monitor weather forecasts, historical weather data, and real-time updates to predict changes in crop production. For instance, forecasts of drought or excessive rainfall can lead to expectations of lower yields, prompting traders to adjust their buying and selling strategies. Historical weather patterns help traders understand seasonal trends, while real-time updates allow them to react quickly to sudden changes, such as unexpected frosts. Weather conditions also impact the supply chain, affecting the availability and cost of commodities. By anticipating these changes, traders can make informed decisions that ultimately influence food prices. Integrating weather updates into economic analysis enhances the understanding of price dynamics and improves the accuracy of predictions.

Table 2.3 Effect of weather shocks on food Prices

VARIABLES	Model 1	Model 2	Model 3	Model 4
Rainfall Variables				
Average season rainfall	-47.863*	-47.863***	-48.839***	-47.275***
	(26.018)	(16.276)	(16.418)	(17.061)
Ave. seasonal rainfall^2	-583.885**	-583.885***	-596.113***	-529.954***
	(266.966)	(167.009)	(168.528)	(174.475)
Ave. seasonal rainfall$_{t-1}$				-5.675***
				(1.802)
Temperature Variables				
Average season temperature	1.730***	1.730***	1.742***	1.728***
	(0.252)	(0.158)	(0.158)	(0.166)
Ave. seasonal tem^2	-34.588***	-34.588***	-34.765***	-34.644***
	(3.983)	(2.492)	(2.506)	(2.527)
Av. seasonal temp$_{t-1}$				0.004
				(0.086)
Co-variate fixed effect				
Market fixed effect	Yes	Yes	Yes	Yes
Crop fixed effect		Yes	Yes	Yes
Month fixed effect			Yes	Yes
Year fixed effect				
Constant	2,366.255***	2,664.032***	2,695.032***	2,564.287***
	(686.822)	(429.875)	(433.58)	(448.553)
Observations	5,016	5,016	5,016	4,978
R-squared	0.147	0.667	0.667	0.669

Notes: *** p<0.01, ** p<0.05, * p<0.1, a detailed explanation of variable interaction appears in *Appendix Table* A.8.

The regression results suggest that food prices have responded inversely to precipitation and contemporaneously to temperature in the region after controlling for markets, commodity, and time-fixed effects *Table* 2.3. The quadratic term and the lag value of the temperature and rainfall variables also confirmed the same magnitude as the level values. These results indicate that the availability of rainfall can reduce the variability of food prices, as traders' anticipation is influenced by weather information. In contrast, rising temperatures lead to higher food prices due to traders' expectations of drought conditions influencing market decisions. This regression reaction also indicates a non-linear relationship between food prices and weather variables, as the quadratic terms suggest that after a certain level of disruption, the price reactions fluctuate.

The quadratic relationship between weather variables and food prices highlights how trader behaviour is influenced by weather information. As rainfall increases, traders anticipate better yields, leading to lower food prices. Conversely, rising temperatures prompt traders to expect drought conditions, which in turn result in higher food prices. This non-linear relationship suggests that traders adjust their strategies in response to the extent of weather disruptions, with significant changes in weather leading to fluctuating price reactions. By closely monitoring weather forecasts and updates, traders make informed decisions that ultimately shape the dynamics of food prices. Integrating these weather variables into economic models enhances the understanding of how traders' anticipation impacts market outcomes.

2.4.6 Non-linearity relation estimate between food prices and weather shocks

We plot the regression result under *equation* 2.4 in the non-linearity estimation. In *Figure* 2.5 below, the food price reactions related to each range of weather data are presented with a 95% confidence interval (the blue line passes through each point that clusters at the market level). In *figure* 2.5 below, a food price function that reacts differently at different intervals with a market level as polynomial regression has been constructed. The upper panel features a reaction to temperature shocks, and the lower panel plot contains rainfall shocks. The green circles represent the regression coefficients of the weather at different intervals, which determine the temperature and precipitation in each month.

The regression analysis reveals a non-linear relationship between temperature variations and regional food prices. Specifically, when monthly average temperatures fall below 20°C, food prices tend to increase significantly, rising by approximately $19.58 to $21.28 per ton. In contrast, temperatures within the 16°C to 20°C range are associated with a modest decrease in food prices, ranging from $2.42 to $3.38 per ton. However, when temperatures exceed 20°C, food prices begin to surge again. This pattern suggests the existence of an optimal temperature window for agricultural productivity, beyond which crop yields and consequently food supply may be negatively affected, driving prices upward. These findings align with previous studies e.g., Richard (2020); Washington and Pearce (2012), which identify 15°C to 20°C as the ideal temperature range for field crop production in East Africa. The results underscore the sensitivity of food prices to climatic conditions and highlight the potential economic risks posed by rising temperatures due to climate change.

The analysis of rainfall bins reveals a differentiated relationship between precipitation levels and food prices, highlighting the sensitivity of agricultural markets to climatic variability. Specifically, when monthly rainfall falls below 100mm in a given regional district or market, food prices increase sharply by approximately $127.8 per ton. This suggests that insufficient rainfall leads to poor crop yields, reduced supply, and heightened market pressure. In contrast, rainfall between 100mm and 300mm appears to stabilise or reduce food prices, reflecting optimal growing conditions that support healthy harvests and improve food availability. However, when precipitation exceeds 300mm per month, the relationship reverses again: excessive rainfall contributes to waterlogging, soil aeration issues, and pre-harvest losses, all of which disrupt production and drive prices upward.

A small rainfall deficit, distributed below normal, slightly increases food prices, as indicated by the coefficient plot of rainfall bins. Food price does exhibit a solid reaction to the precipitation bins higher than the normal average, which shows an immediate price increase of $140 per ton and above. Similarly, a temperature warmer than usual also leads to an increase in food prices, while colder weather episodes lead to a slight increase in food prices in the region. A common estimation of the analysis is that the price absence reacts to mean rainfall and temperature in the region. Coefficients with a small value of both variables do not trigger price movement; however, the reactions to higher values are much more uncertain, as indicated by the extensive coefficient intervals.

The non-linear relationship between weather variables and food prices, as interpreted through trader anticipation based on weather updates, reveals complex dynamics. Traders adjust their strategies based on the extent of weather disruptions, with significant changes in weather leading to fluctuating price reactions. For instance, while moderate rainfall can reduce food prices due to expectations of a good harvest, excessive rainfall can lead to waterlogging and pre-harvest losses, thereby increasing food prices. Similarly, warmer temperatures might prompt traders to anticipate drought conditions, resulting in higher food prices, whereas colder weather episodes might slightly increase prices due to potential impacts on crop growth.

This non-linear response of food prices to rainfall intensity reflects broader economic patterns observed in climate impact studies, where economic output tends to respond differently across varying levels of temperature and precipitation. These studies show that both climatic deficits and excesses can significantly hinder productivity, particularly in regions where agriculture plays a central role in the economy (Kalkuhl and Wenz, 2020). The parallels between food price responses and broader economic performance underscore the vulnerability of climate-sensitive sectors and highlight the need for adaptive strategies to mitigate these risks.

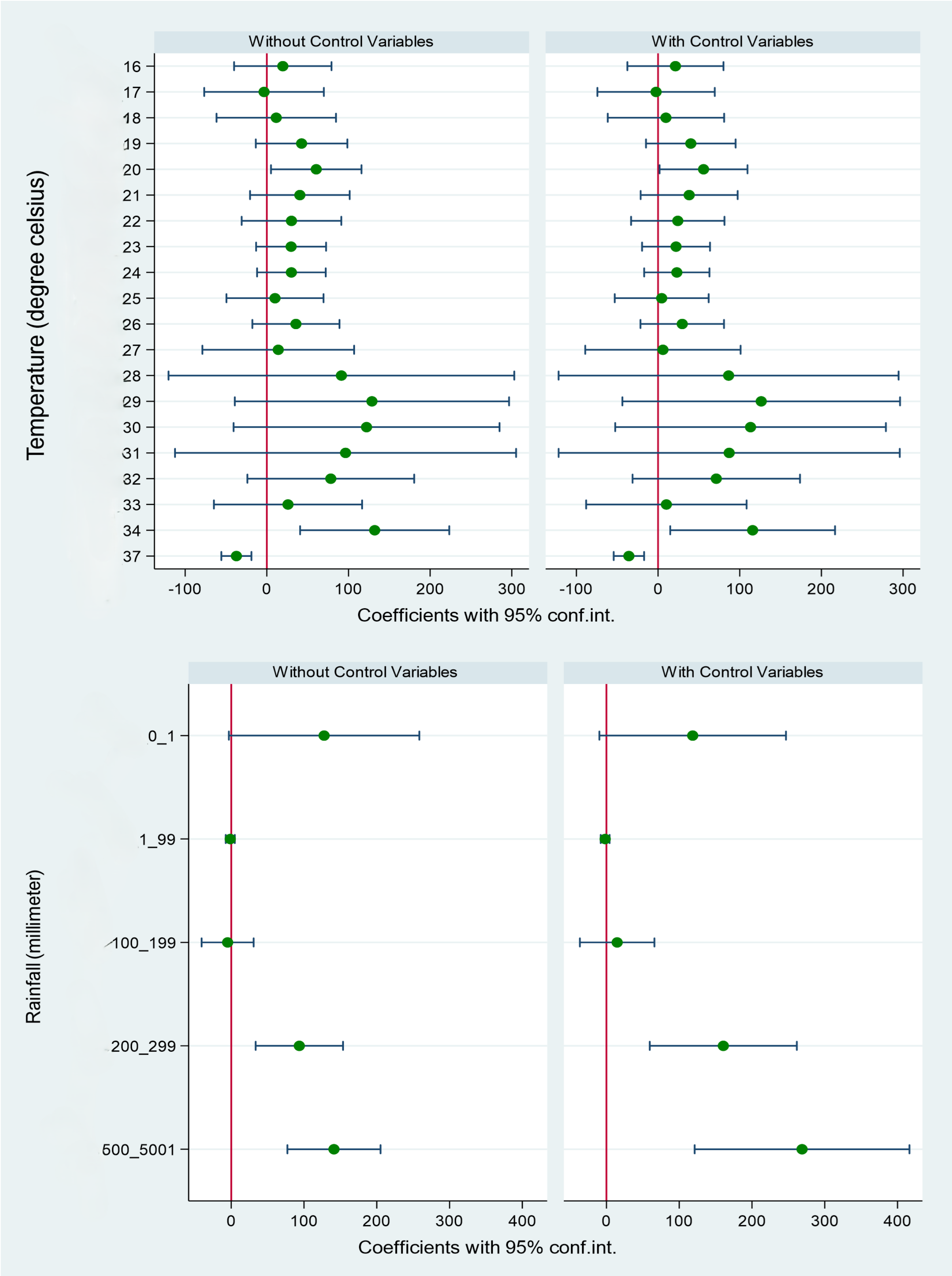


Fig. 2.5 : Illustrates coefficient plots that highlight the relationships between food prices and two critical environmental variables: temperature (top graph) and rainfall (bottom graph). Each graph incorporates segments with and without control variables, such as market, crop, and time-fixed effects, which are vital for understanding food price dynamics. The points denote estimated coefficients with 95% confidence intervals. A red vertical line at zero is a reference point: coefficients to the left indicate a negative relationship. At the same time, those to the right suggest a positive one, revealing the intricate interactions within East Africa.

2.5 Export policy Interventions

2.5.1 Outline of the policy

Temporary export restrictions were implemented through domestic policy interventions in response to food price fluctuations in some East African countries. These measures aimed to prevent food shortages and protect citizens from rising prices during the global food crisis of 2007/08. Ethiopia formally announced restrictions on major staple crops such as maize, wheat, and teff, while Kenya and Tanzania adopted similar policies for maize markets in 2008. As the graph indicates, these policy actions helped manage food price volatility. The red line in *figure* 2.6 marks the specific dates in 2010 when Ethiopia, Kenya, and Tanzania enforced their food export restriction policies. These decisions were crucial in shaping the agricultural and economic landscapes of these countries by managing domestic food supplies and stabilising local markets during periods of global food price volatility.

Fig. 2.6 Effect of Export Restriction Staple Foods

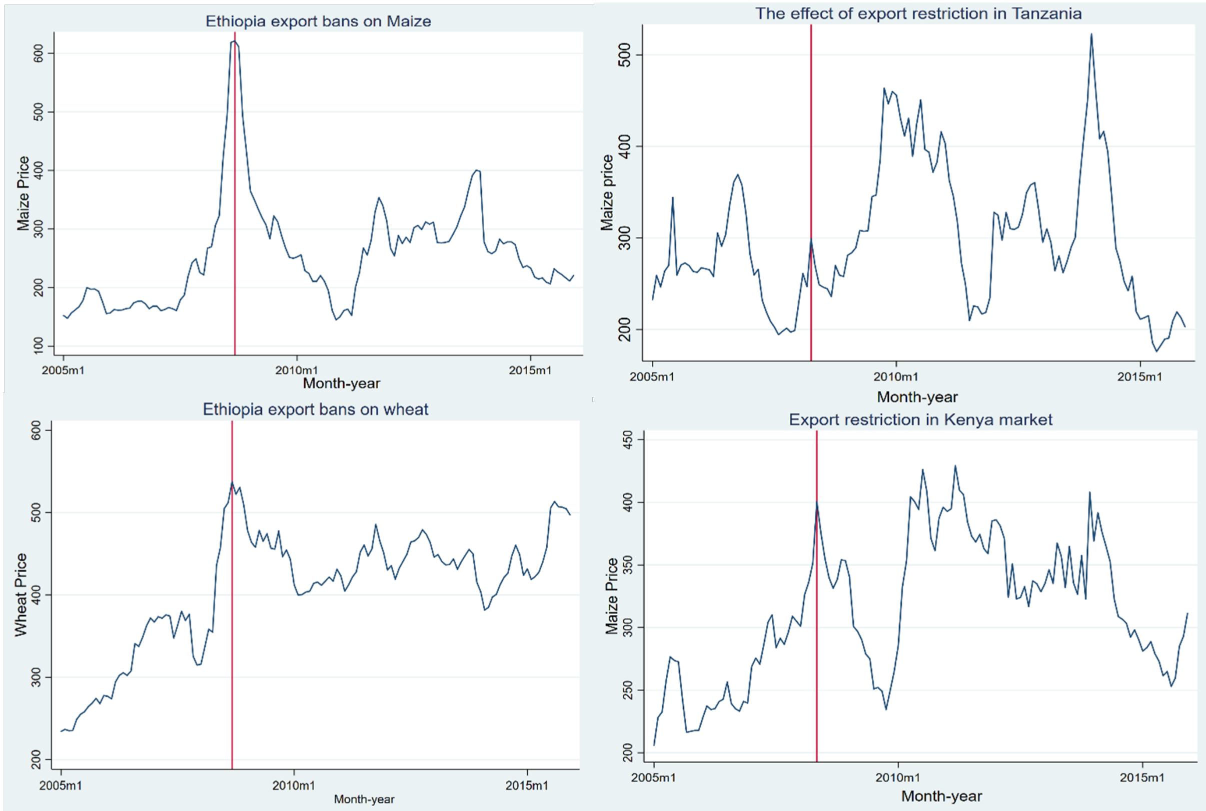


Figure 2.6: East African countries imposed export restrictions during the 2008/09 global food crisis to secure domestic supplies and stabilise prices. Many countries commonly apply restrictions and export bans on cereals to secure domestic supplies and stabilise prices.

2.5.2 Hypothesis

Export restrictions have a long history and continue to be a prominent policy instrument for both agricultural and non-agricultural products. A recent study by the World Bank on distortions in the agricultural market shows the effectiveness and pervasiveness of these policy tools (Anderson, 2009). This policy was pursued by many countries in the form of export restrictions and reductions of export tariffs, and the restriction on foodstuffs came to distinguish between measures of the food crisis and price spikes during 2007-11. With the global food market's continued projection and price volatility increase for several years, an export restriction policy has been singled out as one key measure to address this challenge by several countries worldwide. Therefore, this Essay seeks to understand the specific role of export restriction on price spikes and the joint impact of export restriction with weather variables on price surges in the study region. Within this subsection, the study shall hypothesise the policy intervention as follows. Export restrictions in the exporting country could reduce the domestic food prices relative to the newly rising global prices that are anticipated to be transmitted through trade. In Economic theory, an export restriction is one of the generic factors that affect the shift in supply, i.e., restriction of the supply of food commodities outside the country could increase the domestic supply, and when supply shifts to the right, indeed the price level moves down along the y-axis in the short run. Therefore, the economic theory has supported the hypothesis of this study.

2.5.3 Regression result

The export restrictions or export bans on foodstuffs in the study region have had different experiences for different countries; for instance, Kenya and Tanzania implemented this policy tool on maize crops, while Ethiopia implemented it on cereals during the period, as indicated in *Table* 2.4. Hence, the analysis has been carried out according to this difference by categorising it into general, maize, and cereal bans, as indicated in three columns in the table below. These countries have implemented policies on various foodstuffs, prioritising crops that are most important to local consumers, with the common objective of protecting domestic consumption from global price fluctuations. Countries implement this policy to shield their domestic markets from international price volatility and to ensure the continued availability of food to local consumers.

The analysis was conducted based on a restricted period scenario and an unrestricted period scenario, which were captured as dummy variables. The period export restriction is either one or zero; otherwise, it applies to the same country or market. The weather variables are temperature and rainfall records of the specific market measured in Degrees Celsius and millimetres, respectively. Other covariates, such as crop market and time-fixed effects, were used as control variables for the observations.

A standard panel method was employed for the analysis and time dimension, and variables that might contribute to cross-sectional variation, such as location and crop type, were controlled for in the regression analysis. The effects of weather variables and export restriction policy instruments have been estimated separately and jointly as variable interactions; the latter was included for further investigation of the importance of the restriction in normal weather distribution circumstances. A study conducted by He (2022) has analysed the impact of export restrictions on domestic food prices without controlling for weather; however, omitting weather variables from the analysis may lead to estimation bias. The interaction between these two variables might provide the correct magnitude and direction of the policy variables. Also, export restrictions in the dry district are worthless. The regression analysis has been implemented based on the data observation before and after the policy intervention in three countries. Therefore, according to *equation* 2.5, the regression output was displayed in *Table* 2.4 below.

Table 2.4 The effects of export restriction regression results

VARIABLES	Model 1 (General bans)	Model 2 (Maize bans)	Model 3 (Cereal bans)
Export restriction (Bans)	218.010***	235.866***	275.106***
	(59.521)	(70.386)	(78.678)
Average seasonal rainfall	-6.456***	-6.561***	-7.210***
	(1.289)	(1.288)	(1.282)
Bans # Rainfall	-8.473***	-9.159***	-10.870***
	(2.87)	(3.476)	(3.647)
Average seasonal temp	0.299***	0.300***	0.300***
	(0.056)	(0.056)	(0.056)
Bans # Temperature	0.06	0.06	0.05
	(0.161)	(0.176)	(0.275)
Co-variate fixed effect			
Markets	Yes	Yes	Yes
Crops	Yes	No	Yes
Time fixed effect (month)	Yes	Yes	Yes
Constant	997.183***	992.743***	1,000.675***
	(42.799)	(42.864)	(42.884)
Observations	5,016	5,016	5,016
R-squared	0.657	0.656	0.655

Notes: *** p<0.01, ** p<0.05, * p<0.1, a detailed explanation of variable interaction appears in *Appendix Table* A.8

The regression output in *Table* 2.4 above shows that export restrictions on food prices have a positive and significant effect on prices in the three scenarios (general bans, cereal bans, and maize bans) in the study region. As the country implements an export restriction policy, agricultural food prices have increased by more than 30%. This result suggests that an export restriction policy alone cannot regulate the domestic spike in food prices;

instead, it exacerbates the spike in food prices. However, when the export restriction is integrated with other domestic factors, it can reduce domestic food prices by more than 5% of the price before policy intervention. This finding coincides with the Marta et al. (2015) study on the Indian rice export ban and the study on the determinant of global and local prices by Guo and Tanaka (2020), which resulted in the reduction of domestic producer prices while increasing the world price see *Figure* A.5 in *Appendix* A.

Rainfall in the region has negatively and significantly contributed to reducing food prices. In the three scenarios, on average, one millimetre of rainfall reduces food prices by seven dollars per tonne. Rainfall availability can positively impact crop harvest from an agronomic perspective, and increased production shifts the supply curve to the right, thereby lowering market prices.

The variable temperature has a similar effect to the first section. A rising temperature has a positive and significant effect on food prices. A high temperature indicates drought and dry weather, which can influence crop harvests and grain supplies to the market. Therefore, a rising temperature in the region has reduced crop yields, leading to a surge in food prices.

The interaction between rainfall and export ban variables has had a negative and significant impact on food prices. Implementing export restrictions in areas with normal rainfall distribution can significantly reduce domestic food prices compared to the effect of rainfall alone. The results indicate that implementing an export restriction policy during normal rainfall distribution can reduce food prices by more than 5% in the region. The sign of rainfall and the interaction term (between these two variables) yield the same outcome, indicating a substantial impact of weather conditions (rainfall) on food prices in the short run. The sign of the export restriction coefficient is opposite to that of the interaction term, indicating that policy intervention is successful when rainfall is available. Therefore, an implementation of export restrictions on staple crops has successfully reduced the prices of staple crops in the three cases (general food prices, cereal prices, and maize prices) with the availability of rainfall in the study region.

2.6 Conclusion

This chapter presents an approach to modelling the effects of weather shocks on domestic food prices and the short-run policy interventions that can regulate the food spike. The study proposes a theoretical trader anticipation model to analyse the short-run price response to weather shocks in the East African region. A weather shock is sometimes believed to be non-contemporaneous with supply shocks. Subsequently, the effect of weather shock has several channels that affect food prices. The first and most important channel is trader anticipation. The trader's updated anticipation of future market conditions alters the stock's market valuation compared to past conditions. This channel provides an essential and valuable analysis of market agents' theoretical perceptions and anticipations, as they play a crucial role in shaping market valuations. Regression results from the empirical analysis show that a market food price reacts to weather shocks non-linearly due to the nonlinearity and asymmetric effects of weather on future harvests. This complexity arises from how market agents' climate updates and the anticipation of the next harvest affect their trading decisions.

The export restriction policy implemented in the region has been shown to have a positive relationship with food prices. In contrast, an interaction term (policy action and rainfall) is inverse to food prices in all scenarios. Within this analysis, it has been observed that weather shocks in general (rain pattern) have the lion's share in changing the magnitude and direction of food prices as a single variable and interaction with trader anticipation in the first case and export restriction in the second case, show a similar result in the regression. Therefore, this highlights that the issue of water is a crucial area of research for the remainder of this thesis.

Given the significant influence of rainfall variability on food prices, as seen in its interaction with export restrictions and trader anticipation, the issue of water availability emerges as a fundamental factor shaping economic resilience. Understanding the complexities of water resource management and sustainability within the Nile River Basin is vital for mitigating the risks posed by climate-induced shocks and ensuring stable food production.

Hence, this outcome necessitates a more in-depth evaluation of virtual water flow in the region to inform effective water management and trade policies. Virtual water, the amount of water embedded in agricultural and industrial goods traded between regions, plays a crucial role in national and regional water use efficiency. Assessing virtual water trade helps policymakers optimise resources, ease local water stress, and support sustainable agriculture. This analysis connects micro-level impacts to broader challenges, guiding future discussions on macroeconomic effects, adaptation strategies, and water policy.

Chapter 3

Virtual Water flows Embodied in International Trade of NRB: Implication to Water Scarcity

3.1 Introduction

Today, people in Asia are indirectly affected by the African hydrological system, and Brazil's regional water system may indirectly impact people in Europe or vice versa. This phenomenon may be occurring due to changes in the climate, including global shifts in precipitation, evaporation, and temperature patterns. However, global trade is another route by which impacts might be transmitted across national boundaries (Arjen and Ashok, 2008). International trade can create a link between countries through the demand for water-intensive commodities, where water is used to produce exportable goods that rely on a country's national water system. For instance, Japanese consumers buying a product produced in the USA would put pressure on the water resource consumption in that nation. European consumers may significantly contribute to water demand in Brazil through the water-intensive commodity trade. However, it's essential to identify the extent of virtual water (VW)[1] flow in the international trade from drought-prone areas such as the Nile River Basin countries in the global context. Several authors have already argued about this issue, such as Vorosmarty et al. (2000); a new dimension has been added in this study.

The water flow within the Nile River Basin and the rest of the six continents, including the rest of Africa, was assessed in the international trade context. Water is commonly known as a globally viable imperative for the economy. It is one of the most extracted resources globally, with approximately 4000 BCM and 700 BCM surface and groundwater, respectively, for economic activities (Rockström et al., 2009).

The East-North African region of the Nile Valley is well known for the origin of civilisation and mankind. However, since the early 20th century, the Nile River has been the source of political tensions among the major riparian countries (Ahmad et al., 2024). Rapid population growth and economic development in the region exacerbated the tension in the basin due to the high water demand. It is an essential ecological interference among the territorial ecosystems. Hence, the Nile riparian is the countries associated with the Nile River, such as Burundi, Rwanda, Uganda, Tanzania, Kenya, DR Congo, Sudan, Ethiopia, Eritrea, and Egypt (Okoth, 2007). This region is situated in an arid and semi-arid area, where the temporal pattern of rainfall is erratic, and there is a long history of recurrent droughts, floods, and environmental degradation. As a result of increasing water demand, the Nile River Basin has brought the attention of researchers and policymakers to analyse the efficient use of this resource. Additionally, several researchers and environmental analysts have suggested that the region has a high potential for water conflict due to the high demand for investment by upper riparians on the river, which creates a bottleneck for the sustainable social and economic development of downstream riparians (Polakovic, 2021).

[1]Virtual water, also called “embedded water” or “indirect water,” is the water “hidden” in the products, services and processes people buy and use every day. Although virtual water remains unseen by the end-user of a product or service, it has been consumed throughout the value chain, making the creation of that product or service possible.

Increasing water scarcity places considerable importance on quantifying the water footprint at different levels. Therefore, this research aimed to quantify the virtual water footprint (VWF) [2] and its implications for water scarcity in the Nile River Basin (NRB) located east-to-northwest of Africa. The concept of a water footprint has been a recent addition to scientific research, as it serves as an essential indicator of human-water interactions. Despite the progress made earlier, many water footprint studies still focus on specific river basins, particularly in arid and semi-arid regions such as Africa. The Nile Basin countries are particularly reliant on the physical flow of water from upper riparian nations. However, an alternative water source has not been assessed and documented. Therefore, this research aimed to investigate the concept of 'virtual water flow' in international trade within the Nile River Basin countries and between NRB and the rest of the world.

3.1.1 Problem statement and justification for the study

Water is a vital resource underpinning global economic and social systems (Shiklomanov, 1991). However, rapid population and economic growth have driven a 600% increase in global water demand over the past century, with an annual growth rate of 1.8% (Boretti and Rosa, 2019). Agriculture remains the largest consumer, accounting for 70% of global freshwater withdrawals Khokhar (2017), though industrial and domestic demands are rising faster.

The NRB, a region already under water stress, exemplifies the tension between water scarcity and economic development. Despite achieving a high level of regional water self-sufficiency (90%), the NRB has a low per capita water footprint (230 m^3/year), reflecting both limited access and constrained usage (Hirwa et al., 2020). As a net exporter of water-intensive agricultural products, the NRB faces increasing pressure on its limited water resources, exacerbated by climate change and population growth.

[2] The water footprint is a measure of humanity's appropriation of fresh water in volumes of water consumed and/or polluted.

This pattern extends across Africa, where 95% water self-sufficiency coexists with a below-average water footprint (210 m^3/year). Yet, the continent suffers from severe water scarcity, affecting health, food security, education, and economic productivity (Padder and Bashir, 2023; The Water Project, 2022; WHO, 2017). Sub-Saharan Africa alone loses approximately 40 billion working hours annually to water collection The Water Project (2022), and agriculture accounts for over 80% of the available water (UNDP, 2015).

Globally, 47% of the population experiences water scarcity at least one month per year a figure projected to rise to 57% by 2050 (Dongyu and Houngbo, 2021). Without intervention, over 700 million people could be displaced by 2030 due to water-related stress (Lai et al., 2022).

In this context, the concept of virtual water, the water embedded in internationally traded goods, has become increasingly relevant. Virtual water trade can alleviate local scarcity, but it also creates dependencies. As highlighted by Hirwa et al. (2020), understanding virtual water flows is essential for sustainable water management.

This study aims to assess the role of virtual water and water footprint in the NRB, scale the analysis to the rest of Africa, and evaluate global implications. The findings will support evidence-based policymaking on water allocation, trade, and agricultural strategies in a water-constrained world.

3.1.2 Relevance of the study and contribution to knowledge

The current state of knowledge on virtual water and water footprint is extensively advanced in developed countries (Ma et al., 2020). However, the concept of VW and WFP is limited in developing countries. Hence, this presents an exciting opportunity to address the gap and make this study more relevant in developing countries, particularly in Africa.

The effects of climate change have been occurring alongside water scarcity in several parts of Africa (Gosling and Arnell, 2016). These challenges are more serious in the Nile Valley, which connects East and Northwest African countries. Furthermore, this region is well known for exporting water-intensive agricultural products and, in response, importing chemicals such as fertilisers and pesticides that intensify water requirements in the soil (Chapagain et al., 2006). Hence, this study aimed to evaluate the content of virtual water embodied in international trade using the Multi-Regional Input-Output (MRIO) approach. The MRIO Analysis reveals the links between existing economic activity and water use, including the extent to which water is embodied in international trade. The dimension of virtual water export and import and its contribution to sustainable water availability mitigation for water scarcity has been assessed and documented in several parts of the world; however, limited studies have been carried out in the developing world, particularly in Africa, where a recurrent drought and water stress are the common phenomenon in the region like Nile River basin of sub-Saharan Africa. The availability of non-renewable resources, such as water, depends on their sustainable use. Hence, the study focuses on these challenges to evaluate the extent of virtual water content by using an MRIO analysis of virtual water, which reveals the links between existing economic activity and water use, particularly the extent and dimension to which water is embodied in international trade. Furthermore, the study aimed to identify the implications of virtual water flows on water scarcity and provide policy direction as a contribution to addressing water problems, including those caused by climate change.

3.2 Literature review

3.2.1 Defining the Virtual water and water footprint of a product

According to the Institute for Water Footprint Network (2003), virtual water refers to the invisible water embedded in the production of goods and services. It is the amount of water used in the production process, including producing raw materials, processing, manufacturing, and the distribution of products. Hence, virtual water helps us understand the amount required to produce products and services. The term water footprint refers to the amount of water that is consumed or polluted through human activities. It considers the water used in producing goods and services, as well as the water used for daily activities such as drinking, cooking, and washing. The water footprint is measured in terms of the volume of water consumed or polluted, usually expressed in litres per unit. We can identify water management strategies to reduce our water consumption and pollution by evaluating our water footprint.

The production of goods and services usually requires water. The water used in the production process of agricultural or industrial products, which is contained in the product, is known as virtual water. For instance, to produce 1 kg cereal grain or citrus fruit requires 1-2 m^3 of water and the production of livestock requires a higher level of water per unit; for example, to produce 1 kg beef of beef meat, it requires 15 m^3 of water, one head of cattle require 4000 m^3, one head of poultry require six m^3 of water (Chapagain and Hoekstra, 2004)). A study by Williams et al. (2002) indicates that producing 2 grams of computer chip requires about 0.032 m^3 of water. Hence, if a country exports a water-intensive product to another country, the water used in the production of the product is exported as virtual water. Therefore, a water-rich country supports water-scarce countries by exchanging water-intensive products, as the trade of real water between water-rich and water-scarce countries is impossible due to distance and associated water transport costs. Hence, a water-scarce country can address water security issues by importing water-intensive products instead of producing water-demanding products domestically.

Tony Allan originally introduced the concept of virtual water in the early 1990s (Allan, 1994; Allan et al., 1993). Achieving international recognition as a crucial concept that addresses regional and international security issues took nearly a decade. The first international conference on the concept of virtual water was held in December 2002 in Delft, the Netherlands. A subsequent special session on the virtual water trade issue was discussed at the third World Water Forum in Japan in March 2003.

Virtual water is referred to as ‘water embedded water’ in the product or ‘exogenous water’ imported into the country (Haddadin, 2003). A more precise quantitative definition of virtual water has been proposed, predominantly, using two different approaches. In the first approach, the virtual water content can be defined as the volume of water used to produce a product. The size of water used for production depends on the place of production and the time. According to Haddadin (2003), producing one kilogram of cereal in an arid area probably requires 2-3 times more water than producing the same product in a humid area. The second approach can be defined from a user's perspective rather than a producer's. In this approach, virtual water defines the water content of a product that would be required in the country where the product is demanded. This approach helps calculate the water size saved by importing a product instead of producing it domestically. A difficulty could arise in the second approach to defining virtual water if the imported product cannot be produced due to unfavourable climate conditions.

The virtual water concept has essentially two major functional benefits. First, the virtual water trade is an instrument to achieve water security. A country with water scarcity can relieve its water pressure if it is a net importer of virtual water. A virtual water import is an alternative water source for countries with water scarcity. This additional water source is the modern national or regional water security instrument. More precisely, a political argument on virtual water has been put forward by Tony Allan from the inception of this debate; virtual water trade is the best alternative instrument to prevent geopolitical tension and war over water between nations (Allan, 1998, 2003). The second rational application of the virtual water concept lies in the environmental impact of producing and consuming the product. Knowing the virtual water content of a product could create awareness about the volume of water required to produce different goods. Thus, it provides an idea of which product has the most significant impact on water resources and contributes the most to water resource conservation. The link between consumption patterns and the effect of water has been introduced by Hoekstra and Hung (2002) with the concept *water footprint*: the cumulative volume of virtual water content of a product consumed by a single individual or country.

The water flow between nations through the commodities exchange is referred to as the Water footprint, which takes a consumption perspective (Chen and Chen, 2013).

It provides useful information in addition to traditional indirect water use, taking a production perspective. Therefore, the water footprint of a country is defined as the total volume of water used to produce goods and services that the people of a nation consume. The water footprint of a nation can be measured by the volume of freshwater used to produce a product in the supply chain. A nation's water footprint can be either positive or negative, depending on the size of its commodity imports and exports. For instance, the volume of water used in the European Union is 559 billion m^3/year from a production perspective, while 744 billion m^3/year from a consumption perspective. Similarly, the annual water use for production in Australia is 91 billion m^3/year; however, only 27 billion m^3/year was recorded from a consumption perspective, and the country has experienced a massive volume of water outflow through export in the form of water-intensive commodities (Arjen and Ashok, 2008).

Generally, the water footprint concept has been developed in analogy to the ecological footprint notion introduced in the late 19th century by William and Mathis (Rees, 1992; Wackernagel and Rees, 1996). Water is not only used for direct consumption but also indirectly in the production process. Hence, determining the volume water footprint enables us to quantify the total water consumed along with the global supply chain. In this chapter, we demonstrate how an MRIO model extended with water consumption coefficients can be utilised to calculate water footprints and compare the domestic and international water footprints of various water consumption sectors across 10 Nile Basin countries.

3.2.2 Water resource availability in the NRB

The Nile River Basin (NRB) is one of the largest river basin regions in the world, comprising approximately 10% of the African continent or about 3.1 million km^2. The Nile is the second-longest river in the world, at 6,695 km, spanning over ten countries and supporting a population of approximately 257 million, depending on the Nile's water resources (FAO and IHE Delft, 2020). The NRB region has an incredibly diverse climate, with spatially variable precipitation, temperature, and evapotranspiration. Rapid population growth and a predominantly agricultural-based economy are the main features of the basin.

The water availability within the basin countries varies due to the reasons highlighted above. Egypt and Sudan are highly dependent on the physical flow of the Nile River, while their other water resources are limited. Ethiopia is the origin of the Blue Nile, where 85% of its contribution is for the downstream riparian. Uganda, Burundi, Tanzania, Kenya, and Rwanda are other upper riparian to the White Nile, where its contribution to the Blue Nile is approximately 15% (Wosenie et al., 2015). Except for Egypt and Sudan, other riparian countries have better precipitation, rain distribution, and groundwater resources. The average annual rainfall in the NRB is 650 mm, with 60 mm recorded in downstream countries and 700 mm in upper riparian countries (The World Bank, 2021).

According to the Nile Basin Initiative report, these figures are below both the global (over 990 mm) and African (800 mm) averages (Degefu and He, 2016). Therefore, NRB has shown an increasing concern about water scarcity across the riparian countries and places considerable importance on quantifying virtual water and water footprint at different levels.

Africa is often perceived as having scarce water resources due to climatic conditions such as erratic rainfall and high evapotranspiration. African internal renewable water resources availability is about 3,950 million m^3/year, which constitutes 10% of global freshwater availability (McGrath, 2012). Regardless of the availability of water resources, the average water per capita is 4,008 m^3/year. This is significantly lower than the global average of 6,498 m^3/per capita/year. According to this source, Africa has abundant water resources overall, however the resource are not evenly distributed, with some regions experiencing sever water scarcity such as NRB per capita water availability is 570 m^3/year; it is significantly below the 1,000 m^3/capita/year threshold considered necessary for basic needs, according to the UN (Gleick, 1996). Despite this, the continent is deemed the second driest region in the world, next to Australia, likely due to the uneven distribution of water resources compared to its population density. According to the World Wide

Fund for Nature, the disparity in water resources is significant; approximately 30% of Africa's water resources are utilised by only 10% of the population, primarily around the Congo Basin (Serageldin, 2001). The continent is geographically characterised by extensive deserts and highly densely populated areas, such as Niger and the Nile River Valley. In contrast, it has highly dense forest regions, which are sparsely populated or uninhabited in the central part of the continent.

3.2.3 Climate vulnerability and Water Scarcity in the NRB

Physical water scarcity is common in most African countries. The continent is severely sparse in ground and surface water resources, as indicated in the section above. According to Toulmin (2013), the continent constitutes 15% of the world's population that shares 10% of global water resources. However, most of these water resources are contaminated and are not all used for economic activities. Hence, Africa does have an economic water scarcity. Rapid population growth, global warming, and other large-scale climate patterns have also contributed to worsening water scarcity in Africa (Toulmin, 2013).

According to Mahlakeng (2023), by the end of the 20th century or early 21st century, the realm of international relations will be featured by the growing prominence of water geopolitics. This has highlighted a potential dispute and conflict among basin countries due to water resource scarcity induced by political boundaries. In contemporary literature, scholars speculate that water will be the future cause of interstate or inter-regional conflict (Yoffe and Wolf, 2002). Water is essential for both domestic and agricultural production, and it is guaranteed for industry and investment growth. Subsequently, in a region like NRB, which heavily relies on water, disputes over water allocation among riparian states are emerging, leading to inter-regional and cross-border tensions and conflicts (Van Schaik and Dinnissen, 2014).

The NRB is one of Africa's most complex cross-border basins due to its proximity to riparian and water variability across the season (Ashton, 2002). The Nile Basin countries are facing considerable challenges, such as rapid population growth, climate change, and the inequitable distribution of water resources, which lead to water insecurity. According to Baecher (2000), countries along the Nile River are facing rapid population pressure. According to the International Institute for Social Studies, Abawari (2011) specifies that population growth in the NRB is rising at an unprecedented rate. For instance, in 2010, the population of the Nile River Basin was 424 million, of which 232 million lived along the river basin. This initiative also estimated that the population of riparian countries would grow to 600 million, with over 300 million residing along the Nile Basin. The United Nations Population Division (UNPD) has estimated that the size of the NRB population will reach 647 million by 2030, implying an increase of 52% from 2010 and 7.8% from the population size in 2025.

Over the last two decades, Africa has experienced an increase in recurrent extreme weather events, followed by catastrophic famines and droughts, resulting in loss of life. It has been reported that climate change-related effects contribute to the reduction of economic growth per capita in the region. Africa has limited climate adaptive capacity due to a lack of a structure that helps regulate the effects of extreme climate scenarios; hence, the continent is exposed to vulnerable adverse climate conditions. For instance, the water storage capacity to mitigate drought and attenuation of floods is low compared to the rest of the world. This phenomenon is more severe in the Nile River Basin of Sub-Saharan Africa (SSA), a region that depends immensely on rainfall for agriculture and livelihood. The Nile Basin is the most water-stressed region in Africa, where water shortages and droughts are common phenomena. The agricultural system, dam development, food insecurity, and population growth make the basin extremely vulnerable, a region that primarily depends on agriculture for subsistence (Coffel et al., 2019). This affects the distribution of precipitation, resulting in significant differences between the wet and dry periods of the Nile Basin states. Several studies indicate that NRB is one of the most vulnerable regions to the impacts of weather and climate change (IPCC, 2007). It suggests that the NRB water resources are highly sensitive to climate change, with flow projects in the short term (2020-2049) anticipated to decrease, while in the long term (2070-2099), they show both increasing and decreasing trends (Michael et al., 2016).

The region's main challenge is water availability due to moisture stress. Water is a centre of well-being for human beings, and the quest for development is used in all aspects of life, such as social, economic, political, and cultural. As defined earlier, the water demand has been rising mainly due to population growth and economic development. Population growth increases water demand for basic needs, including drinking water, hygiene, and healthcare. As the world population is expected to reach 9 billion by 2050, over 50% of the additional water demand is expected to be met compared to 2020 (Deconinck, 2017). Likewise, the economy induces higher individual water consumption to meet its basic needs. Additionally, population growth leads to increased agricultural production, and more water will be required to produce the additional food. These can be realised through the expansion of irrigation areas, which may lead to the overexploitation of rivers and groundwater resources.

Furthermore, as societies progressively shift from a rural-based economy to urbanisation and industry, water demand in these sectors grows, and competition with agriculture will emerge in areas where water resources are scarce. In summary, it can be observed that water demand is increasing faster than population growth; the world population has doubled since 1950, while water consumption has tripled. Africa's condition is similar to that of the rest of the world (Björklund et al., 2012).

The water supply remains steady despite increased demand. Conservative estimates indicate that the amount of renewable water on Earth is approximately 9,000 BCM, yet climate change could alter the broader understanding of the actual picture (Donkor, 2006). With a global population approaching 7 billion, there will be an average of 1286 m^3 of water for every person on the earth. However, this average doesn't exist; *Table* (3.1) below demonstrates diversified water availability and consumption in the Nile River Basin and other parts of the world.

Table 3.1 Water withdrawal in Nile River Basin countries compared to Europe

Country	Total water withdrawal (BCM/year)	Population (million)	Water withdrawal per capita (m^3/p/year)
Burundi	0.3	10.7	28
DR Congo	0.7	78.7	9
Egypt	60.9	97.7	623
Eritrea	0.6	3.3	182
Ethiopia	10.3	102.5	100
Kenya	3.2	46.9	68
Rwanda	0.5	11.6	43
Sudan	26.9	38.2	704
Uganda	0.6	37.5	16
Tanzania	5.2	52.5	99
Nile River Basin	109.2	479.6	228
Europe	444.6	508.2	875
Germany	31	81.69	378
France	30	66.55	447
Netherlands	10.7	16.94	647
Belgium	6.2	11	580

Table (3.1): Shows comparative average of water withdrawal per capita among NRB countries alongside the European average. Additionally, it includes data for Belgium as a specific example within Europe. This table allows for a detailed examination of how water resources are managed and utilised across these regions, highlighting variations in water consumption patterns relative to population size. Source: WorldBank (2015)

There is a noticeable high difference in consumption patterns, with DR Congo, Uganda, Burundi, and the upstream riparian countries having relatively low per capita consumption and Sudan and Egypt having considerably higher statistics. Hence, the average level of water consumption per person per year (m^3/p/y) measures scarcity. Numerous international institutions, including the World Bank and UN agencies, utilise the average 1000 m^3/p/year as a water scarcity threshold. If water extraction falls below this level, economic development declines, health problems arise, and society sputters. According to this measurement, the situation in Sudan and Egypt should be more than pleasant. Still, the upper riparian nation must be concerned about the impact of a water shortage on their everyday lives. However, the NRBs' overall water consumption per capita is below the global average, which might be attributed to various reasons.

3.2.4 Review of studies on Virtual water trade and water footprint

Although considerable research estimates countries' water footprints, only limited research has empirically estimated the virtual water flows between regions or nations that share a common river. In the most similar piece to my research, a study undertaken by Tian et al. (2020a) on the concept of "virtual water" in the case of the Yellow River Basin (YRB) in China, using MRIO analysis to address regional water shortages. An MRIO model was used to analyse the IO data from 30 provinces in China in 2012 and estimate the features of virtual water trade in the region. The study results indicate that the YRB provinces are net importers of virtual water through various virtual water pathways. The virtual water net inflow paths are based on agricultural and industrial products, reflecting the province's relative economic and infrastructural development. For instance, the major virtual water inflows of Shandong and Shanxi come mostly from imported agricultural products.

Expanding on this foundation, recent studies, including Wei et al. (2023), have explored the virtual water trade in China's Yellow River Basin (YRB), focusing on the flow of virtual water embedded in industrial products between provinces such as Gansu and Ningxia (An et al., 2021). These studies utilise the Multi-Regional Input-Output (MRIO) approach to analyse the direction and magnitude of virtual water flows, highlighting the net inflow and outflow of virtual water and its implications for sustainable development (Tian et al., 2020b). However, gaps remain in understanding the long-term economic impacts of virtual water trade on local industries and the effectiveness of policy measures in optimising water use efficiency. Additionally, there is limited research on the socio-economic consequences of virtual water trade for less developed regions within the YRB, which could provide deeper insights into achieving balanced regional development and water resource management (Feng et al., 2012; Zhou et al., 2024).

Another interesting study on measuring the water footprint of consumption and production on a transboundary river basis was undertaken by (Xia et al., 2019). The study aimed to design a water-sharing mechanism for transboundary river basin nations by introducing the concept of virtual water. The study identifies and discusses a net virtual water importer and exporter sub-basin transboundary rivers at mesh-based spatial resolution. The study's findings reveal that not only the sub-basin's water resource endowment but also its social, economic, and demographic features influence water footprint consumption and production. Moreover, the research anticipates that the water footprint of consumption and production within the basin units would be a global feature. As a result, sustainable water management strategies within border-crossing basins must encompass both the local and global water footprints associated with water consumption and production.

The research organised by Maite et al. (2009) incorporates the water footprint and virtual water into policy intervention in the case of the Mancha Occidental Region, Spain. The team of experts analysed the water used in production and consumption, which links to a larger range of sectors, thus delivering a potential application to support optimal water management practices through informed production and trade decisions. This research explored the hydrological and economic aspects of agricultural production, distinguishing between the blue and green, or surface and groundwater, intensities used by different sectors. The water footprints of Morocco and the Netherlands were assessed by Arjen and Ashok (2007) through an MRIO analysis of virtual water flows into and out of these two countries. The study has confirmed that both countries are net water importers and concluded that they are the most dependent countries on border water resources.

According to Feng and Hubacek (2015a) Handbook Chapter 10 of Research Methods and Application to Environmental Studies, an MRIO model was applied to 41 world countries and 35 commodities to evaluate the global virtual water flows at the sectoral level for 2008.

The research findings suggest a substantial volume of virtual water is exchanged through international trade. The consumption of goods and services in one region undoubtedly imposes pressure on the water resources of another. Hence, it's crucial to consider regional water challenges in a global context. Furthermore, this study highlights that developed nations, such as the EU, the USA, and Japan, import a sizable amount of virtual water from emerging or developing nations, including Asia and Africa, which are already under water stress. Continuing an export-based economic development paradigm would further deplete water resource availability, affect their hydro-ecosystems, and potentially disrupt domestic consumption and production. Therefore, reducing their economic reliance on exporting water-intensive and low-value-added goods may result in a more reasonable virtual water balance and minimise the pressure on their domestic water resources (Feng and Hubacek, 2015b).

To date, numerous studies have examined the topic of freshwater availability, water use, and water management within the global commodity value chain, particularly in the context of VW and WFP, across various parts of the world (Chapagain and Hoekstra, 2004). However, only a limited number of studies have been undertaken in Africa, such as Hirwa et al. (2022); Zhang et al. (2024), and in the Nile River basin, only Zeitoun et al. (2010). This is due to a limited understanding of virtual water and water footprint concepts. Therefore, this study aimed to replicate the virtual water footprint approach in the current literature in the NRB of Africa, where severe water scarcity exists.

3.2.5 Logical framework

Two approaches are commonly used to estimate virtual water flows in the context of virtual water and water footprint. The first is the bottom-up approach used to calculate the water footprint account, as described by the Water Footprint Network (Chapagain et al., 2011). The second is a top-down approach that is undertaken based on input-output analysis.

The bottom-up approach estimates the virtual water content of goods and services based on the individual commodities' water used for production and related international trade records. According to Chapagain et al. (2011), it's a popular approach to analyse water footprint if the relevant data are available; however, this approach is unable to distinguish between intermediate and final demand users. Hence, it cannot provide an extensive description of the supply chain's consequences on final consumers' allocative responsibility and identify a key driving force. The bottom-up approach is primarily focused on agricultural products, but it does not encompass industrial and service sector products. A good example of this approach is the study conducted by Zeitoun et al. (2010) on the Nile River Basin, which examined the virtual water content of specific commodities with the aim of calculating the volume of virtual water flowing into and out of the region. However, this approach is limited, as it does not account for the full range of products involved in international trade.

The top-down approach estimates the water footprint of the entire region and nation through a traceable global supply chain, based on an input-output accounting framework. In this approach, water used in the production process can be allocated to the final users rather than intermediate consumers. However, the problem with the top-down approaches is a higher aggregation of products and sectors, typically provided in national economic accounts (Feng et al., 2011).

This study employs a top-down approach that integrates smoothly with a multi-regional input-output data set framework to estimate virtual water flows among NRB countries and the rest of the world.

3.3 Materials and Method

3.3.1 Methods

Input-output is an analytical framework initially developed by Professor Wassily Leontief in the late 1930s, for which he received the Nobel Prize in Economics in 1973 (Leontief, 1936). The input-output system was primarily applied to the national level (initially for the United States as a whole); however, over time, interest came from economists to apply it at regional levels, which attempt to reflect the peculiarities of a regional problem (Miller and Blair, 2009b). The ultimate purpose of the input-output framework is to analyse the interdependence of industries in an economy (Miller and Blair, 2009b). An input-output table is constructed from observed data for a specific economic area and illustrates the flow of goods and services between producers and consumers. The core of an input-output table is the inter-industry flows or transaction matrix, which depicts the flow from sector i to sector j. These flows are measured for a particular period (usually a year) and are commonly expressed in monetary terms. However, they could be in physical or mixed units (Hubacek et al., 2012).

Single country/region input-output table

The set of transactions in the input-output table consists of three parts: intermediate transaction (T-matrix), primary input (V-matrix), and the final demand (Y-matrix). An intermediate delivery can be used as input for further processing by another industry. This is usually designated as Z_ij, the primary input is considered as the payment for labour, value-added services and government expenditure, which is represented by V_i and a final demand delivery if it is bought without deliberate further processing which is denoted by y. Assume that the economy comprises n sectors; if the total output of the sector i, denoted by x_i, it can be written in the simple *equation* (3.1) that accounts for sector i distribute its product through sales to other sectors and the final demand.

$$x_i = z_{i1} + ... + z_{ij} + ... + z_{in} + y_i \tag{3.1}$$

There will be an equation as *equation* (3.1) for each of the n sectors.

$$\begin{aligned} x_1 &= z_{11} + ... + z_{1j} + ... + z_{1n} + y_1 \\ x_i &= z_{i1} + ... + z_{ij} + ... + z_{in} + y_i \\ x_n &= z_{n1} + ... + z_{nj} + ... + z_{nn} + y_n \end{aligned} \tag{3.2}$$

There will be an *equation* (3.1) for each n sector. Or in matrix notation as *equation* (3.3)

$$\mathbf{x} = \begin{bmatrix} x_1 \\ . \\ . \\ . \\ x_n \end{bmatrix}, \mathbf{Z} = \begin{bmatrix} z_{11}...z_{1n} \\ .... \\ .... \\ .... \\ z_{n1}...z_{nn} \end{bmatrix}, \mathbf{y} = \begin{bmatrix} y_1 \\ . \\ . \\ . \\ y_n \end{bmatrix} \tag{3.3}$$

For simplicity, the lower-case bold letters **x** and **y** are used to express column vectors, while the upper-case bold letters **Z** are used to express matrices. Using this notation, the data in 3.2 regarding the distribution of each sector's sales can be summarised in matrix notation as:

$$\mathbf{x}_i = \mathbf{Z}_i + \mathbf{y} \tag{3.4}$$

Table (3.2) below represents the flows between economic sectors. The final demand is subdivided into two categories: domestic final demand and foreign final demand. Domestic final demand may consist of household consumption (C), government expenditures (g) and investment (i); foreign final demand is referred to as exports. Thus, the total output in an economy can be summarised as:

$$x_i = z_{ij} + c_i + g_i + i_i + e_i \tag{3.5}$$

Table 3.2 Single country Input-output table

			Intermediate Sectors	Final Demand	Total Output
			$1 \ldots J \ldots n$		
Intermediate sectors		1			
		.			
		.	Z	Y	X
		.			
		i			
		.			
		.			
		.			
		n			
Primary Input (payment sectors)	Value added	V			
	Import	M			
Total Outlays		$\mathbf{X}$			

Equation (3.5) represents the total output of the economy that summarises a column element of intermediate output, private consumption, government expenditure, private investment, and export. These components can be categorised into two major parts: intermediate output and final demand. The latter item is exogenous to the industries in the intermediate sectors and determines the level of economic output externally. Similarly, as the economy engages in the production process, each sector in the intermediate transaction should pay not only for the input from other sectors in the intermediate transaction but also there should be a payment for other inputs such as labour (l), taxes and interest payment on capital investment in the form of value-added, which is part of each sector. This transaction component is known as payment, commonly referred to as primary inputs. The total expenditure of each sector can be summarised as a column sum of the total outlays for import costs of inter-sectoral input flows between sectors and industries, and the direct payments to primary inputs.

$$x_j = Z_{ij} + V_j \tag{3.6}$$

Where Z_{ij} and V_j represent the column element of primary factors of production in the intermediate transaction and primary inputs, respectively.

The input-output transactions matrix can be transformed into a matrix expression by dividing each input transaction in the intermediate sector by its corresponding row sum of gross output. This input-output ratio is a technical coefficient that reflects the production efficiency of each sector or industry with a given technology. i.e., it is a per-unit cost of input required to satisfy the final demand. The technical coefficient can be obtained by dividing the Z_{ij} to x_{ij} – the total input of *jth* sector, and it denoted as α_{ij}.

$$\alpha_{ij} = \frac{z_{ij}}{x_j} \tag{3.7}$$

The technical coefficient α_{ij} in the input-output analysis is noted as A matrix that has $n \times n$ dimension, characterized as the technical structure of the entire economy. The technical coefficient is an array of the production technology for each sector or industry, determined by the composition of input purchases for each sector used as production inputs. Meanwhile, the coefficient across all sectors alongside the row constitutes the sales structure of an economy, as the row entries disclose the sales of each sector's products to the other sectors. Hence, the Z_{ij} can be substituted into *equation* (3.2) instead of the derived technical coefficient α_{ij} in *equation* (3.7), indeed *equation* (3.2) can be written as:

$$\begin{aligned} x_1 &= \alpha_{11}z_{11} + ... + \alpha_{1j}z_{1j} + ... + \alpha_{1n}z_{1n} + y_1 \\ x_i &= \alpha_{i1}z_{i1} + ... + \alpha_{ij}z_{ij} + ... + \alpha_{in}z_{in} + y_i \\ x_n &= \alpha_{n1}z_{n1} + ... + \alpha_{ni}z_{nj} + ... + \alpha_{nn}z_{nn} + y_n \end{aligned} \tag{3.8}$$

The *equation* (3.8) above can be rewritten as:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{y} \tag{3.9}$$

Where X is the total output, A is a technical coefficient of the matrix, and y is a vector of all final demand.

Equation (3.8) can be rearranged to generate *equation* (3.9)

$$\mathbf{x} = \mathbf{(I\text{-}A)}^{-1}\mathbf{y} \tag{3.10}$$

Where matrix $(I - A)^{-1}$ is referred to as the Leontief inverse or multiplier matrix, which shows the total production of each sector required to satisfy the final demand in the economy. Similarly, the Leontief inverse matrix can be described as the amount by which each sector i of the economy must change the level of its product to satisfy an increase of one unit in the final demand from sector j. Hence, the sum of each column of the Leontief inverse matrix conveys each sector's direct and indirect prerequisites to meet the final demand.

Multi-regional input-output model

A researcher's interest in regional economic analyses led to the modification of a single-country or region input-output model, intending to examine the characteristics of a regional economic structure and problems within a single analysis. Indeed, successive development of the input-output model has extended the spectrum to both sub-national and multiregional levels (Miller and Blair, 2009a). Hence, the multi-regional input-output (MRIO) model is an extension of a single region or country IO model, which reveals the inter-regional pattern of the production and consumption of the outputs of sectors, both within the producing region and in other non-local regions. MRIO can be critical for estimating the environmental impact of consumption activities within and outside the producing region, as well as across the inter- and intra-regional supply chain (Wiedmann, 2009). Hence, it's relevant for our analysis.

The implementation of the MRIO model can be applied to the Nile River Basin (NRB) according to the structure of *figure* (3.1) and assuming the NRB has r regions. Each region has n sectors. The destination of production activities in the region r can be specified by *equation* (3.10), i.e., the total output of region r in each sector is equal to output used locally as intermediate inputs or local consumption plus the output in other regions.

$$x^r = A^{rr}x^{rr} + y^{rr} + \sum_{S \neq r} A^{rs}x^s + \sum_{s \neq r} y^{rs} + ex^r \tag{3.11}$$

Where, x^r is an $Nx1$ column vector of output in region r; A^{rr} is an NxN local direct requirement matrix of the region r; each element in matrix A^{rr} denoted as a_{ij}^{rr}which represents the amount of an input from sector i in region r to produce one unit of output in sector j in region r; y^{rr} is an $Nx1$column vector representing the amount of final demand used locally produced commodities and services in the region r. The final demand vector can be categorised into household and government consumption and capital formation. The ex^r is an $Nx1$ column vector of export in region r. the description for the cross regional direct requirement matrix A^{rs} and cross regional final demand vector y^{rs} are analogous with the local requirement intermediate A^{rr} and local final demand y^{rr} used commodities and services.

Fig. 3.1 Basic form of the multi-regional input-output table

Output/Input		Intermediate Product Region 1 (1 ……. n)	….	Intermediate Product Region m (1 ……. n)	Final demand Region 1	…	Final demand Region m	Gross Output
	region (1 … n)	X_{ij}^{11}	….	X_{ij}^{1m}	Y_{ij}^{11}	…	Y_{ij}^{1m}	X_i^1
	….	…… …..	X_i^{rk}	…..	…..	Y_i^{rl}	……	……
Intermediate input	region (1 … n)	X_{ij}^{m1}	….	X_{ij}^{mm}	Y_i^{m1}		Y_i^{mm}	X_i^m
Primary input		V_i^1	….	V_i^m				
Gross Input		X_i^1		X_i^m				
Environmental Indicators (W)		[Q]			[QY]			

Figure (3.1): Presents a foundational dataset for a multiregional input-output table. This dataset spans from *Region 1 … Region m* and is meticulously organised into distinct quadrants: green for the intermediate sector, light blue for final demand, orange for primary input, deep gray for gross input, and gray for gross output. The quadrant marked Q represents water usage in the intermediate sector, and QY indicates water consumption in final demand.

In the multi-regional input-output table, we cannot observe the payment made for labour and other value-added services and the government expenditure to import commodities at the intersection of the import row and final demand column because the import and import transaction carried out under the intermediate transaction; however, this is not the case for MRIO specified as IxI (industry by industry or sect by sector) matrixes, and the final demand spending on each specific country and industry.

According to the Peters et al. (2011) the account balance can be transformed into the matrix as follows;

$$x^* = A^* x^* + y^* \tag{3.12}$$

Where $x^* = \left[x^1, x^2, \ldots, x^R\right]^T$ is the vector for aggregate output of all regions.

$$A^* = \begin{pmatrix} A^{11} A^{12} ... A^{1R} \\ .... \\ .... \\ .... \\ A^{R1} A^{R2} ... A^{RR} \end{pmatrix} \tag{3.13}$$

is the cross-regional aggregate direct requirement coefficient matrix and

$y^* = \left[y^1,\ y^2,\ \ldots,\ y^R\right]^T = \left[\sum_s y^{1s} + ex^1,\ \sum_s y^{2s} + ex^2,\ \ldots,\ \sum_s y^{Rs} + ex^R\ \right]^T$ It is the aggregate cross-regional final demand consumption vector.

According to the MRIO table, each submatrix in the main diagonal, with value A^{11} to A^{RR}, represents domestic interaction within an industry or domestic commodity footprint resulting from domestic consumption. Meanwhile, the off-diagonal matrix $A_{i,j}$ describes the trade between the industry of region i and region j. Values above the diagonal element denote export, whereas the value below the diagonal signifies import from the region i to industry j.

Environmental extended multi-region input-output analysis

Input-output models have accounted for environmental pollution and resource consumption since the late 1960s (Daly, 1968; Isard et al., 1968; Leontief, 1970). Environmental extended input-output analysis has been applied to broad ranges of environmental issues such as CO_2 emission (Davis and Caldeira, 2010; Feng et al., 2013), land (Feng et al., 2013; Hubacek and Sun, 2001; Weinzettel et al., 2013) and materials (Wiedmann et al., 2013), SO2 (Prell et al., 2014), and biodiversity (Lenzen et al., 2012).

However, from an economic perspective, little attention has been given to water consumption input-output analysis, despite the first studies dating back to the 1950s (Liu, 2012). The main reason for the dearth of studies on water consumption is the methodological complexities that arise when water variables are introduced into the IO model (Wang et al., 2009). In particular, the monetary transactions are proportional to physical transactions in the traditional IO framework. At the same time, in the extended IO environmental context, this assumption is incorrect because water prices vary across different sectors. Thus far, the hurdles have been overcome by using physical unit water introduction as an input requirement into the IO framework Lofgren et al. (2002) and (Koudou, 2012).

Water embedded input-output analysis.

The basic framework of the Leontief input-output analysis involves the flow of products from one sector or region, considered as a producer, to each other sector or region, which could be considered consumption (Miller and Blair, 2009b). The input-out data is generated at a particular period from observed or recorded sources for a specific country or region. This input-output data set includes ten Nile River Basin Countries and six regions. All countries and regions are assumed to have open economies, so the output produced might be sold to the final consumers of foreign countries. Moreover, the production sectors may utilise primary inputs, such as labour and capital, to produce output.

The mathematical structure is represented by a set of linear equations, which are expressed as a matrix. The row represents the distribution output, and the column contains the required inputs by a distinct sector to produce output, *figure* (3.1).

As explained in the introduction and literature, the extension of the traditional input-output approach to water consumption is employed by adding an extra row (W) where the physical data of water used by each sector is considered as a factor of production *figure* (3.1).

Calculating direct and indirect water consumption per unit of output produced is crucial for formulating a matrix of intersectoral water relationships. Hence, the water usage coefficient can be defined as the ratio of the total amount of direct water consumed by each economic sector (W_i) to the total output of each sector. (X_i) Velazquez (2006) i.e., expressed as follow;

$$s_i = \frac{x_i}{w_i} \tag{3.14}$$

Where s_i is the direct unit water usage of the i^{th} sector, w_i is the total water consumption by sector i in region r for production and x_i is the total output produced. Moreover, the production vector x_i can be reformulated as a Leontief model to obtain the total water consumption base Environmental Water Footprint of the economy, expressed in terms of final demand, as follows.

$$WFP = s(I - A)^{-1}y^* \tag{3.15}$$

Water footprint disaggregated by source/sector

$$WFP = \widehat{s}(I - A)^{-1}y^* \tag{3.16}$$

Where $\widehat{s}$ implies a diagonal matrix with the elements of water coefficient on the leading diagonal, A represents the technical coefficient matrix y* is a column vector of the final demand, and WFP is the total volume of water withdrawal driven by final user (y*) and 1 x (NxR) vector of water withdrawal coefficient by sector and region. One represents an identical matrix with R dimensions. To extract water withdrawal linked with a particular water consumption activity in a specific region/country, the aggregate final consumption vector (y*) with a simplified vector in which the final consumption of sector i in region r remains.

Implication of Virtual water flow to Water Saving, Water Dependence and Self-sufficiency

This analysis aims to identify the implications of virtual water flow for national water scarcity and beyond. One would logically assume that a country with a high water scarcity scenario would seek to gain from virtual water trade as a net importer. Similarly, a country with abundant water resources could benefit from exporting virtual water through trade. Therefore, it is essential to investigate the assumption that water-abundant countries are net exporters and water-scarce countries are net importers of virtual water based on the extent of both induced water saving and VW import dependency analysis.

The NRB country's water scarcity (WS) depends on the temporal and spatial differences of water resources among basin states. According to Brown and Matlock (2011) the water scarcity of a country can be categorised into four: first, if a country water scarcity is greater than 100 ($WS > 100$) overexploited country, second if ($60 \leq WS < 100$) – heavily exploited, third if ($30 \leq WS < 60$) - moderately exploited and fourth if ($WS < 30$) it's slightly exploited country. A water scarcity value of 100 implies a complete consumption of available blue water. In contrast, a water scarcity greater than 100 indicates an environmental flow requirement is not met (Hoekstra et al., 2011). A country's water scarcity index can be estimated based on the ratio of total water use to the available water.

$$WS = \frac{WU}{WA} \tag{3.17}$$

Where WS is a country's water scarcity (%), WU is the total annual water use in the country $BCMyr^{-1}$, and WA is the annual water availability of a country ($BCMyr^{-1}$. Normally, the WS value is between 0 and 100%; however, in exceptional cases, it can exceed 100% when a country undertakes water mining. Generally, the annual renewable freshwater resource available or obtained from precipitation is assumed to be the measure of the national WA. Similarly, the total WU refers to the summation of green and blue water.

The national water saving $W_s[p]$ (volume/year) of a country due to international trade in commodities is defined as:

$$W_s[p] = (T_i[p] - T_e[p])\, xWF_{prod}[p] \tag{3.18}$$

Where $W_s[p]$is a national water saving (volume of water per year), $WF_{prod}[p]$ is water footprint in volume of water per unit of a product in the trade, $T_i[p]$volume of product imported, and $T_e[p]$is the volume of product exported. A country that exports a higher volume of agricultural products than it imports has negative national water savings, and we call such a country a net virtual water exporter.

The global water saving $W_s[p]$ via the international trade in product from exporting nation n_e and importing nation n_i can be rewrite as:

$$W_s[n_e, n_i, p] = T[n_e, n_i, p] xWF_{prod}[n_i, p] - WF_{prod}[n_i, p] \tag{3.19}$$

Where T is the volume of commodities traded between nations, hence the global water saving can be obtained as the difference of water productivities between the trading partners.

Subsequently, to estimate the extent to which a nation depends on foreign water resources through imported commodity embedded water resources. The virtual water dependency (WD, %) of a nation is defined as the ratio of external water footprint to the total water footprint consumption of the nation; the virtual water import dependency can be calculated as *equation* (3.20).

$$WD = \begin{cases} \frac{NVWI}{WU+NVWI} \times 100, & \text{if } NVWI \geq 0 \\ 0, & \text{if } NVWI \leq 0 \end{cases} \tag{3.20}$$

The water dependency index value ranges between (0 – 100%), a zero WD implies the gross virtual water import and exports are balance or there a net virtual water export. While a 100% WD value indicates that the country is almost dependent on the virtual water import. The counterpart of the water dependency index is the water self-sufficiency index (WSSI) which can be estimated as follows:

$$WSS1 = \begin{cases} \frac{NVWI}{WU+NVWI} \times 100, & \text{if } NVWI \geq 0 \\ 0, & \text{if } NVWI \leq 0 \end{cases} \tag{3.21}$$

The national WSSI is related to WD as follows:

$$WSSS = 1 - WD \tag{3.22}$$

Ultimately, the WSSI measures a country's capability to supply the level of water required to produce domestic goods and services. A 100% WSSI indicates that a country's water self-sufficiency means all the required water is available within the country. In contrast, if WSSI approaches zero, it reveals that a country heavily relies on water imports. Based on the net virtual water import and country water resource abundance, their trade relationship could be categorised into mutually beneficial, partially beneficial, unsustainable, and pressured. A country engaged in a VW trade is considered to have abundant water resources if its internal freshwater per capita exceeds that in the region (Zhang et al., 2016).

3.3.2 Materials

This research employed the Eora Multi-Regional Input-Output (MRIO) database that contains an intermediate demand matrix (**T**), final demand (**Y**), and value-added (**V**).

The Eora MRIO data produced a comprehensive, consistent, and balanced world MRIO table, organised from primary sources such as the UN System of National Accounts, UN COMTRADE, Eurostat, and numerous national-level input-output tables. The Eora table is more extensive, with a satellite account (**Q**) that holds data on water used by sector and country, collected from FAO's AQUASAT database, which covers global virtual water flow through international trade (Lenzen et al., 2012).

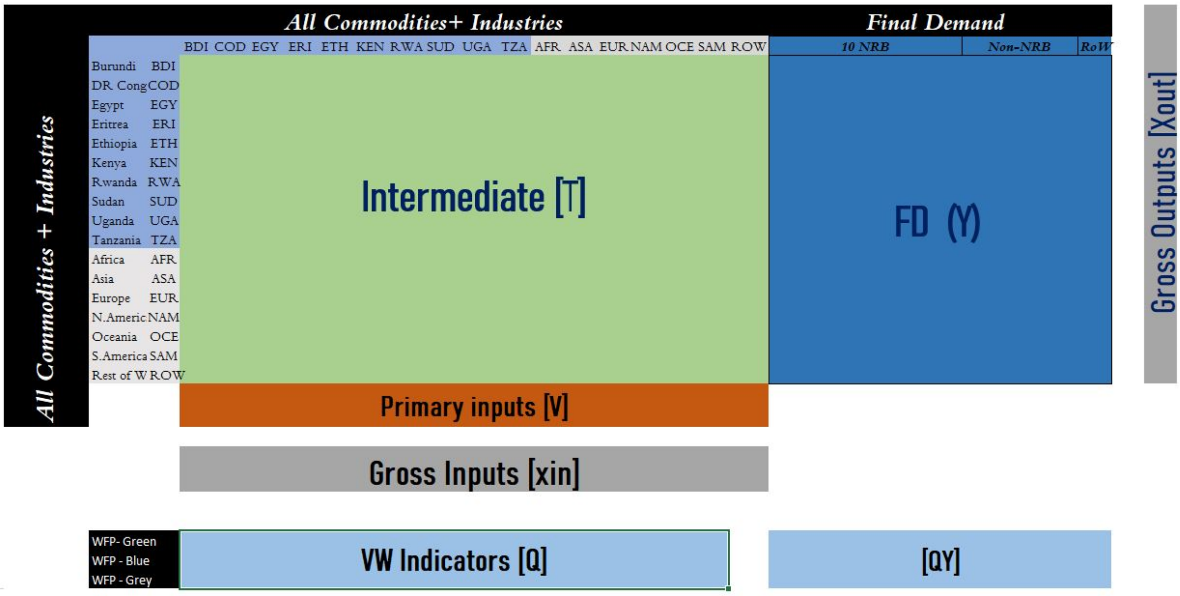


Fig. 3.2 Structure of MRIO Data for NRB

The Eora database includes national input-output tables, as well as environmental accounts, for 189 countries and a 'Rest of the World' category. These tables detail economic activities, including inter-sectoral transfers, primary inputs, final demand blocks, and trade relationships. It also encompasses environmental data, including greenhouse gas emissions, air pollution, energy use, water footprint, land occupation, nutrient emissions, and agricultural inputs. For this analysis, the environmental component is the water footprint for the corresponding intermediate sectors and final demand, which are used. The detailed water footprint data category is divided into green, blue, and gray water, which are already integrated within the Eora database. This comprehensive dataset is crucial for analysing economic and environmental interactions globally. The 189 countries include ten Nile River Basin countries such as Burundi, DR Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Uganda, and Tanzania and other non-NRB countries in Africa, as well as countries in Europe, Asia, North and South America and Oceania. The MRIO Table consists of 26 economic sectors in the intermediate transactions. Six categories in the final demand are household consumption, non-profit institutions serving households, government consumption, gross fixed capital formation, changes in inventories, and acquisitions less disposals of valuables. Additionally, there are six primary inputs, such as compensation of employees, taxes on production, subsidies on production, net operating surplus, net mixed income, and consumption of fixed capital. The environmental component is the Water footprint (WFP), which consists of three categories: green, blue, and gray WFP, as indicated in *Table* 3.2. The Eora database offers a comprehensive time series of MRIO tables covering the period from 1990 to 2015. This rich dataset enables the analysis of global economic and environmental interactions over time. In this study, we selected two specific years, 2007 and 2015, for a comparative analysis. The year 2007 represents the period immediately preceding the onset of the global food crisis, while 2015 reflects the conditions that followed the crisis's unfolding. This two-period approach enables us to examine the volume of virtual water flows in the NRB and with the rest of the world during these two periods. We aim to understand whether trade policy shifts influenced the region's water security and external water dependency.

To assess virtual water flows, we utilised the MRIO table in combination with water use data. Our analysis focuses on the exchange of virtual water among the ten countries within the NRB, the six inhabited continents, and a collective category labelled Rest of the World. Since our primary interest lies in understanding the broader patterns of virtual water trade rather than country-specific interactions outside the NRB, we aggregated all non-NRB countries at the continental level as the Rest of Africa. This approach simplifies the analysis while still capturing the major flows of virtual water into and out of the NRB. The water data under the environmental satellite account on the MRIO tables refer [Q] on the data structure 3.2. The Environmental satellite account further categorises virtual water footprint into blue, green, and gray water, which is key to this study. According to a series of studies on the estimation of virtual water footprint by Mekonnen and Hoekstra (010a,b, 011a,b), this study further assessed the ratio of water withdrawal to water availability to investigate the status of water scarcity in each NRB country.

3.4 Result and Discussion

3.4.1 Vector of Virtual Water embodied in the industry of production.

The volume of virtual water utilised in the industries of production in the Nile River Basin and the six continents is presented in *Table* 3.3 and T*able* 3.4 below. The multiregional input-output analysis enables the calculation of the total volume of water utilised in production industries and the extent of domestic and foreign demand for water consumed in international trade. Hence, according to the equation specification 3.15, the levels of water consumption in each country and continent, the sectoral levels of each industry, and the levels of demand by domestic and foreign customers are estimated and detailed below.

The first column indicates the total virtual water embodied in the commodities produced in a specific country, the second column indicates the total virtual water retained in the country due to domestic demand, and the third column indicates the total virtual water embodied in the international trade from a specific country to the rest of the world. The estimated figure indicates that, except for Ethiopia, the rest of the Nile River Basin countries consumed domestically about 50% of the virtual water embodied in international trade. However, Ethiopia retains only 1% of the total virtual water embodied in commodities.

Table 3.3 National Water embedded in commodities of production

Country	Water embedded industry of production (10^9 m^3 /year	Water embedded in product domestically demanded (10^9 m^3 /year)	Water embedded in product demanded in foreign markets (10^9 m^3 /year)
Burundi	5.79 0	4.700	1.101
DR Congo	26.710	22.970	3.824
Egypt	62.670	42.690	20.177
Eritrea	2.780	2.420	0.403
Ethiopia	77.500	0.490	77.129
Kenya	27.430	25.190	2.365
Rwanda	7.560	6.560	0.698
Sudan	58.070	51.770	6.4320
Uganda	35.540	20.320	15.248
Tanzania	38.940	13.690	25.320
NRB	342.990	190.800	152.700

Note: It is a volume of water extract at the national level for production, further details the volume of virtual content in the commodity consumed in the domestic and foreign market

The *Table* 3.4 below describes the total water embodied in the international trade and consumption at domestic and foreign markets of the six regions grouped for this research. The first column shows the total volume of virtual water embedded in commodities produced in specific regions, the second column depicts the virtual water embedded in commodities consumed in the domestic market, and the third column indicates the volume of virtual water embodied in commodities that foreign customers consume in international trade. Except for NRB and Oceania, over 50% of the virtual water is embodied in a commodity used in the region, while these two regions export more than half of it to the rest of the world.

Table 3.4 Global water embedded in the industry of production and consumption

Region	Water embedded in industries of production (10^9 m^3 /year)	Water embedded in product domestically demanded (10^9 m^3 /year)	Water embedded in product demanded in the foreign market (10^9 m^3 /year)
Nile River Basin	342.99	190.80	152.70
Rest of Africa	729.99	476.45	277.53
Asia	4,016.23	4,223.28	250.96
Europe	1,179.45	1,491.63	142.58
North America	1,185.06	1,192.33	246.17
Oceania	164.38	101.56	85.23
South America	1,109.29	1,035.76	173.64

Note: It is a volume of water extract at the regional level for production, further detailing the volume of virtual content in the commodity consumed in the domestic and foreign market

3.4.2 Regional and Global Water Footprint

The total water use within a country is not the right measure of the nation's accurate water resources. In this case, the net virtual water import into a country should be added to the total domestic water use to accurately represent the global water resource used in a year. Likewise, the net virtual water export from a country should be deducted from the volume of domestic water use. Hence, the sum of net virtual water import and domestic water use can be viewed as a country's water footprint, or its equivalent to the ecological water footprint of a nation (Hoekstra and Hung, 2002). In simplified terms, the ecological footprint refers to the amount of productive land and water required to produce goods and services that a country's domestic residents consume. *Table* 3.5 and T*able* 3.6 below show that in some countries or regions, the ecological footprint is smaller than the required area of the national territory. At the same time, in other cases, it is bigger than the nation's territory. The latter means that some countries or regions may eventually need to acquire land outside their territory to produce goods and services. Hence, except for Ethiopia and Tanzania, all the other Nile River Basin states benefited from the water footprint as a result of regional and international trade in both years. At the same time, Sudan showed a positive benefit in 2015.

The water footprint refers to the total volume of freshwater directly or indirectly used in the production of goods and services by a country. It can be quantified as the volume of water consumed in blue and green water, as well as the water used in the production process, which is consumed through international trade chains (Maite et al., 2009). Similarly, the total water footprint of the NRB countries and the global regions/continents grouped for this study have been estimated as shown in *Table* 3.5 and *Table* 3.6 below, respectively. It is the summation of the internal and external water footprint embodied in commodities traded between countries. The volume of water imported through trade in NRB countries is less than 5% of the total WFP, except for Ethiopia. The Ethiopian case is exceptional in terms of virtual water import and export, with 99.99% of total water withdrawal being exported in the form of virtual water. Out of the total WFP, 92% is external. Hence, this indicates that NRB does not have a water policy that enhances the utilisation of virtual water options as alternative sources for water to overcome the challenge of water scarcity.

Table 3.5 Water footprint of Nile River Basin

Country	Internal WFP (10^6 m^3/year)	External WFP (10^6 m^3/year)	Total WFP (10^6 m^3/year)	WFP per capita (m^3/p/year)
Burundi	4,643.31	31.56	4,674.86	436.90
DR Congo	22,464.74	337.60	22,802.33	289.74
Egypt	42,686.43	859.95	43,546.37	445.72
Eritrea	2,415.27	6.77	2,422.04	733.95
Ethiopia	4,861.66	73,510.48	78,372.15	764.61
Kenya	25,186.79	6,869.71	32,056.50	683.51
Rwanda	6,560.93	293.82	6,854.75	590.93
Sudan	51,768.48	66.14	51,834.62	1,356.93
Uganda	20,319.61	283.91	20,603.52	549.43
Tanzania	13,686.67	121.31	13,807.98	263.01
NRB	194,593.88	82,381.26	276,975.14	577.51

Note: The volume of the virtual water footprint in countries of NRB and exported to the rest of the world

This value has been calculated based on *equation* 3.15; as explained under the methodology section, the diagonal value represents the internal water footprint, while the off-diagonals are exports (values above diagonal) and imports (values below diagonal). The external water footprint of the NRB is only 30%, implying that the region has a low share of the world's available freshwater resources. At the same time, the remaining percentage represents the internal water footprint resulting from inter-industry commodity exchanges. Hence, this region has limited dependence on external water from foreign countries, despite experiencing water scarcity on a global scale.

The water footprint per capita is another concept that measures the volume of freshwater used throughout the production and trade chain of consumer goods. It shows the extent of water used in relation to the commodities consumed by people. However, the WFP per capita in countries worldwide varies due to differences in commercial agriculture, industrialisation, and tourism. For example, the water footprint of high-income countries is much higher than that of low-income or less industrialised countries. Hence, the water footprint network categorises the global water footprint per capita of nations that a country is high if the WFP per is over 2000 m^3/year, medium WFP per capita if it's between 1000-2000m^3/year and low WFP per capita if it's below 1000m^3/year (Hoekstra, 2003). Hence, as indicated in *Table* 3.5 above, the NRB nation's WFP per capita falls below a low standard category, which implies that the region has a low share of the available freshwater resources in the world or is an indication of severe water scarcity in the region.

Table 3.6 below shows a global water footprint in 2015, as indicated; except for the special region (NRB), the rest of the continents benefited from international trade even if it has shown a varying trend in different regions, as these regions have access a productive resource (ecological footprint) outside their territory through means of trade. The two continents (Africa and Oceania) have shown quite insignificant amounts of water footprint compared to the other continents. Asia, a highly populated continent where the water footprint per capita was much less than Western continents *Appendix* B.3 and B.4, is the biggest region in terms of ecological footprint. The European and North American regions are the average continents that have benefited from international trade, with average annual WFPs of 1,491 billion cubic meters, 1,192 billion cubic meters, and 1,035 billion cubic meters, respectively.

According to *Table* 3.6 below, the average annual water footprint (WFP) of the NRB and the rest of Africa are 276 and 476 billion cubic meters, respectively. This suggests that the region isn't benefiting significantly from international trade in terms of virtual water to address water scarcity, compared to other regions. The primary reasons for this could be geopolitical factors, trade policies, or water management strategies. Therefore, further investigation is needed to address the overuse or mismanagement of water resources.

Furthermore, the extended virtual water footprint analysis of world countries indicates that Africa's external WFP is less than 5% while other world regions have over 10% of the annual water footprint. Therefore, NRB and the broader African continent have weak water management policies and international trade strategies.

Table 3.6 Water Footprint of world regions

Region	Internal WFP (10^6 m^3 /year)	External WFP (10^6 m^3 /year)	Total WFP (10^6 m^3 /year)
Nile River Basin	194,593.88	82,381.26	276,975.14
Rest of Africa	452,464.95	23,983.49	476,448.44
Asia	3,765,276.43	458,000.76	4,223,277.20
Europe	1,036,873.84	454,753.10	1,491,626.94
North America	938,896.53	253,431.79	1,192,328.31
Oceania	79,141.30	22,419.76	101,561.07
South America	935,650.84	100,106.78	1,035,757.62

Note: The volume of the virtual water footprint in regions and exported to the rest of the world

3.4.3 Water Footprint Account of NRB

The water footprint account refers to the three components (green, blue, and gray) that contribute to the overall assessment of water usage associated with production and direct consumption. The share of each component has been estimated to assess the source of virtual water embedded in products, activities, or trade.

The total water footprint related to economic sectoral production in NRB in 2007/15 was on average 353.1 Billion m^3y^{-1} (81% green, 6% Blue and 13% gray), refer *Table* 3.7 and 3.8. The largest share (98.7%) of this water footprint was attributed to agricultural products, and the remaining share (1%) was distributed across the 25 sectors of the economy. Hence, the main source of water footprint in the NRB region is agricultural products. Rainfall is a major source of water for agricultural processes, as the green water footprint constitutes approximately 81% of the total water footprint in the region. Therefore, the region has been exposed to weather fluctuations as economic activity depends on a green water footprint. Blue and gray water footprints account for only 20% of the total water footprint.

As presented in *Tables* 3.7, agricultural production accounts for the highest volumes of both blue and gray water footprints, estimated at approximately 47.3 billion m^3/year and 15.9 Billion m^3/year, respectively. Agricultural inputs, such as fertiliser and insect-pest chemicals, are the major source of the gray water footprint in agricultural production. The increase in agricultural yields over the last few decades is primarily due to the use of fertiliser in agricultural systems. However, the most significant proportion of Nitrogen application to agricultural products in the form of fertilisers and pesticides leaches into the freshwater system, causing deterioration of water quality and eutrophication of groundwater, rivers, lakes, and generally, marine systems. According to the Mekonnen and Hoekstra (2015), Africa contributes 5.4% of global water pollution because of the gray water footprint, the discharge to lakes, rivers and marine systems. Water pollution level is commonly expressed in terms of the effect of Gray Water Footprint (GWF) per river basin on the region's water quality. The GWF refers to the volume of fresh water (m^3/y) required to assimilate pollutants and maintain water quality standards. Essentially, it is the amount of water needed to dilute pollutants to a level where the water remains usable and meets environmental standards. This concept is crucial for understanding the impact of pollution on water resources and the capacity of a river basin to handle waste.

The Nile River is the largest river that crosses ten African countries and has extensive coverage worldwide, followed by the Amazon and the Yangtze (Chang Jiang) rivers. Over the past 5 decades, intensive economic activities, particularly the agro-irrigation system, have been carried out on the Nile River to produce agricultural goods. In the modern agricultural farming system, the use of fertiliser and insecticide chemicals is a common practice, resulting in immense waste discharge from farms to rivers. Thus, the volume of gray water footprint (16 billion m^3/y) in the Nile River Basin in the form of fertiliser and chemical seepage contributes to global water pollution.

Table 3.7 The Water Footprint of intermediate Sectors NRB (Billion m^3/year)

Sectors/Industry	2007			2015			Average	
	Green	Blue	Gray	Green	Blue	Gray	$BCMy^{-1}$	(%-age)
Agriculture	285.0	47.3	15.9	285.9	47.3	15.9	348.6	98.7%
Fishing	0.1	0.0	0.1	0.1	0.0	0.1	0.3	0.1%
Mining and Quarrying	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.1%
Food & Beverages	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.1%
Textiles and Wearing Apparel	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.1%
Wood and Paper	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.0%
Petroleum and Mineral Products	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.1%
Metal Products	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.1%
Electrical and Machinery	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.1%
Transport Equipment	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.0%
Other Manufacturing	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.0%
Recycling	0.0	0.0	0.1	0.0	0.0	0.1	0.2	0.0%
Electricity, Gas and Water	0.2	0.1	0.2	0.2	0.1	0.2	0.4	0.1%
Construction	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0%
Maintenance and Repair	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0%
Wholesale Trade	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0%
Retail Trade	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0%
Hotels and Restaurants	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0%
Transport	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.1%
Post and Telecommunications	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0%
Financial Intermediation and Business Activities	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.0%
Public Administration	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0%
Education, Health, and Other Services	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0%
Private Households	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0%
Others	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.0%
Re-export & Re-import	0.0	0.0	0.2	0.0	0.0	0.2	0.2	0.0%
Total	285.4	47.6	19.7	286.3	47.6	19.7	353.1	100.0%
%-age	81%	13%	6%	81%	13%	6%		

Note: The volume of the water footprint in the commodities in the intermediate sector that is segregated into green, blue, and gray water

In summary, the study identifies that agriculture is the largest water-intensive sector in the NRB region and globally, in terms of water footprint in international trade. Food production consumes over 90%, industrial about 6%, and the remaining is consumed by the service sector. In the final demand, households are the major consumers of virtual water, which constitutes 78.5%, and gross fixed capital formation is the second-highest sector. In contrast, the average annual consumption was about (13%). Institutions serving households, government consumption, changes in investments and acquisitions of disposable assets constitute the remaining shares of the water footprint. *Table* 3.8 below shows the total volume water footprint in the final demand, households are the major consumer of VWF, which comprises over 78.5% of the virtual water flow in the final demand. Gross capital formation and the government sector are the second and third consumers of the virtual water embedded in goods and services, as well as the direct water used in final demand. Similarly, the final demand's green, blue, and Gray water footprint pattern is the same as the intermediate inputs.

Table 3.8 Water Footprint in Final Demand

Final demand consumers	2007			2015			Average	
	Green	Blue	Gray	Green	Blue	Gray	$BCMy^{-1}$	%-age
Household final consumption	219.34	47.05	13.76	217.12	40.80	16.38	277.3	78.5%
Non-profit institutions serving households	12.99	0.24	0.81	11.85	1.15	0.59	13.80	3.9%
Government final consumption	16.11	0.07	1.46	18.35	1.50	0.74	19.10	5.4%
Gross fixed capital formation	28.64	0.16	2.97	31.47	3.10	1.62	34.00	9.6%
Changes in inventories	5.42	0.00	0.53	5.52	0.84	0.23	6.30	1.8%
Acquisitions less disposals of valuables	2.85	0.04	0.21	1.96	0.18	0.14	2.70	0.8%
Total	285.37	47.58	19.74	286.27	47.58	19.74	353.14	100.0%
%-age	81%	13.5%	5.5%	81%	13.6%	5.4%		

Note: The volume of the water footprint in the final demand has been segregated into green, blue and gray water.

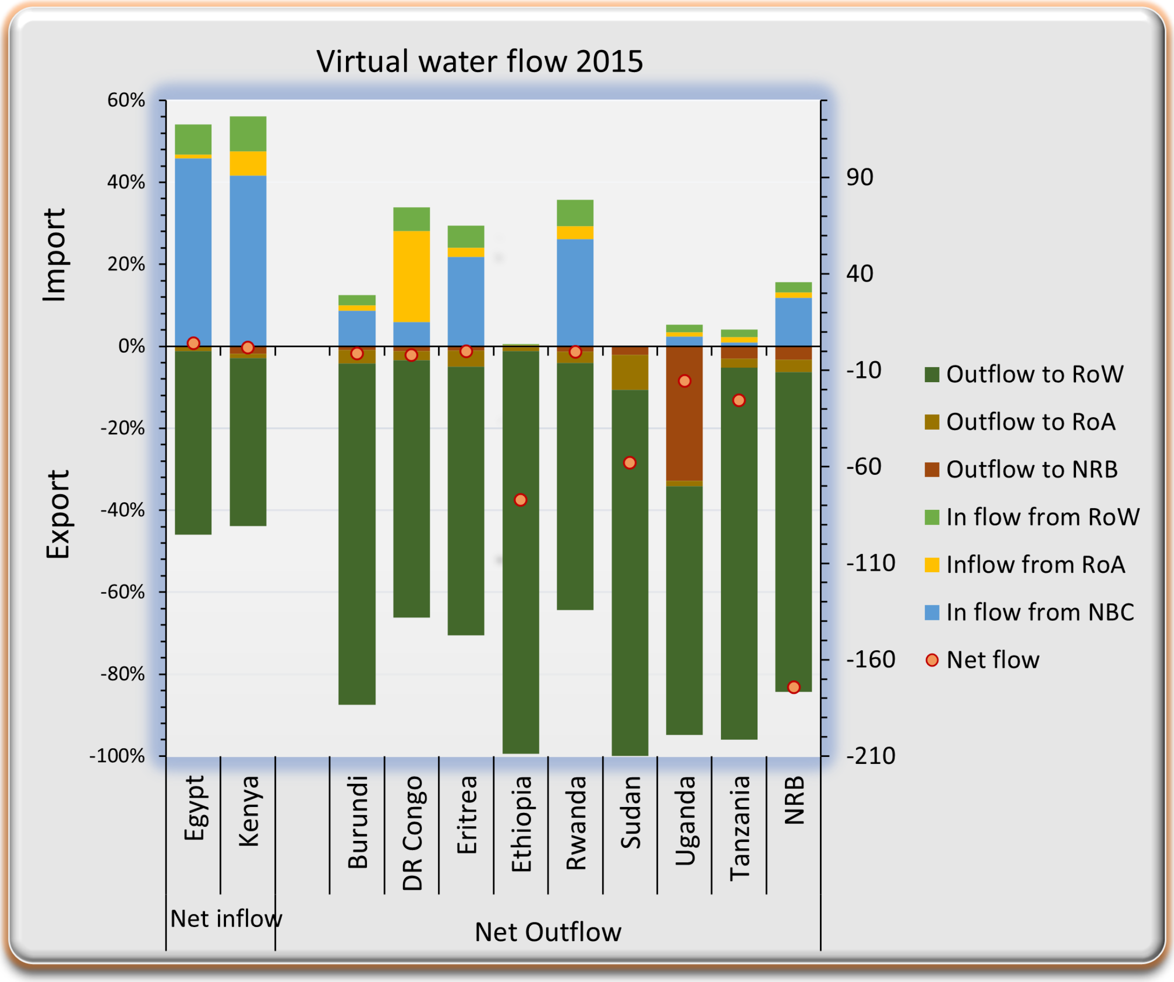
The study identifies agriculture as the largest water-consuming sector in the NRB region and globally, in terms of water footprint in international trade. Food production consumes over 90%, industrial activities about 6%, and the remaining is consumed by the service sector. In the final demand, households are the major consumers of virtual water, which constitutes 78.5%, and gross fixed capital formation is the second highest sector. In contrast, the average annual consumption was about (13%). Institutions serving households, government consumption, changes in investments and acquisitions of disposable assets constitute the remaining shares of the water footprint.

3.4.4 Net Virtual Water Flow

The virtual water flow in the Nile River Basin is divided into three categories: the water flow through trade between the Nile River Basin states, the water flow through the trade between NRB states and the Rest of Africa and the international trade between NRB and the Rest of the World. The first part of the virtual water trade belongs to the Nile River Basin region in both years. *Appendix* B.1 and *Appendix* B.2 indicate the virtual water inflow and outflow of each country in the Nile River Basin in 2007 and 2015, respectively. NRB has an overall virtual water net outflow of 174 and 137 billion m^3 in 2007 and 2015, respectively. The virtual water flow in international trade is considerably higher than in the Nile River region. In the Nile River Basin region, about 38 and 19 billion m^3 volume of virtual water flowed among the basin states in 2007 and 2015, respectively. The VWF inflow from Rest of Africa 3 billion m^3 and 4 billion m^3 and outflow 7 billion and 3 billion m^3, the NRB is net exporter of virtual water to the Rest of Africa in both periods. While, in the international trade, the virtual water inflow was 6 billion m^3 in both periods, the outflow was 198 billion m^3 and 144 billion m^3 in both periods, and again the NRB region is a net exporter of virtual water to the rest of the world in both periods. Therefore, the main problem of water scarcity in the region could be due to the high volume of water export and mismanagement of water balance and ecosystem.

The details of the virtual net flow between each country of the NRB region are shown in *Figure* 3.3. The regional water flow indicates that the trade relationship among NRB countries declined in 2015 compared to 2007. When looking at the net inflow of individual countries, Egypt and Kenya are net importers of virtual water. In 2007, Egypt and Kenya's net inflow was 4 billion m^3 and 2 billion m^3, respectively, while in 2015, Kenya was the only country in the region that was a net importer of virtual water, which constituted 6 billion m^3. The net flow diagram indicates that Kenya and Egypt maintained a strong trade relationship with the Nile River Basin countries during both periods. The major sources of Keynya's virtual water are Egypt, Tanzania, Uganda, Ethiopia, and Sudan. According to Marshall (2011), Kenya is one of the East African countries enduring a severe water crisis; nevertheless, as Hoekstra and Mekonnen (2014) confirmed, Kenya imports, on average, about 4 million m^3 yr^{-1} of virtual water through trade. Rwanda and DR Congo are exceptional countries that effectively utilise their domestic water resource for production and are entirely used for internal consumption. However, in the NRB, Ethiopia is an exceptional country that exports about 99% of its domestic water withdrawal through international trade. The massive volume of virtual water (98%) from Ethiopia was exported to Asia, Europe, and North and South America, while only 2% went to Africa through trade.

Fig. 3.3 Net VW flow in NRB



Notes: The graph illustrates the virtual water inflow, outflow, and net inflow of the 10 NRB countries. Red dots within the graph represent the water flow balance, indicating that all countries, except Egypt and Kenya, experience a negative inflow. A detailed table containing this data is provided in the *appendix* B.1 and B.2.

Hence, the economic growth and development challenge in the NRB region is due to a shortage of water resources, which could be alleviated with the help of virtual water trade, particularly for Egypt and Sudan. Indeed, the shortage of water resources has consequences for local development and subsequent sustainable economic and social development for the water-scarce region.

The global net inflow is shown in the *Figure* 3.4 below; the bar graphs illustrate a two-period comparison of net water inflow. For example, in 2007, Asia's water inflow was

24.68 billion m^3, Europe 438.10 billion m^3, and North America 142.18 billion m^3 are a net importer of virtual water through trade while Nile River Basin (195.94 billion m^3), Rest of Africa (230.15 billion m^3), Oceania (47.77 billion m^3), and South America (131.10 billion m^3) are net export of virtual water. In 2015, Asia (207.04 billion m^3), Europe (312.18 billion m^3), and North America (7.26 billion m^3) are net importer of virtual water through trade while Nile River Basin (136.59 billion m^3), Rest of Africa (253.54 billion m^3), Oceania (62.81 billion m^3), and South America (73.54 billion m^3) are net export of virtual water. The net virtual water flow analysis has shown that less developed countries or regions are net exporters of freshwater, as they primarily export water-intensive agricultural products, while the developed world is the net importer of freshwater, importing water-intensive agricultural products and exporting less water-intensive industrial products. The virtual water net importer in 2007 continued a virtual water net importer in 2015, and the net virtual water exporting regions in 2007 are continued a net export 2015. Therefore, this indicates the net exporting region hasn't changed its policies for water conservation.

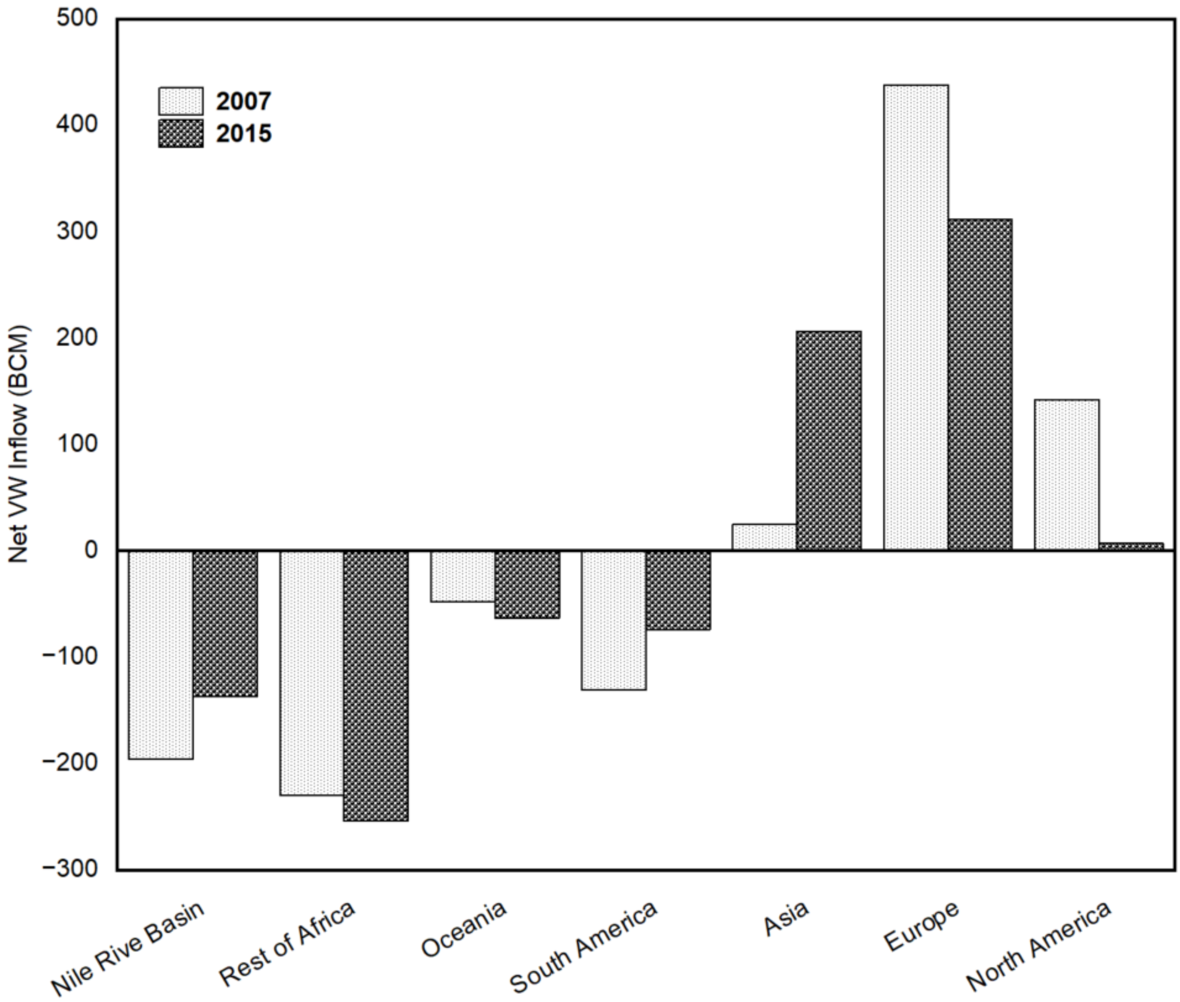


Fig. 3.4 Net VW inflow into each region for the years 2007 and 2015

3.4.5 Virtual Water Network in NRB

Generally, the NRB region is a net exporter of virtual water, with 81% originating from green water or rain, 13% from blue or groundwater, and 6% from gray water used for production and processing purposes.

The chord diagram [3] in *Figure* 3.4 offers a nuanced understanding of VW dynamics within the NRB, revealing Egypt not as a passive recipient of water resources, but rather as a net exporter of virtual water to several countries in the region. This finding challenges the conventional narrative that positions Egypt primarily as a water-scarce importer reliant

[3]In a chord diagram format, we can visually represent the connections between data points in a matrix by positioning the data in an arrangement and linking them with arcs to show their relationships.

on upstream flows (Allan, 2003). Instead, the data suggest a more complex and proactive role for Egypt in shaping regional water and trade relationships.

The coloured arcs in the figure represent VW flows between countries in the Nile River Basin. Each arc's colour corresponds to the exporting country, with the direction of the flow indicating the destination. For example, Egypt exported substantial volumes of virtual water embedded in agricultural commodities to countries such as Burundi (35%), the Democratic Republic of Congo (20%), Kenya (20%), Uganda (10%), and Tanzania (10%). These flows are visually represented by thick green chords extending from Egypt in the diagram, indicating both the scale and diversity of its trade connections within the basin.

Several interrelated factors help explain this pattern. First, Egypt's trade openness and economic integration play a pivotal role. With a relatively liberal trade regime, diversified agricultural production, and robust export infrastructure, Egypt is well-positioned to engage in intra-regional trade despite its physical water scarcity. Its export-oriented agricultural sectors, particularly in processed foods and cereals, enable the externalization of water through trade a strategy consistent with the concept of hydro-economic interdependence (Hoekstra et al., 2011).

Second, Egypt appears to be making strategic use of virtual water trade as both an economic and geopolitical tool. Rather than relying solely on physical water flows from the Nile, Egypt leverages its agricultural exports to maintain influence and foster interdependence within the region. This aligns with Zeitoun and Allan (2008) theory of hydro-hegemony, which emphasises that power in transboundary water governance is exercised not only through control of water sources but also through economic and discursive strategies. By exporting virtual water, Egypt may be reinforcing its regional leadership while managing domestic water stress through the cultivation of high-value, water-efficient crops.

Third, the increase in VW flows among NRB countries, notably between Egypt, Uganda, Kenya, and Tanzania, can be linked to the 2012 regional agricultural trade agreement.

This policy initiative aimed to reduce trade barriers and harmonise standards across the basin, thereby facilitating greater exchange of agricultural commodities. The resulting intensification of VW flows reflects a broader trend toward regional economic integration, with water embedded in trade serving as a medium of cooperation.

Finally, Egypt's role as a net VW exporter is supported by its comparative agricultural advantage. Despite its arid climate, Egypt's advanced irrigation systems, access to international markets, and logistical capacity allow it to produce and export water-intensive goods more efficiently than some of its neighbours. This apparent paradox of exporting water while facing scarcity is explained by the economic efficiency of water use, where countries with better infrastructure and market access can afford to externalise water through trade (Allan, 2003).

In general, the evidence of Egypt as a net exporter of virtual water reframes traditional assumptions about dependency and scarcity in the NRB. It highlights the growing importance of economic and trade-based mechanisms in shaping regional water dynamics. This perspective underscores the need for integrated water and trade policies that recognise the strategic role of virtual water in promoting regional cooperation, resilience, and equitable resource distribution.

Fig. 3.5 Virtual Water Flow among NRB

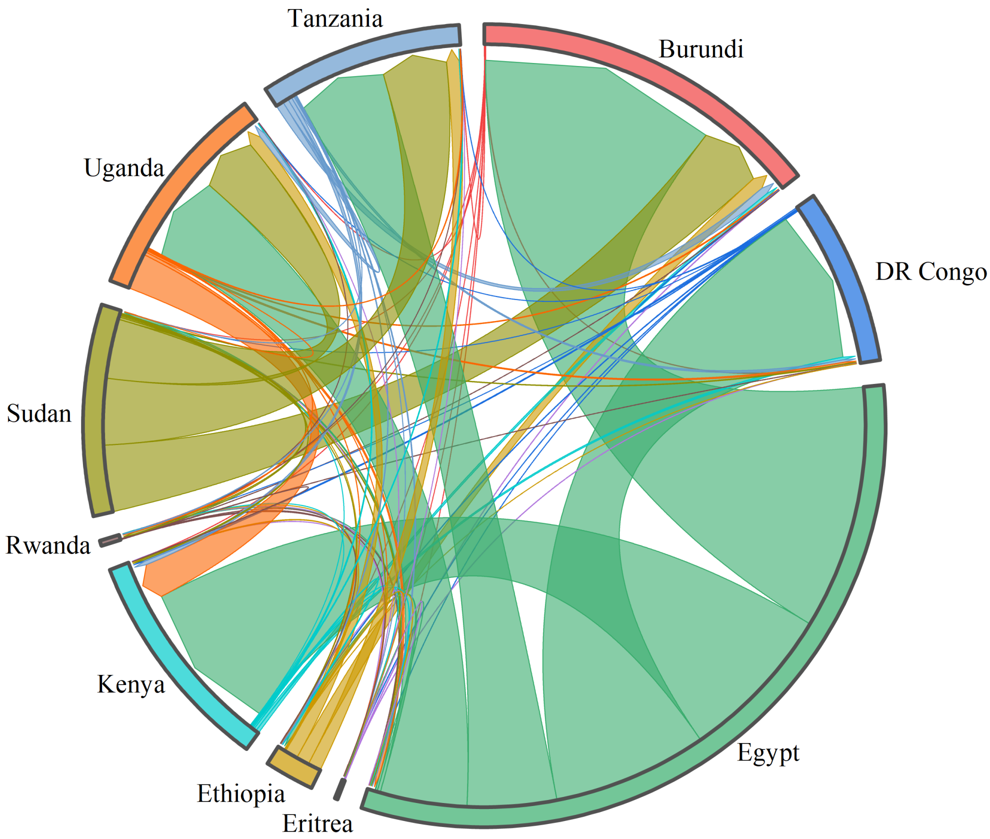


Figure (3.5) shows the virtual water network among NRB, which is crucial for understanding trade connections among basin countries. It reveals limited trade connections, with Egypt, Sudan, and Kenya standing out as better connected with Burundi, Uganda, Tanzania, and the Democratic Republic of Congo, as evidenced by the volume of water flow. In contrast, countries like Eritrea, Ethiopia, and Rwanda have weaker trade ties within the NRB, as they primarily export their products to the rest of the world. This data underscores the importance of the NRB's virtual water network in analysing trade connections.

3.4.6 Global Water Network

The chord diagram in *Figure* 3.6 reveals that the Nile River Basin (NRB) functions as a net exporter of virtual water, sending more water-embedded goods to other regions than it receives. This finding challenges the common assumption that water-scarce regions, such as the NRB, are primarily dependent on imports. Instead, the NRB appears to be actively engaged in the global agricultural trade, exporting significant volumes of virtual water to regions such as Asia, Europe, and the Americas.

The network diagram shows the outflow to and inflow from six continents for specific regions for 2015. As indicated on the bar chart 3.4 above, the NRB and the Rest of Africa are net exporters of VW water through international trade. In the next diagram, the origin and destination of water flows and the extent of the water balance of each region are illustrated with the help of chord charts. The colour of the Arc represents the origin of VW; the inner lines' arrows indicate each region's inflow and outflow. The thickness of the strips represents the magnitude of VW flows between two connected regions. Asia is the largest exporter of water, followed by the rest of Africa and the Nile River Basin, where the size of virtual water exports is 374 billion m^3, 257 billion m^3, and 205 billion m^3, respectively, in 2007. Similarly, these regions were exports about 251 billion m^3, 278 billion m^3 and 147 billion m^3, respectively in 2015. Asia exports volumes of virtual water to Europe and North America, and a non-negligible volume of water is exported to South America, Africa, and Oceania in both years. Africa, including the Nile River basin states, exports huge volumes of water to Europe, Asia, and North America in descending order in both years. These findings provide a global perspective on water withdrawal, consumption, and export through international trade. The analysis indicates that African countries are the most significant trade outflows of VW, especially the NRB, which was verified by Hirwa et al. (2022) to be the largest net VW exporter in Sub-Saharan Africa.

This dynamic aligns with the concept of hydro-economic interdependence Hoekstra et al. (2011), where water-rich or agriculturally productive regions export water-intensive goods, while others import them to conserve domestic resources. However, as Allan (2003) and Zeitoun and Allan (2008) caution, such trade patterns can mask underlying vulnerabilities. For the NRB, exporting virtual water may generate economic benefits, but it also risks depleting local water resources and increasing exposure to global market fluctuations. Generally, the NRB's role as a net exporter of virtual water underscores its active participation in global trade, but also raises important questions about sustainability, equity, and long-term water security. These insights underscore the need for integrated water and trade governance that strikes a balance between economic opportunity and environmental stewardship.

Fig. 3.6 Global Virtual Water Network

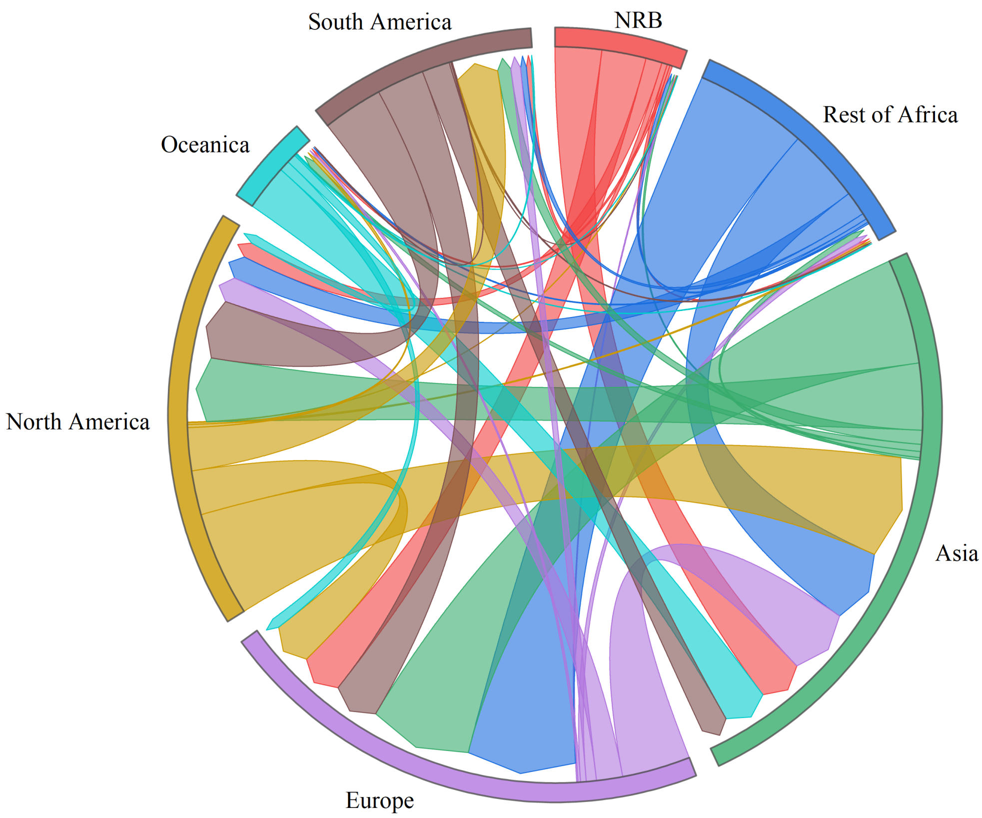


Figure 3.6 illustrates the virtual water flow network among global regions. In comparison to the NRB, the six regions exhibit stronger trade connections, as demonstrated by the water flow diagram linking them.

Virtual Water Use Pattern in NRB and Global Context

The analysis of virtual water distribution in *Appendix* B.4 and B.5 reveals significant regional and global disparities in water resource use, particularly in the context of agriculture. *Appendix* B.4 illustrates that most NRB countries, including Burundi, DR Congo, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, and Tanzania, depend overwhelmingly on green virtual water, derived from rainwater stored in the soil, with shares ranging from 84% to 99%. This reliance reflects the predominance of rain-fed agriculture in these countries. In contrast, Egypt exhibits a more complex water profile, with 48% blue water (irrigation from surface and groundwater), 23% green water, and a substantial 29% gray water, indicating significant water pollution or treatment needs. Uganda also shows a notable 15% blue water share, suggesting a partial shift toward irrigation-based agriculture.

In comparison, *Appendix* B.4 presents the global perspective, where green virtual water remains dominant across all regions, particularly in the Rest of Africa (95%), South America (89%), and Oceania (86%). The NRB region, as shown in both annexes, aligns with this trend, having 81% green water. However, regions such as Asia and North America show a more balanced distribution, with Asia having the lowest green water share (70%) and higher proportions of blue (16%) and gray (14%) water. North America stands out with the highest gray water share (17%), reflecting intensive agricultural practices and greater environmental pressures.

These graphs underscore the contrast between developing regions, which rely heavily on natural rainfall, and more industrialised regions, where irrigation and water treatment play a larger role. The NRB countries, particularly upstream ones, mirror the broader African trend of green water dominance, while Egypt's profile is more aligned with global patterns seen in Asia and North America, highlighting its unique position within the basin.

3.4.7 Virtual water trade and its implications to water scarcity

With the declining availability of water resources and increasing demand for water in various sectors of an economy, it's a challenge to deliver a necessity to citizens and maintain that demand while ensuring water sustainability in the long run (Grey et al., 2013). Additionally, the extent of population growth and the changing consumption patterns affect the food supply (Liu et al., 2009). Hence, these factors are strongly related to water resource availability and the management of water for agricultural production and the delivery of sustainable food to citizens. This is because freshwater availability is a global concern, and there is increasing sectoral competition for scarce resources. Even water-rich countries struggle to endure a flourishing water scarcity to satisfy national demand (Kummu et al., 2016). Therefore, water-scarce countries or regions need to pay attention to the emerging concept of virtual water trade in the context of water saving and water sustainability (Chittaranjan et al., 2018). Thus, in addition to calculating the volume of virtual water flow between countries and regions, the extent of national water saving and the degree of water dependency have been precisely determined.

National water saving

An indisputable effect of international trade of water-intensive commodities is undoubtedly to save water or create an alternative water source for an importing country. This alternative water sourcing has become a subject of scientific research and discussion since the mid-1990s (Hoekstra, 2003; Oki and Kanae, 2004; Yang et al., 2006). The national water savings related to imports can be estimated by multiplying the volume of imported products by the volume of water required to produce the product domestically.

In several countries, international agricultural product trade reduces domestic water demand. A country that imports water-intensive commodities and exports less water-intensive commodities benefits from international trade. Egypt, the largest water-saving region in the NRB, followed by Kenya, has an annual average of 55 and 31 billion cubic meters of domestic water resources. In addition to the current water use, this volume of water would be required if both countries were to produce all their imports domestically. Likewise, Sudan annually saved 25.38 billion cubic meters, DR Congo 24.93 billion cubic meters, Uganda 20 billion cubic meters, Tanzania 13.43 billion cubic meters, Rwanda 7.13 billion cubic meters, and the rest three countries, such as Ethiopia, Burundi and Eritrea, in total can save only 7.44 billion cubic meters. One of the countries with the most water scarcity, which is primarily dependent on the import of water-intensive products, is Jordan. The national water imports range between 5-7 billion cubic meters in virtual form per year, in contrast with the one billion cubic meters of water withdrawal from domestic water sources (Haddadin, 2003; Hoekstra and Chapagain, 2007). People in Jordan thus survived because international trade and the national water footprint have been externalised to other parts of the world, such as the USA.

For countries that depend on importing water-intensive products, it is essential to recognise that the water saved has a higher marginal benefit than the additional cost associated with importing these products. Let's consider the case of Egypt, a country with very low precipitation, where the mean annual rainfall is only 18mm per year, and most of its agriculture is irrigated. For instance, an increase in domestic wheat demand in Egypt implies a corresponding increase in water usage, which amounts to 3.6 billion cubic meters of domestic water resources, constituting 7% of the country's total water consumption. The national savings due to imports could be achieved with an annual investment of foreign exchange of $593 million ITC (2004), resulting in a marginal cost of virtual water in Egypt of 0.16$/m^3. Indeed, this cost would be much lower as importing wheat covers virtual water and includes the cost of inputs such as land, fertiliser, and labour. In Egypt, fertile land is also a major scarce resource; thus, the import of wheat not only relieves the pressure on the dispute over Nile water but also reduces the pressure to increase the land for wheat production. Therefore, from an international context, Egypt has a comparative disadvantage in wheat production; hence, importing wheat into Egypt not only saves physical water but also results in economic savings due to international trade.

Table 3.9 National water saving due to international agricultural trade

Country	Total use of domestic water resources in the agricultural sector (10^9 m^3 /year)	Water saving due to import of agricultural product (10^9 m^3 /year)	Water loss due to export of agricultural products (10^9 m^3 /year)	Net water saving due to trade in agricultural products (10^9 m^3 /year)	Ratio of water saving to water use (Percentage)
Burundi	5.68	0.16	1.29	4.54	80%
DR Congo	26.17	2.4	3.65	24.93	95%
Egypt	61.42	15.01	21.53	54.9	89%
Eritrea	2.72	0.1	0.38	2.44	90%
Ethiopia	75.95	0.45	75.94	0.46	1%
Kenya	26.89	8.82	5.16	30.54	114%
Rwanda	7.41	0.46	0.74	7.13	96%
Sudan	56.91	0.06	31.59	25.38	45%
Uganda	34.83	0.85	15.66	20.02	57%
Tanzania	38.16	0.98	25.71	13.43	35%
NRB	336.13	29.29	181.65	183.77	55%

Notes: The table highlights the pivotal role of international trade in water saving, particularly by importing agricultural products. The table clarifies the amount of virtual water used to produce agricultural goods, providing a clear picture of the water footprint of international trade. It includes columns showing the volume of water imported along with agricultural products, the volume of water exported with the products, net water flow, and the resulting net water savings due to international trade. This study underscores the significant impact of international trade on water saving, making it a topic of utmost importance.

National water Scarcity vs water dependency

Nations can be water-dependent in two ways: first, a nation that shares a common river is interdependent regarding water resources. A downstream nation depends on the inflow of water from the upstream basins or the mutual dependency of the nations that share a common river. This kind of water interdependency is often quantified by considering the ratio of external water to a country's total renewable water resources. FAO defends the latter as an external renewable water resource, part of a country's overall renewable water resources, which are inflows from other bordering countries (Padder and Bashir, 2023). For instance, in the Nile River shred among ten countries, the downstream nation like Egypt is extremely high-water dependent because the country hardly receives precipitation and hence mainly depends on the inflow of physical Nile water and, for instance, the annual external water resource of Egypt is about 55.5 billion cubic meters per year or 93% of national demand (Alsharhan et al., 2020). Similarly, Pakistan is also strongly dependent on water from India, and Cambodia relies on water from the Mekong, which originates from the Euphrates and Tigris rivers. Considering these circumstances, water is a crucial geopolitical resource that affects the power dynamics between countries sharing a river basin.

The second focus of this research is virtual water dependency, which has been enhanced through international commodity exchange or trade. From a water resource perspective, it can be argued that there is a positive relationship between water scarcity and virtual water dependency, particularly in the context of a nation experiencing severe water scarcity. A virtual water dependency can be defined as the ratio of a country's external water footprint to its total water footprint. As shown in *Figure* 3.7 and 3.8 below, countries in the Nile River Basin have shown a different degree of both water dependency and water scarcity; for instance, Sudan, Kenya and Tanzania are countries with extreme water scarcity, while Rwanda, Egypt, Eritrea, Ethiopia, Burundi and Uganda have severed water scarcity. DR Congo has not shown a water scarcity scenario in either period. Egypt and Kenya are the most water-scarce countries, and consistently, they are the highest virtual water import-dependent (>20%) in the Nile River basin region. The water footprints of these two countries have mainly been externalised. Egypt imports approximately half of its domestic renewable water resources; Kenya imports one-third of its domestic water resources annually. Although it helps both countries conserve their domestic water resources, it makes them heavily dependent on other countries. Other water-scarce countries with moderate water dependency (5 - 20%) are, for example, DR Congo and Rwanda.

Except for a few countries, such as Egypt, Kenya, and Sudan, the remaining Nile River Basin countries exhibited a low level of virtual water dependency in both periods. The three countries revealed a higher virtual water dependency than the rest, possibly due to their agricultural food import nature or better policy intervention regarding water resource management.

The tendency of virtual water dependency trends in NRB countries changed in 2015 compared to the previous period (2007); this is mainly due to the imposition of agricultural export restriction policies in some African countries after the global food crisis in 2009, as confirmed in the first essay of this study. However, Kenya remains consistent in terms of virtual water dependency, and it exhibited a virtuous propensity towards external water dependency in 2015.

Fig. 3.7 National Water Dependency vs Water Scarcity of NRB in 2007

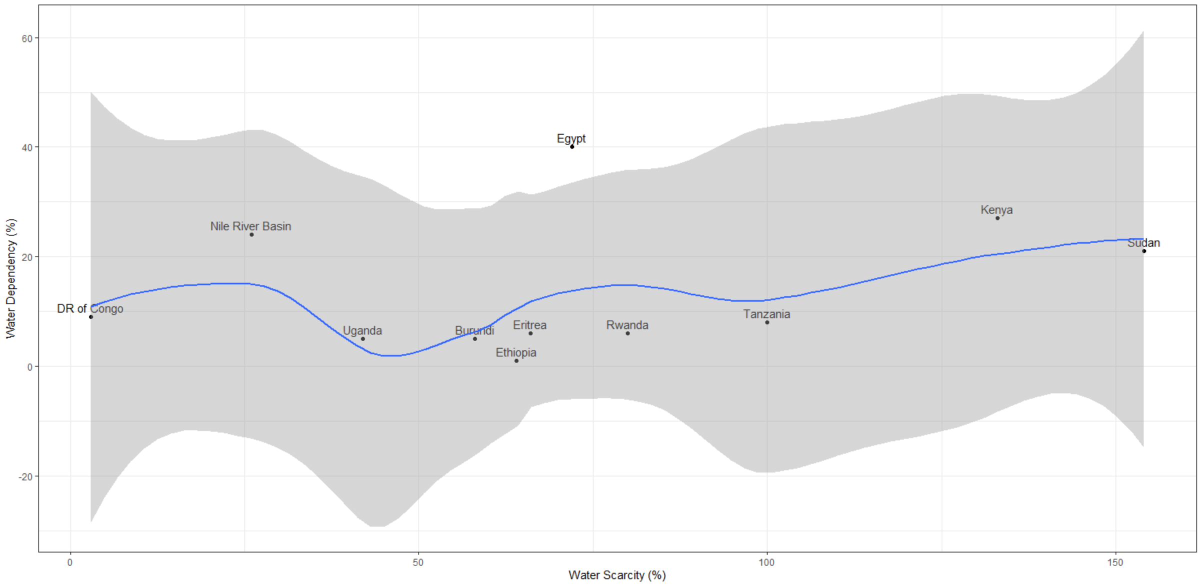


Figure 3.7 This plot illustrates the relationship between water scarcity and water dependency among Nile Basin countries in 2007. The blue line represents the non-linear trend, showing that countries with moderate water scarcity (e.g., Uganda, Ethiopia) tend to have lower water dependency. In contrast, those with very high or very low water scarcity (e.g., Sudan, DR Congo) exhibit higher dependency on external water sources. The gray shaded area indicates the confidence interval of the regression, with wider bounds at the extremes, suggesting greater uncertainty and more reliable estimates in the mid-range. Overall, the plot reveals a complex, non-linear association between water scarcity and dependency.

Fig. 3.8 National Water Dependency vs Water Scarcity of NRB in 2015

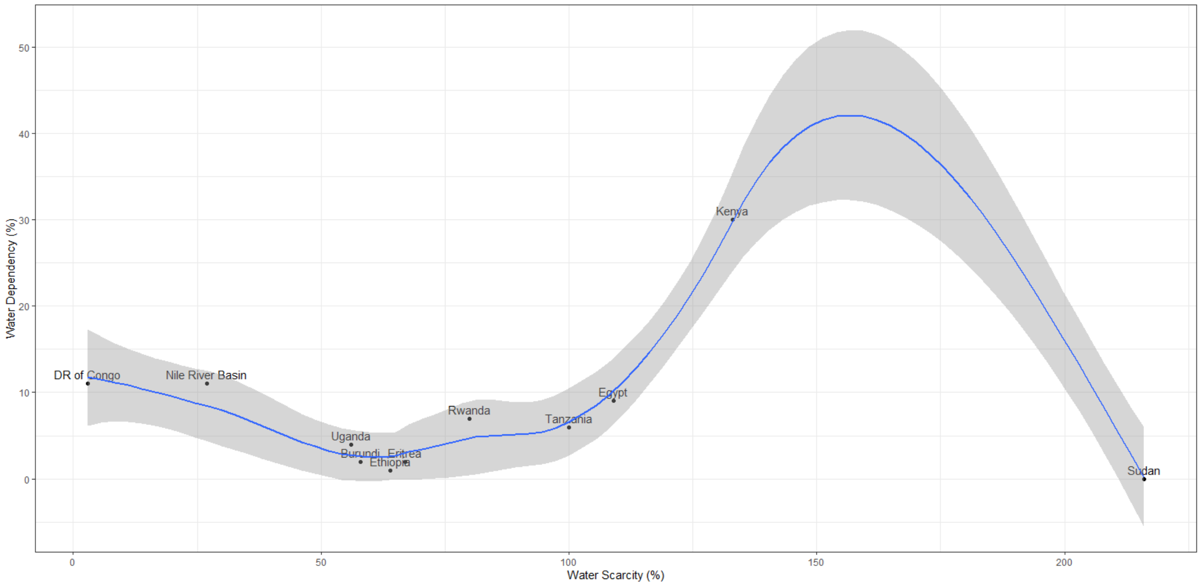


Figure 3.8 This plot illustrates the non-linear relationship between water scarcity and water dependency among Nile River Basin countries in 2015. Water dependency initially declines with increasing scarcity, then rises to a peak around 160% scarcity, before dropping again. The gray shaded area represents the 95% confidence interval, showing greater uncertainty at very low and very high scarcity levels. The curve suggests that moderately water-scarce countries are most reliant on external water sources, while extremely water-scarce nations may depend primarily on internal supplies due to limited alternatives.

Global Virtual water dependency and water Self Sufficiency

Table 3.10 presents the average annual volume of regional water footprint, water self-sufficiency and water dependency of each region. This implies that even a region like Europe, which does not have a reputation for water scarcity, has a high dependency on water imports. In such cases, a large volume of virtual water imports coexists with national water abundance. The importance of virtual water is not directly related to water scarcity, but can be reasonably explained by other factors.

Water scarcity remains a significant challenge for many regions worldwide, particularly in arid and semi-arid zones where water resources are limited and unevenly distributed. In response, countries have adopted varying strategies to enhance water self-sufficiency. These strategies often fall into two broad categories: the over-exploitation of domestic water resources, as seen in Egypt, or a growing reliance on virtual water imports, exemplified by Jordan. Both approaches carry significant long-term risks, either through the depletion of local ecosystems or by increasing vulnerability to fluctuations in global trade.

The Nile River Basin stands out as a unique case. It is currently the largest region globally with the highest level of regional water self-sufficiency, estimated at approximately 90% (see Table 3.10). Despite this high degree of self-reliance, the NRB exhibits a relatively low per capita water footprint, averaging around 230 m^3 per person per year (refer to Appendix B.3 and B.4). This suggests that while the region is largely self-sufficient, it operates under significant water use constraints, likely due to both climatic limitations and economic factors.

A similar pattern is observed across much of the African continent. African countries, on average, maintain a high water self-sufficiency rate of approximately 95%, while their per capita water footprint remains below the global average, at around 210 m^3 per person per year. This indicates a continent that, while largely independent in terms of water use, is also characterised by low levels of water consumption, often a reflection of limited access rather than sustainable abundance.

However, this delicate balance is vulnerable to disruption. Should water consumption patterns in Africa shift due to population growth, economic development, or climate change, the implications could extend far beyond the continent. Many regions that currently depend on food imports from Africa or rely on Africa's low water footprint to balance global water trade, such as parts of Europe, could face intensified water stress. These regions may struggle to maintain their current levels of water self-sufficiency if African nations begin to import more food, thereby externalising their water demand.

This raises a critical question for the future: How will the Nile River Basin and the broader African continent ensure food security in the coming decades? If African countries increasingly turn to food imports to meet domestic needs, this will place additional pressure on global land and water resources, particularly in already water-stressed exporting countries. The global water system is interconnected, and shifts in one region can have cascading effects across continents.

In light of these dynamics, it is essential to consider integrated water and food security strategies that balance local resource use with global interdependencies. Enhancing water use efficiency, investing in sustainable agriculture, and fostering regional cooperation will be key to navigating the complex challenges of water scarcity and self-sufficiency in an increasingly interconnected world.

Table 3.10 Global Annual Virtual Water Dependency

Region	Internal Water footprint (10^6 m^3 yr^{-1})	External Water footprint (10^6 m^3 yr^{-1})	Water self-sufficiency (age-%)	Water dependency (age-%)
Nile River Basin	176.72	20.24	90%	10%
Rest of Africa	444.13	25.67	95%	5%
Asia	3721.86	428.58	90%	10%
Europe	1044.91	509.68	67%	33%
North America	961.78	298	76%	24%
Oceania	86.07	23.01	79%	21%
South America	912.72	94.26	91%	9%

Notes: The table represents a two-period (2007 and 2015) average of regional water self-reliance and dependency, examining how regions manage their water needs internally and from external sources.

3.5 Conclusion

The Essay applied a multi-regional input-output framework with a water-extended (MRIO-W) model to assess the domestic and international water footprint of the Nile River Basin region. The study assessed virtual water flows in the Nile River basin and between six continents, categorised into seven regions: the Nile River Basin, the Rest of Africa, Asia, Europe, North America, South America, and Oceania. The MRIO framework enables the examination of the study region's status regarding water self-sufficiency, water scarcity, and water dependency. The study was conducted by comparing water usage and flow patterns to identify water-intensive sectors during two distinct periods, focusing on changes in global trade.

The literature review highlights that different water footprint calculation methods lead to diverse outcomes. This study, employing a top-down approach to analysing virtual water footprints, yields results that are not only consistent with several previous studies but also align with the findings of the Water Footprint Network (WFN) from 2015. This alignment with established research provides a solid foundation for the validity of our findings. On the other hand, developing nations present a different scenario, acting as net exporters of virtual water. This is particularly true for countries within the Nile River Basin (NRB) and the rest of Africa. However, the imbalance in water flow within the NRB or across Africa, reflecting a lack of trade networks due to insufficient infrastructure and trade agreements, underscores the need for more equitable water resource management. Only a few NRB countries exhibit strong trade connections. For example, Egypt maintains trade relationships with Kenya, DR Congo, Tanzania, Burundi, and Uganda, while Sudan trades with Tanzania, Uganda, and Burundi.

On a global scale, the virtual water flow network appears robust, thanks to well-established trade arrangements and infrastructure. The NRB region primarily trades with Asia, Europe, and the Americas, and the rest of Africa follows a similar trend within its sub-regions. However, the issue of significant variation in water-saving trends is concerning. The NRB and the rest of Africa exhibit very low water savings compared to other regions, resulting in the overexploitation of non-renewable water resources. This unsustainable use underscores the urgent need for sustainable water management to prevent severe water scarcity across Africa.

Chapter 4

Implications of Climate Change-Induced Water Scarcity for the Egyptian Economy: A Multi-Sectoral Analysis Using CGE Approach

4.1 Background

Water is one of the most essential elements for human life on earth, and water resource scarcity is a concern of the global community that has received wider and long-term attention. Several research studies have confirmed that the global water shortage has been driven by population growth. At the beginning of the 1960s, only 2% of the world's population suffered from water scarcity. However, this figure increased to 9% in the 1990s, 35% in 2005, and is expected to reach 40% by 2050 (Liu et al., 2017). In Africa, the concern about water scarcity is significantly higher than the global average, especially in the Sahel region of the Nile River Basin States. According to Will Freitas, approximately

10% (25 million) of the Nile Basin's population currently faces chronic water scarcity, and this number is projected to increase to 39% by 2040, resulting in 87.5 million people with limited access to water (Freitas, 2020). Even if several factors contribute to the reduction of water resources in the Nile River Basin, Global climate change amplifies the intensity of water scarcity in the region. Link et al. (2012) concluded in his research that the effect of future climate change on Nile River flow will extend the uncertainty of water availability in the region.

Drought is a frequent and severe phenomenon in most African countries, occurring due to climate change and extreme rainfall variability in the extensive arid and semi-arid areas (Haddout et al., 2020). Many sub-Saharan African (SSA) economies are widely perceived as particularly vulnerable to the effects of drought due to the significant role of rain-fed agriculture and livestock production in their national GDP. Moreover, the Nile Valley is commonly a dry region in Africa. Since the 1980s, the economic decline and structural adjustment problems have also made many SSA economies potentially more exposed to internal and external shocks (Elbadawi et al., 1992). From an economic perspective, agricultural drought may be considered a supply-side exogenous shock, widely recognised as a sharp reduction in agricultural productivity, export earnings, widespread asset losses, reductions in employment, and the associated losses resulting from declines in rural income (Benson and Clay, 1994).

4.2 Introduction

Agriculture is one of the most climate-sensitive sectors of an economy; its responses to temperature, precipitation, soil radiation and others are directly associated with climate change (Baptista et al., 2022). Soaring temperatures, erratic rainfall, and other climate failures have long-term effects on the economy of agricultural-dependent regions in the Nile River Basin (Edame et al., 2011). The Nile River, the world's longest river, runs through 11 countries in Africa and has a basin that covers approximately 3 million square kilometres, nearly 10% of the continent's landmass. Over 250 million people rely on the

Nile's water in Ethiopia, Uganda, South Sudan, Sudan, and Egypt. Nearly all the rainfall that feeds two Nile major tributaries- the Blue Nile and the White Nile- falls in the upper Nile basin, found in South Sudan, western Ethiopia, and Uganda. The lower Nile basin (Sudan and Egypt) receives very little rainfall and heavily depends on the Nile for water. Climate projections suggest that the amount of rain in the upper Nile basin could decrease by up to 20% annually (Mankin, 2020).

The productivity of weather-dependent sectors, such as agriculture, is likely to be substantially affected by climate change (Sachs et al., 1999). Hence, the adverse economic impacts of climate change are expected to be borne by countries with large agricultural sectors in the tropics and subtropics, where agricultural production is highly weather-sensitive and adaptive capacities are limited. Examples of partial equilibrium studies assessing the micro impacts of climate change on the performance of agriculture in developing countries include those by (Calzadilla et al., 2013; Chalise and Naranpanawa, 2016; Kurukulasuriya et al., 2006; Reilly et al., 1996; Rosenzweig and Parry, 1994; Seo and Mendelsohn, 2008).

Given the importance of agriculture in many developing countries for GDP, employment, and livelihood, the impact of climate change on agriculture will reverberate throughout their economies. Indirect effects are felt in sectors concerned with the processing and distribution of agricultural products, as well as in numerous other economic sectors. Direct or indirect interactions between different sectors must be studied to assess the impact of climate on agriculture. Hence, CGE models are well-suited to capturing the complicated dynamics and interdependence between the agricultural and other economic sectors. These models provide a comprehensive framework for illustrating how changes or shocks in agriculture, such as changes in agricultural productivity, ripple through the entire economic system. It also excels at simulating the impacts of alterations in agricultural productivity on macroeconomic variables, including national income, exports, household welfare, and others. This holistic perspective enables policymakers, researchers, and analysts to understand the broader economic implications of agricultural changes (Brooks, 2018).

Another crucial aspect to consider is the incorporation of natural capital inputs into the CGE model. The inclusion of natural capital as a factor of production within the CGE framework is significant for several reasons. First and foremost, natural capital, including resources such as land and water, plays a pivotal role in various economic activities, particularly agriculture. By integrating natural capital input into the CGE model, we better represent real-world interactions between natural capital availability, agricultural production, and the broader economy. This enables us to analyse the economic consequences of changes in natural capital, such as variations in soil fertility, changes in land use policies, or the effects of water reduction due to climate change. Moreover, including natural capital input allows us to explore the intricate trade-offs and synergies between different sectors of the economy. For instance, changes in natural capital availability can have cascading effects on agriculture, energy production, manufacturing, and other sectors. By considering natural capital as an input across these sectors, CGE models facilitate a comprehensive understanding of how adjustments in one area can ripple through the entire economic system. Furthermore, integrating natural capital into the CGE model is instrumental in addressing natural resource-related policy questions and sustainability challenges, enabling policymakers and researchers to assess the economic implications of natural capital management strategies (Shihao et al., 2023).

Water is a significant component of natural resources, particularly in agriculture. In countries like Egypt, where agriculture heavily depends on irrigation, water constitutes approximately 85% of the natural resources used in agricultural production. This reliance underscores water's critical role in determining agricultural productivity. Effective water management is crucial for maintaining crop yields and ensuring food security. The availability and quality of water resources have a direct influence on crop growth, making them a critical factor in the agricultural sector's overall performance. Changes in water availability due to climate change, policy adjustments, or infrastructural developments can profoundly impact agricultural output and, by extension, the broader economy (Sharef, 2019). This highlights the necessity for comprehensive water management strategies and policies that prioritise the sustainable use and equitable distribution of water resources to support agricultural productivity and economic stability in regions where water is a pivotal natural resource (Fuglie et al., 2021). Water scarcity, arising from climate change, basin-level water resources, and the adaptive capacities of managed systems, is a dynamic and complex issue (Canta et al., 2023). Beyond geophysical aspects, it is crucial to consider how economic factors at multiple scales mitigate or exacerbate water shortages. Global water scarcity poses a significant challenge to human development and the achievement of the Sustainable Development Goals. Agricultural commodities, the primary source of global water consumption, are often traded and consumed outside their regions of production, linking global consumption patterns to local water systems. Consequently, changes in local water availability can impact global consumption, highlighting the interconnectedness of water scarcity and economic dynamics.

Water scarcity is a dynamic and complex concept resulting from the combined influences of climate change, basin-level water resources, and adaptive capacities of managed systems (Yang et al., 2020). Beyond geophysical water stress and responses, it's crucial to consider how multi-sector, multi-scale economic challenges exacerbate global water scarcity, a pivotal factor in human development and the attainment of Sustainable Development Goals. Water scarcity, typically perceived as a local river basin issue, is often driven by global factors; for example, agricultural commodities, the primary global water consumers, are frequently traded and consumed far from their areas of production. These economic trade connections mean that a global shift in consumption affects the local water system (Dolan et al., 2021). Likewise, regional water system shocks can also affect global consumption.

The concern over the potential impacts of greenhouse gas and carbon emission-induced climate change in Egypt has been motivated primarily by the implications of rising temperatures, declining rainfall, and a reduction in agricultural production and productivity (El-Ramady et al., 2013). These have exposed Egypt's population, agriculture, and industrial activities to risk as all of them are located in the low-lying Delta. The primary causes of water scarcity, reduction in agricultural productivity, and economic distortion are potentially linked to climate change-induced global warming (Gamal et al., 2021).

There is also the possibility that additional impacts could arise from related changes in production in the rest of the world, to which the Egyptian economy is linked through trade (Yates and Strzepek, 1998). Therefore, national assessments of the potential effects of climate change have often failed to integrate such global-level changes in commodity production and trade. Building on the benefits of earlier efforts, this study aims to fill the gap by analysing the economic impact of Climate change-induced changes in agricultural productivity on the Egyptian economy. Climate change directly affects the availability of water resources, leading to reduced access to irrigation water and, consequently, less water for agricultural production. Climate change severely affects Egypt's water availability, resulting in national water scarcity (Gad, 2017).

The link between water scarcity and economic growth is complex and has become increasingly evident, particularly in Egypt, where agriculture plays a crucial role. Several studies have persuasively linked water scarcity to economic growth. For instance, Sadoff et al. (2017) provides seminal findings indicating a strong relationship between water scarcity and economic growth in OECD countries, projecting a 55% increase in the demand for fresh groundwater (excluding rainwater) over the next two decades. This highlights the severity of water scarcity, particularly in drought-prone regions such as Sub-Saharan Africa. Hertel and Liu (2019) further enhances our understanding by comprehensively assessing the global economic impact of water scarcity using a CGE model. Their study reviews various facets of water, including scarcity, sectoral activities, and economic growth, while identifying opportunities and challenges in integrating water use considerations into a CGE framework. They examine water consumption across agriculture, energy production, households, and services, highlighting the potential for conservation and economic incentives to boost water efficiency. Given that agriculture is a cornerstone of Egypt's economy, making significant contributions to its GDP and employment, the decrease in agricultural productivity due to water scarcity presents a potentially considerable economic shock. The OECD. (2018) Environmental Outlook anticipates substantial increases in groundwater demand, underscoring the seriousness of this issue for countries like Egypt. Climate change exacerbates these challenges, as higher temperatures and shifting precipitation patterns result in reduced water availability, directly impacting agricultural output. Jaume et al. (2014) demonstrated the broader effects of water scarcity on less developed economies using CGE models, which effectively illustrate interactions between agriculture and other economic sectors.

Therefore, examining the economic impacts of water scarcity in Egypt through a CGE model is not only relevant but also crucial. This research aims to assess the influence of climate change on Egypt's economy by analysing the whole-economy consequences of productivity loss in the agricultural sector. By integrating natural capital inputs, such as water, into the CGE model, we can gain a deeper understanding of the real-world interactions between water availability, agricultural production, and the broader economy. This comprehensive approach equips policymakers and researchers with the knowledge to devise informed strategies to mitigate the adverse effects of climate change on Egypt's economic growth.

4.2.1 Motivation and Rational Justification

Egypt heavily relies on the Nile River as its primary source of water. However, water availability in this region is mainly affected by climate change. This situation necessitates an examination of the consequences, as water plays a crucial role in various aspects of life. In fields such as agriculture, manufacturing, and household consumption, these risks are all vulnerable (Mancosu et al., 2015). Agriculture in Egypt accounts for 11% of the country's economy and 12% of its exports while providing jobs for a quarter of the population (Ismail, 2020).

Nevertheless, the national economy faces a risk due to its susceptibility to the impacts of climate change. The connection between water and the economy mainly arises from its impact on agricultural output. Lack of water availability can lead to disruptions in agricultural productivity, which in turn affects the national economy. Henceforth, grasping these impacts for strategic policy planning is imperative and vital.

4.2.2 Research Objectives

This study aims to assess the economic impacts of climate-induced agricultural productivity loss on the Egyptian economy using a multi-sectoral CGE model. It enables a rigorous evaluation of the potential economic impacts of climate change by linking climate change, water scarcity, and economic dynamics. Specifically, it seeks to analyse how changes in agricultural productivity, influenced by climate change, affect key economic indicators such as national GDP, output, capital remuneration, value addition, trade dynamics, and output price stability. The findings will contribute to a deeper understanding of the scientific dimension of climate change challenges in Egypt and provide evidence-based recommendations for designing effective national adaptation strategies and participating in global climate policy agreements.

4.3 Literature review

Egypt is one of the most water-scarce countries in Africa. Lack of water is a common phenomenon that poses a significant challenge to the national economy. This country has already exploited its available water resources, and most of its watersheds have passed the sustainable water withdrawal level (Taheripour et al., 2020). Egypt utilises water extensively for agricultural production; however, precipitation has decreased over time due to climate change. These patterns suggest that Egypt will face substantial challenges in sustaining crop production in the future. The reduction in agricultural productivity has a direct impact on Egypt's overall economy, making water scarcity a central aspect of this chapter's study. Consequently, agricultural productivity loss due to water scarcity is a key focus within the CGE model, underscoring the critical role of water in sustaining economic stability and growth (Liu et al., 2016). CGE models are flexible enough to adapt their nested production function to incorporate natural capital as production inputs and the commodity consumed by households (Osman et al., 2016). Likewise, it enables us to consider the effects of water scarcity on agricultural productivity loss and broader economic sectors, such as GDP and household income, resulting from changes in water availability.

In the following subsections, we will critically review the impact of climate change on Egyptian agriculture and its significant contribution to the national economy. Furthermore, we will explore how other research studies have utilised the CGE model to assess the effects of climate change on agricultural productivity and the broader economy.

4.3.1 Climate change impact on Egyptian Agriculture

Agriculture is a central part of the Egyptian economy; the Nile Valley has historically been a fertile region, providing the source of agricultural income (Ruf, 1993). In terms of size, the Nile Valley is a relatively narrow strip of land along the Nile River, which is a critical driver of development and civilisation; almost all the arable land lies along the banks of the Nile River. The agricultural sector covers 3% of the total landmass, contributing one-eighth of the GDP and over a quarter of employment. According to the USAID report 2020, about 80% of national water demand is used for agricultural production (Hopwood and Holt, 2020). With increasing stress on water resources along with the increased severity and length of drought, concerns about the sustainability of this sector under a future climate are growing. According to Abd-Elhamid and Abd-Elaty (2017), the drought and water stress around arable lands have increased saline intrusions into the surface. Also, Abdelhamid highlighted that about 10-12% of farmland could be at risk and damaged due to saltwater intrusions to agricultural land (Abd-Elhamid and Abd-Elaty, 2017). Another study from 2010 estimated that around 25-30% of farmland is already affected by saline intrusions (Shaaban and Ramzy, 2010). In the analysis, they highlighted that the impact of climate change on the country's most critical stable crops is significant. More specifically, they highlight that the productivity of certain crops, such as wheat and maize, is projected to decline by 15% and 19%, respectively, by 2050 (UNFCCC, 2017). Similarly, the study found significant impacts of climate change on animal health. As cropland productivity decreases due to increased temperatures and a decrease in water supply, competition for grassland and fodder is increased (Rabie, 2020). Additionally, the range of certain animal diseases is expanding into Egypt; these include devastating outbreaks like Rift Valley fever and blue tongue disease (Khalifa, 2014).

A study by William (2007) analysed the functional relationship between climate change and agricultural productivity, taking into account location and other factors. For the 1^0C temperature change, there would be a modest increase in agricultural productivity in the temperate region. With a 2^0C temperature change, agricultural yield would decline sharply (5-10%) in African tropical areas. A 3^0C change in global temperature would put 150-550 million people at risk of hunger. A 4^0C change in temperature would lead to a 15-35% decline in agricultural productivity in Africa, and a warmer temperature beyond this would bring about the entire region's production loss (William, 2007).

Climate change, both directly and indirectly, affects agricultural productivity, directly through crop growth and CO2 fertilisation, and indirectly by reducing water availability, rising sea levels, and increasing pests and diseases (Mahmoud, 2019). A comprehensive assessment of all potential direct and indirect effects of climate change on agricultural productivity has yet to be conducted. This type of assessment could provide valuable context to inform decision-making in areas of high uncertainty and also inform future research directions.

4.3.2 Economic Implications of Agricultural Productivity Loss

The economic implications of agricultural productivity loss are a significant concern in the face of Climate change-induced challenges. Recent studies highlight the severe threat that climate change-induced water scarcity poses to agricultural productivity and its economic implications worldwide. Fatima et al. (2020) highlighted the loss of agro-biodiversity and productivity in Asia due to climate change, emphasising the need for sustainable agricultural practices. Ahmed and Hefny (2001) examined the impacts of drought and climate change on irrigation schemes in Sub-Saharan Africa, highlighting regional challenges to agricultural systems. Khan et al. (2020) conducted a study in

Pakistan using global Climate, crop, and economic models to evaluate the economic impact of climate change-induced loss of agricultural productivity by 2050. Utilising crop models such as CERES-Wheat, CERES-Rice, and APSIM, they assessed yield decline and its economic effects. In the context of land use change, Zhao et al. (2020) proposed a land use modelling framework that accounts for land productivity differences and conversion costs, providing welfare decomposition based on land heterogeneity to enhance the accuracy of economic models. Morabito et al. (2020) highlighted that agricultural workers face heat-related productivity loss, estimating the economic cost for moderate work activities and emphasizing mitigation importance.Bhat et al. (2020) discussed the role of plant growth-promoting rhizobacteria (PGPR) in enhancing plant productivity and alleviating salinity stress, highlighting PGPR's role in minimising plant salt uptake and mitigating productivity loss. Zisopoulou et al. (2021) explored physical water scarcity in agriculture and its economic implications, highlighting the complexities of translating physical variables into economic terms. Celmi et al. (2021) discussed managing glacial lakes in Peru to address water scarcity under future climate change scenarios, emphasising long-run planning. Ismail et al. (2021) conducted a techno-socioeconomic analysis of fog-to-water solutions in Indonesia, highlighting the impact of water scarcity on livelihoods. Assefa et al. (2021) explored the devastating effects of climate change on agricultural communities, advocating adaptation strategies to mitigate vulnerability. Sultan et al. (2022) advocated climate-smart agriculture in Pakistan to strengthen agricultural resilience. Paudel et al. (2023) addressed challenges posed by the COVID-19 pandemic, climate change, and agricultural conflicts, emphasising the need for strategies to ensure global food security. Semeraro et al. (2023) focused on the impact of climate change on agroecosystems and potential adaptation strategies, highlighting the role of new technologies in enhancing agricultural resilience. This literature highlights the pressing need to address the economic implications of agricultural productivity loss resulting from climate change-induced water scarcity through sustainable practices, adaptation strategies, and the adoption of climate-smart agriculture, thereby ensuring food security and economic stability in vulnerable regions.

4.3.3 CGE Modelling and Climate Change

Integrating climate change impacts within a CGE framework is beneficial because the model can capture all critical parts of an economy and their interconnections. Climate factors, such as temperature, precipitation, and extreme weather events, have an impact on economic activities. It reduces agricultural productivity through lower crop yields, altered rainfall patterns, and increased pests and diseases, creating a supply shock (Fonta et al., 2011). This leads to higher food prices, contributing to overall inflation. As food prices rise, household purchasing power declines, particularly for low-income families, which in turn increases poverty rates. The agricultural sector faces lower incomes and reduced employment, while industries that rely on agricultural inputs experience higher costs, which impact their profitability. Overall economic growth slows as the agricultural sector's contribution to GDP decreases (Nelson et al., 2009). These changes affect the productivity of inputs, production parameters, or final demand and can be directly fed into the CGE model (Cutler and Davies, 2010). The model then calculates indirect effects on other sectors through these interconnected relationships. This multi-sectoral, multi-regional approach is essential for assessing climate-economic interactions. By breaking down data by sectors, the CGE model analyses structural shifts due to climate change and examines the distributional impacts of climate policies.

Climate change triggers various questions and challenges to design, particularly as countries are recently contending with macroeconomic disparity. Global warming is one of the new dimensions that have contributed to the current economic anxiety, including disproportionate income distribution, low standards of living, fiscal instability, trade imbalances, oil price volatility, and deteriorating growth, along with the political feasibility of climate change policy measures (Babatunde et al., 2017). The immediate consequence of climate change is a rise in temperature and a reduction in precipitation. Agricultural production is susceptible to climate change, as it depends on fundamental climate conditions, such as temperature and rainfall patterns. Economists and water practitioners have conducted various cost-benefit analyses of water using a simple economic model of water availability.

The first example of a CGE model incorporating water as a production input was a study conducted by Berck et al. (1990) in the San Joaquin Valley, California. Water was considered a factor of production in the model, and water allocation was determined by solving linear programming (LP) problems to select the optimal water-land input at the bottom nested production function in the CGE model simulation. This study analyses the effect of water reduction on agriculture on the aggregate economy of the San Joaquin Valley Diao et al. (2008), Dwyer et al. (2005), Goodman (2000), and Wattanakuljarus (2006), which also incorporate water as a factor of production into sectoral CES for a single country CGE Model. The primary use of this model is to help water basin planning countries, such as Pakistan, Morocco, and Egypt, assess the impact of anticipated water system investments, like irrigation schemes, on the national economy.

The extraordinary impacts of climate change can be captured in the CGE analysis through various channels, based on the linkage between environmental inputs and the national economy of the specific country. Hence, it is essential to establish the linkage between climate change and the national economy. The Egyptian economy heavily relies on climate-related inputs, such as water, for production, processing, and value addition. Several research studies in the Sahel region, as well as research undertaken in Egypt, have demonstrated that global climate change has a significant impact on water availability in Egypt (Omar et al., 2021). Water is a crucial input for production, processing, and value addition in the Egyptian economy's agriculture, industry, and service sectors (Fuglie et al., 2021).

The linkage between water economy and climate change analysis has a long history. The earlier example of the water-incorporated CGE model is the work of Berck et al. (1990) in their assessment of the San Joaquin Valley in California. Similarly, the CGE model incorporates water as a natural capital input in the sectoral CES production function, as drawn from existing literature, for this chapter's study.

The CGE models enable the translation of long-run projections of various biophysical climate change impacts into sectorally disaggregated economic shocks to model parameters

(Delzeit et al., 2020). The unique advantage is that the simulation of economic responses systematically accounts for inter-sectoral spillover effects and macroeconomic feedback effects arising from the economy-wide input-output linkages and economy-wide system constraints. Furthermore, the simulation results capture the market-mediated endogenous autonomy adaptation responses of consumers and producers to changes in relative prices and real incomes triggered by climate shocks. Additionally, the CGE approach enables multi-sectoral simulation scenarios to address the uncertainty surrounding long-term projections of climate change impacts.

In Egypt, the pressing impact of climate change on the national economy, driven by the ripple effect of water scarcity and its subsequent impact on agricultural productivity, warrants exploration, primarily through the CGE approach. Therefore, linking the effects of climate change on the economy through reduced agricultural productivity, which diminishes the output of each sector contributing to the national economy, is a valuable focus for our analysis.

4.3.4 Exploring Key Insights: A Review of Similar Studies on Climate Change

The impact of climate change on the national economy concerns scientific communities, policymakers, environmental professionals, consumers, trading partners and nations worldwide (Vogel, 2009). Numerous research studies have been conducted on this issue in various parts of the world. Using a semi-parametric panel approach, the most recent study by Song et al. (2022) analysed the effect of general climate factors and extreme weather events on agricultural productivity across three economic regions in China. The study concluded that climate change could reduce agricultural productivity, with broader implications for the national economy, urging policymakers to mitigate these impacts. However, the study has limitations. They primarily focus on the aggregate impacts of climate change and do not incorporate specific adaptation strategies, such as crop diversification, irrigation techniques, or land-use changes, which could help mitigate adverse effects. Furthermore, the models lack a long-term perspective on the evolving impacts of climate change and do not account for regional variations in agricultural systems. The gap lies in the limited consideration of adaptation measures, long-term dynamics, and regional differences, which could provide a more comprehensive understanding of the diverse impacts of climate change on agriculture.

Another important study on this issue is the work by Ogundari and Onyeaghala (2021), which assessed the effect of climate change on African agricultural productivity using a cross-country panel approach covering 35 countries from 1981 to 2010. The empirical results indicate that the African TFP levels are converging over time, with the rate of TFP growth positively affected by rainfall, while temperature shows no significant effect on the development of African agricultural TFP. Therefore, precipitation plays a crucial role in Africa's agricultural productivity, thereby having a significant impact on the continent's broader national economy. However, the study lacks a detailed regional analysis that could better capture the diverse agricultural systems and vulnerabilities in different African countries. The gap lies in the absence of a region-specific approach, which could provide policymakers with more practical insights to address the diverse challenges posed by climate change in African agriculture.

On the other hand, numerous studies have been conducted on the impact of climate change on the national economy using the CGE model. A study by Arndt et al. (2015) assessed the economic costs of climate change to Vietnam using a multi-sectoral CGE approach, focusing on the biophysical damages and their economic impacts. The study found a modest impact on agriculture and transportation, but significant effects from rising sea levels and cyclone strikes, projecting a 1-2% reduction in the national economy by 2050. The authors suggest improvements in future research, including the adoption of a stochastic baseline scenario to reduce reliance on historical weather events, which would require better integration between biophysical and economic models. Additionally, they highlight the importance of incorporating forward-looking expectations for autonomous adaptation, particularly in developing nations. The study also notes the well-established link between rising temperatures and a decline in agricultural productivity. However, the model could be improved by incorporating more detailed regional variations in climate impacts, as different regions in Vietnam are exposed to diverse climate risks. Furthermore, it lacks a dynamic long-term framework to capture evolving adaptation strategies and technological shifts, which would provide more realistic projections for future economic costs and inform more effective policy responses. A study by Turpie et al. (2002) predicted that global climate change has contributed to a rise in temperature between 1.5 – 4°C in South Africa. This study further forecasts that, due to rising temperatures in South Africa, the mean annual runoff is expected to decline between 5% and 20% as a result of increased evaporation and extreme precipitation. According to Turpie et al. (2002), a 1% increase in temperature can reduce water availability by about 5%, a 2% rise in temperature is a 10% reduction in water, and a 3% increment in temperature could bring about 20% reduction in water availability in Tropical Africa. A recent study by Hoegh Guldberg et al. (2018) team of experts from IPCC also confirmed that global warming has contributed to a 1.5 - 2°C rise in temperature in Africa.

Several studies have been conducted on the loss of agricultural productivity due to climate change and its impact on the national economy. These studies have utilised CGE models to assess the economic effects of these changes on national economies. Nazareth et al. (2022) assessed the economic effects of projected decreases in Brazilian agricultural productivity under climate change using a CGE model. Their study found that climate change would lead to significant productivity losses in key agricultural sectors, such as soybeans, maize, and sugarcane, impacting Brazil's economy through reduced exports and income. However, a notable gap in their analysis is the lack of integration between climate-induced productivity losses and other macroeconomic factors, such as labour migration and changing consumption patterns. The model focuses on sectoral productivity changes without considering how shifts in agricultural output might influence broader economic dynamics, such as labour shifts to other sectors or changes in domestic consumption due to income changes. Including these broader macroeconomic linkages could provide a more comprehensive understanding of the full economic impact of climate change on Brazil's economy. Solomon et al. (2021) employed a dynamic CGE model to evaluate the impacts of climate change on agriculture in Ethiopia, highlighting significant reductions in crop yields and associated economic effects. However, the model's assumption of a uniform agricultural response to climate change may overlook sectoral variations within agriculture, such as differences in crop-specific vulnerabilities or adaptive capacities. Incorporating heterogeneous responses across agricultural sectors could provide a more accurate and detailed analysis of climate impacts.

Sumartono et al. (2021) assessed the impact of climate change on food and energy production in the coastal areas of Bengkulu, Indonesia, aiming to understand how climate change could affect agricultural productivity and energy needs. Using an impact assessment model, they analysed how changes in temperature and precipitation patterns could alter crop yields and energy production. Their findings showed significant negative impacts on food and energy production, with coastal regions particularly vulnerable. Despite its insights, the study lacks consideration of regional variability within Bengkulu's coastal areas. A gap exists in the model's assumption of uniform impact across crops and sectors, as it does not account for the varying sensitivities of specific crops or energy sources to climate change. A similar study by Abeysekara et al. (2024) used a CGE model to assess the economic consequences of climate change impacts on South Asian agriculture, focusing on how changing climate variables affect agricultural productivity and the broader economy. The study found that climate change could significantly reduce agricultural output, leading to lower economic growth, particularly in countries heavily dependent on agriculture. While the CGE approach provided valuable insights into the economic impacts, the model's lack of detailed regional differentiation within South Asia limits its ability to capture the diverse climate risks and agricultural vulnerabilities across the region. Moreover, the study does not incorporate the potential for adaptation or technological advancements, which could mitigate some of the adverse effects. A gap remains in understanding how different adaptation strategies could offset the economic losses projected in the study.

Additionally, a growing body of literature has focused on regional-level analyses of climate change impacts, using varying modelling frameworks that align with the regional scope of this study. Sawyer et al. (2022) evaluated the costs of climate impacts in Canada, emphasising rising damages from floods and wildfires; however, their analysis lacked a CGE framework to capture broader intersectoral effects. Banerjee et al. (2021) applied the IEEM platform to analyse agricultural losses in Latin America and the Caribbean but did not incorporate household-level adaptations or informal economies. Liu et al. (2020) employed a regional CGE model to evaluate China's sectoral impacts, highlighting vulnerability in water-scarce provinces; however, the model omitted trade feedback and technological mitigation. García-León et al. (2021) focused on heatwave-induced productivity loss in Europe using econometric tools but without linking to economy-wide modelling. Sun et al. (2024) demonstrated how global supply chains amplify heat-related losses through network modelling, yet excluded adaptive trade responses. Wang et al. (2021) examined the effects of climate-induced crop yields on agri-food sectors using partial equilibrium analysis but did not account for broader macroeconomic dynamics. A common gap across these studies lies in the limited integration of dynamic and multi-sectoral feedback, which are better addressed through advanced CGE or hybrid modelling frameworks.

Building on these regional-focused studies, this research (*chapter* 4) advances the analysis by applying the AMOS CGE model to assess the economy-wide implications of climate change-induced water scarcity and agricultural productivity losses in Egypt. Despite the growing recognition of climate impacts, existing literature has rarely utilised dynamic, multi-sectoral CGE models like AMOS within the Egyptian context. This model fills a critical gap in understanding how climate stressors propagate through various sectors by capturing the interlinkages between climate, water availability, agriculture, and the broader economy. The study's regional focus and integrated framework offer valuable insights to inform targeted mitigation and adaptation strategies tailored to Egypt's economic structure and resource constraints.

4.4 Research Methodology

4.4.1 Introduction of Egypt CGE Model

Egypt's CGE model was developed by adapting the AMOS model initially developed by Harrigan et al. (1991) for the Macro-micro simulation framework, parametrised for regional economy analysis. Because of its environmental integration nature, we adapt it to the Egyptian economy to evaluate how climate change-induced losses in agricultural productivity affect the overall Economy. The model facilitates the evaluation of the impact of climate change shocks on agricultural output, commodity prices, employment, export competitiveness, and GDP. The assessment helps understand the economic challenges caused by possible changes in agricultural productivity and develop effective adaptation strategies tailored to Egypt's specific conditions.

The AMOS CGE model, developed by the Fraser of Allander Institute at the University of Strathclyde, is dynamic (Figus et al., 2017). It is designed to analyse the economy over multiple periods, capturing the evolution of various economic variables and incorporating inter-temporal decision-making and expectations about the future. This provides a comprehensive understanding of the long-term policy effects and economic adjustments in both the short and long run. In this study, we primarily focused on the long-run effects of climate change on the Egyptian economy, as the consequences of climate change unfold over time. On the other hand, Static CGE models analyse the economy at a single point in time, assuming equilibrium within that period without accounting for future changes, which is not the case for our study. This simplicity makes them useful for evaluating the immediate impact of policy changes. In contrast, dynamic CGE models examine the economy over multiple periods, capturing the evolution of variables such as capital stock and labour productivity. These models incorporate intertemporal decision-making and expectations about the future, making them more complex but valuable for understanding the long-run effects of policy. Dynamic models require detailed data to reflect changes over time, including investment and savings behaviour. Choosing between these approaches depends on the specific research question and policy context, with static models providing a snapshot and dynamic models offering a comprehensive view of economic adjustments over time.

An alternative model to CGE is the Input-Output (IO) model. The AMOS CGE model has several advantages over the IO model, primarily due to its active supply-side, which includes factors of production, allowing for substitution between capital and labour based on relative prices (Fraser of Allander Institute, 2022). This leads to more realistic economy-wide impacts compared to the passive supply-side of IO models, which rely solely on fixed proportions of industrial output. CGE models, including AMOS, incorporate micro-functions for firms, households, and governments, providing a consistent economic theory and flexibility to analyse various shocks. However, this flexibility also means CGE models are sensitive to configuration and parameter choices, which must be carefully selected to ensure accurate results. Despite using restrictive production functions, such as Cobb-Douglas or CES, CGE models simplify finding solutions but may not fully represent production behaviour. While CGE models offer robust and comparable results, their complexity and sensitivity to parameters are notable limitations. Another limitation relates to the temporal resolution of the data used within this model. The model's data and simulation outputs are organised annually, meaning that short-term climate shocks—such as a particularly dry summer or an unusually wet winter—are likely to be smoothed out in annual averages (Dellink et al., 2017). As a result, the model may underestimate the economic significance of intra-annual fluctuations that can profoundly affect agricultural yields, input use, commodity prices, and household food security.

4.4.2 Social Accounting Matrix (SAM) and Data Sources

The primary source of information for the SAM is the Eora database, organised as MRIO (2023), which typically comprises 26 sectors classified as symmetric, industry-by-industry or sector-by-sector data from the input-output Table. Additionally, we use the national income account as another source of information to construct the SAM. Therefore, the

SAM synthesises the input-output table and national income accounting for the Egyptian economy in 2011.

The SAM is structured into five major data components, as outlined in *Appendix* C.1:

1. **Intermediate inputs**: Comprising 26 economic sectors derived from the Eora national input-output table.
2. **Value addition**: Encompassing 10 inputs, including capital inputs, which are further disaggregated into natural and physical capital based on Egyptian national account data.
3. **Imports**: Categorised into two sources—imports from the rest of NRB and the ROW.
4. **Final demand**: Represented by 10 institutional agents.
5. **Exports**: Divided into two destinations, including the rest of NRB and ROW.

Except for intermediate inputs, all components are compiled from Egypt's national accounts. A distinctive feature of the AMOS CGE model, and a key reason for its selection in this study, is its explicit disaggregation of capital inputs into natural and physical capital. This approach allows for a more nuanced analysis of resource constraints. According to Reuter et al. (2016), natural capital in developing countries primarily comprises soil and water, with water accounting for approximately 80% of the natural capital inputs.

Given data integration from multiple sources, statistical discrepancies were encountered, necessitating the rebalancing of the compiled Water-embedded Social Accounting Matrix (WSAM) for Egypt. To address this, the synthesised SAM was rebalanced using the cross-entropy method proposed by Robinson et al. (1998) to ensure consistency across the matrix.

Developing a water-embedded SAM is essential for conducting water-embedded CGE simulations, as it provides the consistent macroeconomic dataset required to calibrate the model parameters. In the case of Egypt, water is explicitly incorporated into the SAM as a natural capital input within the value-added component. This modelling approach reflects the economic significance of water as a productive asset, particularly in water-intensive sectors such as agriculture. By treating water as a capital service, the SAM captures its contribution to sectoral output, enabling the CGE model to simulate the effects of water-related constraints and policy interventions. This includes evaluating the impacts of water scarcity, with the model allowing for substitution between water and other inputs based on sector-specific elasticities. This approach is particularly relevant in Egypt, where over 85% of water resources are allocated to agriculture, and water scarcity poses a significant threat to economic sustainability (Elzoughbi, 2022). The primary source is the Nile River, which supplies approximately 85% of the country's total water resources. The majority of this allocation is used for agriculture, which alone consumes around 85% of the national water supply. Groundwater contributes about 11%, supporting both agricultural and domestic needs, while the remaining supply comes from drainage reuse and treated wastewater, primarily used in agriculture and landscaping. These sources are represented as distinct production activities within the SAM, enabling a detailed mapping of water flows across sectors. Crucially, Egypt's heavy reliance on the Nile, whose waters originate from upstream riparian countries, makes it highly vulnerable to transboundary water dynamics and climate change impacts occurring in the Nile Basin. Variability in rainfall, rising temperatures, and upstream water developments can significantly affect the volume and timing of Nile flows, posing risks to Egypt's water security and economic stability. The WSAM structure enables the capture of these dependencies and vulnerabilities in CGE simulations, supporting more informed water policy and planning (Osman et al., 2016). The detailed structure of the Egyptian WSAM and the underlying data used for its construction are presented in *Figure* 4.2, Appendix C.1 and C.2, respectively.

4.4.3 Theoretical Framework of the Model

The AMOS model, a standard CGE calibrated to the Scottish Economy, has been successfully adopted and applied to Egypt's Economy and water resources. This model is mainly used to capture the impact of environmental shocks in the CGE model. The model's successful application to various sectors of the Scottish Economy, such as energy, labour market dynamics, climate change, greenhouse gases and infrastructure, is a testament to its effectiveness (Allan et al., 2018, 2008a; Allan and Gilmartin, 2011; Allan et al., 2008b; Connolly, 2018; Figus, 2017; Gilmartin and Allan, 2015; Lecca et al., 2013).

For a comprehensive analysis, it's crucial to integrate a unified framework that links the macroeconomy with environmental services. Incorporating the environmental component into the CGE model, we categorised the capital input for the agricultural sector into water and non-water capital.

As we embark on this analysis, we must acknowledge the complexity of the following assumptions. The assumption of a market-clearing and abstraction process is limited in the Walrasian model due to several factors, including real wage rigidity, sticky prices, and labour mobility. This complexity underscores the need for a comprehensive understanding of labour mobility between sectors but fixed between regions, particularly in policy issues such as migration control and other legal barriers (Smith and Favell, 2006). According to Lofgren et al. (2002), the cost function of the primary factors describes the production of intermediate and commodities.

Figure 4.1 shows the nested production function for Non-agricultural sectors. Non-agricultural industries produce value added by combining capital and labour. Value added combines with Intermediate inputs in the production of output, where domestic and imported intermediates are differentiated via the Armington assumption that imports are imperfect substitutes (Armington, 1969). Consequently, activities and commodities are classified into three sectors: agriculture, industry, and services. Intermediate inputs are distinguished as domestic or imported, with imports further categorised into those from the Nile River basin states and those from the rest of the world. This categorisation helps in understanding the regional and international consequences of climate shocks.

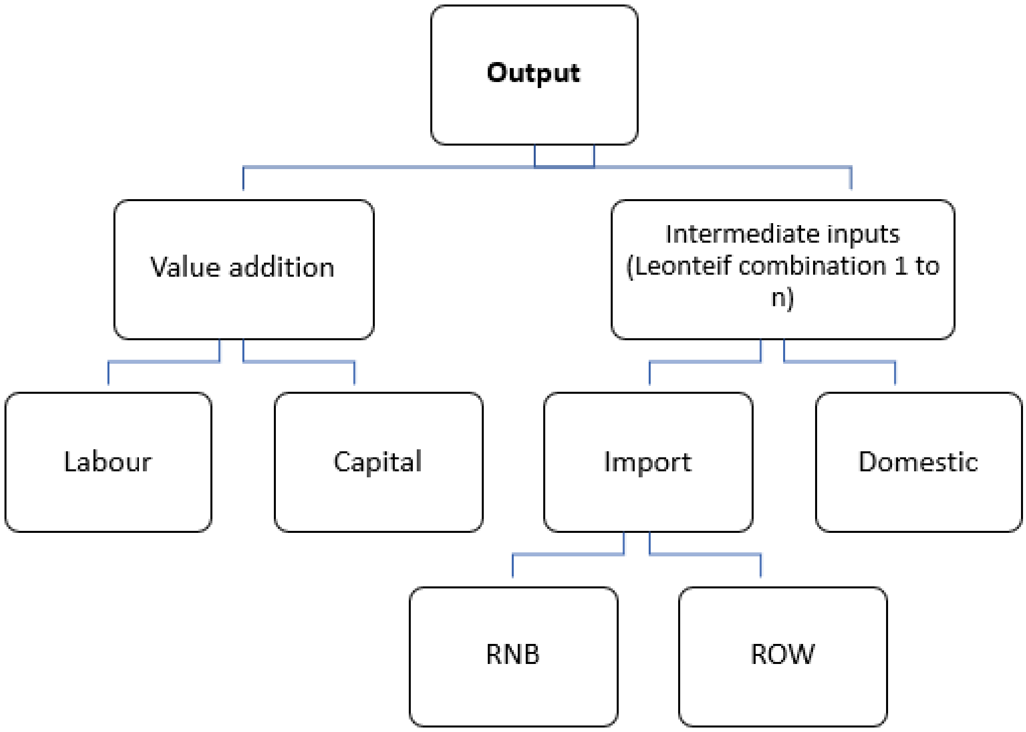


Fig. 4.1 The structure of nested production function

The capital input is further categorised into water and other capital in the agricultural sector, as indicated in *figure* 4.2, to identify the link between the environment and the national economy. The production structure for the Agricultural sector is different from that shown in *Figure* 4.1 and is illustrated in *Figure* 4.2. Here, the agricultural sector combines water and other capital to produce capital, combined with labour to produce value added. This permits us to focus productivity changes on the Water element of capital within the Agricultural sector. As set out in *Figure* 4.1, other elements of the production function are unchanged.

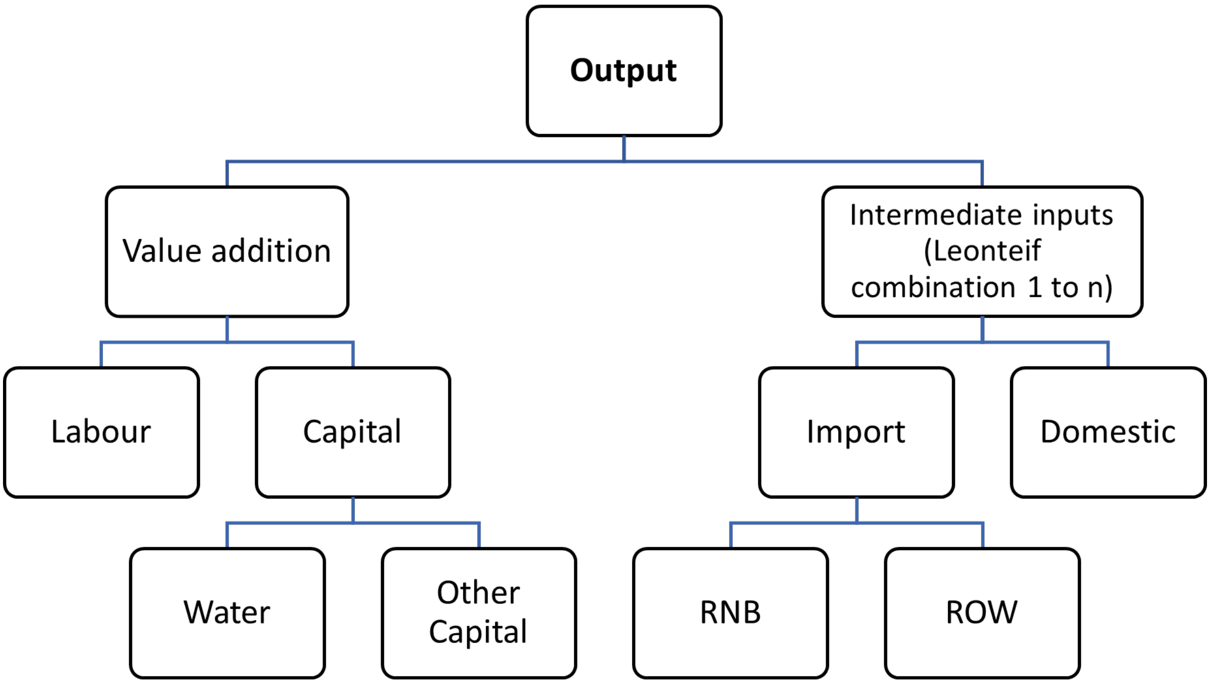


Fig. 4.2 The structure of nested production function in the Agricultural sector

4.4.4 CGE Model Specification

The Egyptian CGE model comprises 26 key production sectors and four economic agents: households, firms, the government, and foreign entities. The model's incorporation of market-clearing conditions ensures equilibrium in all markets. This analysis, with existing factors such as the availability of technology and resources, aims to determine how productivity loss could affect Egypt's Economy.

Each production sector is represented by a nested production function, which typically combines inputs with a CES function. This approach allows for different rates of substitution between various inputs. Here is the production function of other sectors that used CES in the Egyptian CGE model:

$$Y_{JT} = \left[\alpha_J \left(EK_{JT} KD_{JT}\right)^{\rho Y} + \beta_J \left(EL_{JT} LD_{JT}\right)^{\rho Y}\right]^{\frac{1}{\rho Y}} \tag{4.1}$$

The parameters α and β represent the proportions of capital and labour inputs that collectively sum to 1, ensuring constant returns to scale in the production function. The parameter ρ_J^Y indicates the elasticity of substitution between these factors.

In this context, we have modified the production function to account for economies that mainly utilise non-physical capital inputs alongside labour, physical capital, and intermediate inputs in the production process. According to Lecca et al. (2011) and Allan et al. (2018), energy is included in their CGE models when examining the Scottish Economy. Similarly, in the Egyptian Economy, water is included in the model as an input to investigate the impact of climate shocks on the national Economy. According to the model structure, inputs are composed in two stages of the CES production function as follows:

$$Y_{KW} = A(\alpha K^{-\rho 1} + (1-\alpha)W^{-\rho 1})^{\frac{-1}{\rho 1}} \tag{4.2}$$

$$Y = A(\beta Y_{kw}^{-\rho} + \beta(1-\beta)L^{-\rho 1})^{\frac{-m}{\rho 1}} \tag{4.3}$$

Where Y_{KW} represents the composite capital that incorporates physical and non-physical capital; Y is the value added; A represents technical efficiency; m represents the return to scale; α and β are shared parameters where $(0 < \alpha, \beta < 1)$; and (ρ_1 and ρ) are shift parameters where $(\infty > \rho_1, \rho > -1)$. The detailed model equations, including the production function, value addition, labour demand and supply, and all market closures, are provided in Appendix C.1 to C.88, Equation CGE Modelling.

4.4.5 Model Calibration and closure

This model calibrates household and government consumption, average savings, tax rate, and share parameters into the disaggregated environmental-augmented SAM. The model is calibrated with the assumption of fixed real wages and no migration, while allowing labour mobility between sectors. Researchers can reproduce the initial data set for the calibration from the benchmark test procedures. Also, the model includes elasticity parameters as essential components in the calibration model. Therefore, other authors such as Haddad et al. (2016) have already determined the value of constant elasticity of substitution between primary factors and intermediate inputs, including the Armington elasticity and own price elasticity of substitution. According to the theoretical structure of the model, researchers determine these parameters exogenously, outside the model (Asafu-Adjaye, 1996). Therefore, the parameter value choices can steadily affect the simulation output of the model.

In this study, water is introduced as an explicit factor of production within the CGE model, reflecting its critical role in Egypt's economy and its vulnerability to climate-induced shocks. The model employs a nested CES production function, where the three primary inputs, labour, water (as natural capital), and physical capital, are combined in two stages. This structure enables the analysis of substitution possibilities between water and other inputs, which is essential for evaluating the economic impacts of water scarcity and climate change. The elasticity of substitution between water and physical capital is a particularly influential parameter, as it determines how easily sectors can adapt to reductions in water availability through technological or capital-based adjustments. In Egypt's context, this elasticity is generally assumed to be low to moderate, typically ranging from 0.2 to 0.5 Kahsay et al. (2017), reflecting the limited substitutability between water and physical infrastructure, especially in agriculture, where water cannot be easily replaced without significant investment. The elasticity values used in this analysis are based on empirical estimates from Lord (1999), who studied Egypt's economy, and are further tested through sensitivity analysis to assess the model's robustness under varying climate scenarios. The upper and lower bounds of the elasticity parameters are selected around a base value to simulate different degrees of economic resilience. These assumptions are consistent with international modelling practices, such as those used in the GTAP-W model, and are adapted to Egypt's specific conditions using national data and sectoral studies. In the absence of detailed econometric estimates, sensitivity analysis ensures that the model remains robust and policy-relevant under a range of plausible substitution behaviours.

Table 4.1 Elasticity of Substitution

Elasticity Parameters	Symbol in Model	Parameter Value
Armington Elasticity: Elasticity of substitution between imports and domestic output in domestic demand	σ_V	2.00
CET Elasticity: Elasticity of transformation between exports and domestic supplies in domestic marketed output	σ_X	2.00
Elasticity of substitution between factors: Capital and Labour	σ_F	0.30
Elasticity of substitution between factors: Water and Other Capital	σ_1	0.30
Wage differential	ϕ	1.00
Elasticity of substitution between intermediate and value added	σ_Z	0.30

Notes: Elasticity of Substitution. It's estimated that Egypt's trade and investment can be modelled using a utility-maximisation model, allowing for the calculation of Marshallian own-price and income elasticities of demand. It accounts for competing suppliers in foreign markets. It employs highly disaggregated data and conducts a thorough analysis to improve price proxies, offering a more comprehensive and accurate analysis than traditional approaches using aggregate trade data (Lord, 1999). The detailed elasticity values for each sector are presented under *Appendix Table* C.1.

4.4.6 Simulation scenario

The simulation scenario is framed based on considering the ranges of the Shared Socioeconomic Pathways (SSP) storylines. The SSP pathways are primarily used to examine how societal choices will impact greenhouse gas emissions and how the climate goal of the Paris Agreement can be achieved in an economy (Fujimori et al., 2017). The entire set of SSP storylines has been described by (Kriegler et al., 2012; O'Neill, 2016). The standardised

SSP storyline will be used to assess the effect of climate change on Egypt's macroeconomic variables. Each storyline has been estimated in terms of the level of economic productivity loss. These outcomes of each storyline are used in the CGE model for simulation.

The SSPs are typically not assumed to reflect a specific policy choice; however, they indicate future uncertainty in short-run or long-run potential socioeconomic development, behaviour, and the role of global policy coordination. The SSP framework has primarily been used to assess future scenarios related to greenhouse gas emissions, to inform strategic policy options, and to suggest energy and land-use patterns.

We built a scenario on a general narrative with a specific dimension relevant to the agricultural sectors: a change in agricultural productivity loss. The simulation value for the specific scenario in agricultural productivity loss was initially taken from the analysis of climate change's impact on agriculture under the socioeconomic pathways (Wiebe et al., 2015).

In theory, each SSP is consistent with multiple greenhouse gas emission pathways, depending on the specific level of mitigation efforts for emissions. Therefore, each SSP combines with climate change impacts to limit the number of scenarios for a unique Representative Concentration Pathway (RCP) (Kriegler et al., 2012; Moss, 2010; Vuuren, 2011).

SSP1 characterises lower population growth, high GDP per capita, faster globalisation, and more integration of global markets. SSP2 is a pathway characterised by intermediate population and income growth, as well as a slow pace of overall trade liberalisation. SSP3 describes a fragmented world with weak international trade integration, higher population growth, and low GDP per capita income. Hence, the intermediate scenario (SSP2) is selected for this analysis as the Egyptian climate effect closely aligns with the SSP2 scenario.

The time horizon for each SSP scenario SSP1 (Sustainability), SSP2 (Middle of the Road), and SSP3 (Regional Rivalry) extends to the end of the 21st century, typically around the year 2100. These scenarios are designed as *alternative futures*, not simultaneous realities. Each represents a distinct trajectory based on different assumptions about global cooperation, technological development, and climate policy. SSP1 projects a warming of 1.0–1.4°C, SSP2 projects 2.0–2.4°C, and SSP3 projects 3.0–3.4°C by 2100, with some models projecting even higher values depending on emissions trajectories (Masson-Delmotte et al., 2021). They are used in climate modelling to explore a range of possible outcomes, but only one scenario can unfold in reality. They do not happen simultaneously; instead, they serve as tools to assess how different choices today could shape the future climate and socioeconomic conditions.

Table 4.2 This scenario table is compiled from various literature sources discussing the relationship between climate change and agricultural productivity.

SSP Scenarios	Scenario line	Model and hosting institution	Radiative Forcing	Agricultural Productivity loss
SSP1 Sustainability – The green Road in climate management with low challenges to mitigation and adaptation. The average surface temperature warming ranges from 1 - 1.4°C.	B1 (Lowest)	IMAGE (PBL) SSP1 (Van Vuuren et al., 2016)	RCP 4.5	5%
SSP2 Middle of the road - medium challenges to mitigation and adaptation. A path in which the world follows BAS toward economic, social and technological trends that don't shift significantly from a historic pattern. The average surface temperature warming ranges from $2 - 2.4$°C.	A1B (Moderate)	MESSAGE-GLOBIOM/IIASA SSP2 (Fricko et al., 2016)	RCP 6.0	10%
SSP3 Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation). A path in which the world is concerned about competitiveness and security, regional conflicts push countries to focus on domestic issues. The average surface temperature warming ranges from $3 - 3.4$°C.	A2 (worst)	AIM/CGE (NIES) SSP3 (Fujimori et al., 2016)	RCP 8.5	20%

The SSP2 (Middle of the Road) scenario has been chosen for simulating the impact of climate change on the Egyptian economy because it reflects moderate economic growth, population increase, and technological progress, aligning well with Egypt's current socioeconomic conditions. Combined with RCP6.0, this scenario represents a medium-high emissions pathway consistent with global climate policies that fall short of ambitious mitigation targets (Pörtner et al., 2022). It captures the uncertainties of climate action and enables realistic policy simulations for adaptation and mitigation strategies, making it highly relevant to Egypt's climate and economic planning. Therefore, an estimated reduction of mean annual runoff is anticipated due to the reduction of freshwater availability. We have simulated the impact of a 10% reduction in agricultural productivity due to water availability on total output, value-added, household income, and various sectors of the Egyptian economy. This percentage reduction of water availability in the SAM estimates the effect on the macro-economy. Then, the percentage change in sectoral output, household income and consumption, and value-added indices are evaluated after simulation, offering a hopeful path forward.

4.4.7 Sensitivity Analysis

A sensitivity analysis of Armington elasticity is conducted within the CGE model framework to examine the responsiveness of demand for domestic and imported goods to changes in relative prices. Armington elasticity represents the degree of substitution between domestic and imported goods. It plays a crucial role in determining the impacts of changes in the productivity of natural capital in the agricultural sector. The decline of natural capital in Egypt's agricultural sector would reduce agricultural productivity, resulting in a decrease in domestic agricultural production. Consequently, the relative prices of agricultural products would increase compared to imported agricultural goods. The sensitivity analysis of Armington elasticity helps quantify how consumers and producers respond to changes in prices.

The sensitivity analysis of Armington elasticity used values such as 0.5, 1, 1.5, 2, 3, and 5 to cover a wide range of elasticity levels, ranging from relatively inelastic to highly elastic. This range helps to understand the different degrees of substitution between domestic and foreign goods. The relationship between elasticity and economic outcomes can be non-linear, and using a range of values captures these non-linear effects, providing a more comprehensive understanding of the results' sensitivity. Additionally, these values are commonly used in economic modelling and literature, allowing for better comparison and validation against other studies. They also reflect realistic scenarios for different types of goods and sectors, such as agricultural products having different elasticity than manufactured goods. Lastly, examining these values helps assess the stability and robustness of the model. If the model produces reasonable and stable results across this range, confidence in its reliability increases. These values ensure a detailed and robust examination of how substitution between domestic and foreign goods affects economic outcomes under various scenarios.

Together, these comprehensive analyses provide policymakers with valuable insights for designing strategies that enhance economic resilience and sustainability in Egypt, particularly in the context of climate change, thereby reassuring them of the thoroughness of our research.

4.5 Results and Discussion

This section presents the simulation result of the impact of Climate change-induced agricultural productivity losses on the Egyptian economy. The simulation results reflect the model specification and simulation strategy outlined in section 4.4. The results presented here are the long-run changes in GDP, output prices, exports, labour employment, and household income, which have been assessed to identify the effect of climate change both at the sectoral and aggregate levels. A sensitivity analysis has been conducted to further examine the international competitiveness of the Egyptian economy in response to climate shocks.

4.5.1 Natural Capital Productivity Loss in the Agricultural Sector

This chapter selects the intermediate scenario of Shared Socioeconomic Pathways, assuming an average surface temperature warming between 2 - 2.4$^{\circ}C$ (Pörtner et al., 2022). The simulation results indicate that reductions in natural capital productivity in the agricultural sector have a significant impact on macroeconomic variables. However, one of the key challenges in modelling the impacts of climate change on agriculture is capturing seasonal variations. For example, the consequences of a particularly dry summer or wet winter may not be fully reflected in annual data, potentially underestimating the significance of climate effects. As the model operates on an annual rather than seasonal or quarterly scale, such short-run and intra-annual dynamics are not directly captured in the simulation outcomes.

Despite the temporal limitation of annual aggregation, the simulation results yield critical insights into the macroeconomic repercussions of climate-induced natural capital degradation, particularly water scarcity. As shown in *Table* 4.2, the model estimates a reduction in Egypt's national GDP by 0.53%, signalling a measurable contraction in overall economic output due to diminished agricultural productivity. Concurrently, consumer price inflation (CPI) rises by 0.33% , reflecting increased production costs within the agricultural sector, which are subsequently passed on to consumer prices. More strikingly, the unemployment rate is projected to rise significantly by 8.4%, underscoring the vulnerability of labour markets, especially those dependent on agriculture and related value chains, to environmental stressors.

Furthermore, declining agricultural product demand due to rising prices can weaken the agricultural sector's contribution to Egypt's national GDP. The ripple effects of reduced agricultural productivity result in higher CPI levels, which in turn suppress overall demand for goods and services, amplifying the downward pressure on GDP growth. Overall, climate-induced reductions in natural capital productivity in Egypt's agriculture sector can exacerbate inflationary pressures, increase unemployment, and diminish aggregate demand, posing serious threats to long-term economic stability.

The simulation also shows that natural capital productivity losses in agriculture do not affect real wages or total labour supply, which is consistent with the model's assumption of fixed real wages. Labour mobility is permitted across sectors but not across regions, reflecting the structure of Egypt's labour market and the broader NRB region. This assumption constrains the reallocation of workers from climate-vulnerable agricultural sectors to less-affected sectors or regions. Consequently, employment losses in agriculture due to declining productivity directly translate into higher unemployment rates, as observed in the results.

In the short run, the absence of regional labour migration and the assumption of fixed real wages result in a stable labour supply in the agricultural sector, despite declining productivity. Additionally, the price increase of capital does not significantly alter labour demand, as the elasticity of substitution between labour and capital is assumed to be inelastic *table* 4.1. Nevertheless, persistent reductions in productivity have the potential to adversely affect sectoral output and macroeconomic performance in the long run in Egypt's context, where agriculture employs a large share of the labour force and is a vital contributor to economic output and rural income.

The simulation output further indicates that a 10% reduction in natural capital productivity in the agricultural sector results in a 0.33% decline in the overall capital stock of the Egyptian economy. This reduction has compounding effects on household welfare, as household consumption drops by 0.36%. Analysing the changes in consumer consumption patterns across different channels. A decrease in agricultural productivity and output can result in a decline in household income. Hence, as agricultural income decreases, households relying on agriculture for their livelihood experience lower purchasing power, which, in turn, leads to reduced consumption across all goods and services as the CPI increases. The reduction in agricultural productivity and output resulting from the depletion of natural capital leads to job losses, as evidenced by the rising unemployment rate.

Finally, the decline in natural capital within Egypt's agriculture sector reduces the country's export competitiveness. The model shows a 0.79% decline in exports to the NRB countries and a 1.56% decline in exports to the ROW, respectively. These export contractions stem from increased production costs, which drive up the prices of agricultural and related goods, eroding Egypt's competitiveness in global markets. This underscores how climate-related stressors on water and land can disrupt domestic markets and weaken Egypt's external trade performance, further highlighting the need for robust water and climate resilience strategies within the country's economic planning framework.

These effects are driven by a decline in the productivity of natural capital, primarily water, which is a critical input for agriculture. Reduced water availability disrupts agricultural output, thereby increasing the marginal cost of production. This leads to price inflation for agricultural commodities, reducing their affordability and curbing aggregate demand. The contraction in demand and supply responses further amplifies unemployment, particularly in rural and agrarian regions. These findings highlight the systemic nature of climate impacts, wherein environmental shocks cascade through production networks, prices, and labour markets, ultimately affecting the broader economy. Thus, addressing natural capital degradation, especially water scarcity, is not only an environmental imperative but a macroeconomic necessity.

A 10% decline in agricultural productivity represents the current level of climate mitigation capacity, while the 5% and 20% declines are considered extreme cases. The impact on key economic variables is profound. With a 10% loss in agricultural productivity, GDP decreases by 0.533%, indicating a moderate negative effect on economic output. This decline in productivity also leads to a significant rise in the unemployment rate by 8.374%, reflecting substantial job losses. Exports are heavily affected, with NRB exports declining by 0.794% and exports to the rest of the world decreasing by 1.561%. These reductions in export activity underscore the economy's vulnerability to changes in agricultural productivity. Additionally, household consumption falls by 0.356%, showing a moderate decline in consumer spending, which further dampens economic growth. The Consumer Price Index increases by 0.325%, indicating higher prices and inflationary pressures. These variables underscore the critical importance of maintaining agricultural productivity to ensure economic stability and growth. The extreme cases of 5% and 20% losses illustrate the potential for even more severe economic disruptions, emphasising the need for robust climate mitigation strategies to protect agricultural output and overall economic health.

Similar studies have highlighted the urgency of addressing declines in agricultural productivity caused by climate change. Research from Stanford, Cornell, and the University of Maryland suggests that substantial public sector investment in research and development is necessary to mitigate the adverse effects of climate change on agricultural productivity (Gollin et al., 2025; Lobell et al., 2025).

Table 4.3 A long-run Aggregate effect of Agricultural Productivity Loss

Aggregate Sectors	Long Run Effect - % Change from Base		
	S1: Agricultural Productivity Loss (5%)	S2: Agricultural Productivity Loss (10%)	S3: Agricultural Productivity Loss (20%)
GDP	-0.443	-0.533	-2.251
Consumer Price Index	0.088	0.325	2.725
Unemployment Rate	3.758	8.374	24.845
Employment	-0.279	-0.441	-0.785
Nominal Gross Wage	0.759	0.325	-0.363
Real Gross Wage	0.000	0.000	0.000
Labour Supply	0.000	0.000	0.000
Capital Stock	0.000	-0.325	-2.330
Household Consumption	-0.97	-0.356	-0.712
Export NRB	-0.241	-0.794	-2.664
Export ROW	-0.630	-1.561	-3.564
Export Tot	-0.766	-1.556	-5.732

Notes: The Table shows a long-run impact of a 5%, 10% and 20% reduction of capital productivity in the agricultural sectors. This shock happened in one sector and was reflected in the entire economy. As a result, key economic sectors such as GDP, unemployment, and exports have shown a significant response to these shocks. Egypt's current capacity for climate mitigation aligns with the middle-case scenario (10% reduction). The country faces challenges in funding climate resilience and sustainability efforts due to economic struggles (Khalil and Hamzawy, 2025). However, measures such as modern irrigation techniques and wastewater reuse have been implemented to improve water efficiency (Mostafa et al., 2021). Despite these efforts, Egypt's ability to fully mitigate the impacts of climate change remains limited, necessitating further investment in green projects and regional cooperation (Mantlana et al., 2022).

Macroeconomic Impacts of Agricultural Productivity Loss under Climate Scenarios

Figure 4.3 visually presents simulation results for a range of macroeconomic indicators under three scenarios of agricultural productivity loss (5%, 10%, and 20%) due to climate change-induced natural capital degradation, specifically water scarcity in Egypt. This section presents a critical analysis of the results, drawing on previous literature to provide a deeper understanding of the impact of climate change on Egypt's economy. These graphs illustrate the sensitivity of key macroeconomic variables to varying degrees of productivity shocks, offering an insightful understanding of the cascading impacts such losses have across the economy.

The GDP graph shows a progressive decline from Scenario 1 to Scenario 3. A 5% reduction in agricultural productivity results in a GDP loss of approximately 0.5%, which steepens dramatically to around 2.2% in Scenario 3 (20% loss). This non-linear response reflects the compounding of negative feedback loops in the economy as agricultural productivity continues to decline. The steeper decline after Scenario 2 suggests that the economy becomes increasingly vulnerable as the shock intensifies, possibly due to the exhaustion of buffers within the economic system. Similar findings are reported in studies by Hertel et al. (2010), which emphasise the strong linkage between agricultural productivity and overall economic output in agrarian economies.

The CPI increases steadily across scenarios, with a notable acceleration in Scenario 3. This is expected, as reduced agricultural output leads to higher food prices due to supply shortages. Given Egypt's heavy reliance on agriculture for food production and consumption, this leads to inflationary pressures. This pattern aligns with Nelson et al. (2009), who observed that climate-induced yield losses tend to be inflationary, especially in food-importing, water-stressed economies. Mirroring the unemployment trend, the employment rate declines more sharply with each scenario. From a modest drop in Scenario 1, the rate falls considerably in Scenario 3. This is consistent with the structural dependence of Egypt's labour market on agriculture and the limited inter-sectoral labour mobility within the CGE framework. Nominal gross wages show a declining trend, particularly evident between Scenarios 2 and 3. As unemployment rises and labour demand falls, wage levels are suppressed. This reflects labour market saturation, which causes downward pressure on wages despite the model's fixed real wage assumptions. This also echoes the findings in Deaton and Laroque (2003) that wage rigidity often delays full labour market adjustment in low-income settings.

The contraction in capital stock across all three scenarios, most notably under Scenario 3, where it declines by nearly 3%, highlights the decline in investment confidence as agricultural productivity weakens. This reflects reduced profitability in agriculture and related sectors, shrinking incomes, and growing investor uncertainty in the face of climate-induced water stress. Such trends are consistent with Dell et al. (2012), who demonstrate that temperature shocks negatively impact investment and capital accumulation, particularly in low-income, agriculture-dependent economies like Egypt. Similarly, Burke et al. (2015) report non-linear effects of rising temperatures on capital productivity and economic growth, with more severe impacts in countries that rely heavily on climate sensitive sectors. In parallel, household consumption shows a kinked pattern: an initial drop in Scenario 1, a modest recovery in Scenario 2, potentially due to temporary consumption smoothing through savings or credit and a further decline in Scenario 3 as sustained income losses and price inflation overwhelm household coping mechanisms. This trajectory aligns with Ahmed et al. (2009), whose CGE analysis shows that while households can temporarily adjust to climatic shocks, their resilience erodes with prolonged exposure. Hallegatte et al. (2016) similarly emphasises that repeated climate-related disruptions eventually reduce household welfare and limit their ability to maintain consumption, especially in economies facing food and water insecurity.

Exports to both the NRB and the RoW show a steady decline, more severe in Scenario 3, with RoW exports contracting by nearly 4%. This can be attributed to two factors: first, the reduction in surplus agricultural products available for export; second, the increase in domestic prices, making Egyptian products less competitive internationally. These patterns are consistent with findings from the World-Bank (2016), which underscore how climate change can reduce trade competitiveness in water-stressed economies.

The kinked or non-linear transitions between Scenario 2 and Scenario 3 across most variables indicate threshold effects—points beyond which the economic system's response becomes disproportionately negative. This reinforces the need to adapt agricultural systems and invest in water-efficient technologies. Overall, these results underscore the systemic vulnerabilities of Egypt's economy to water-induced productivity losses in agriculture, validating broader concerns in the climate-economy literature regarding food security, inflation, and economic resilience in the face of climate shocks.

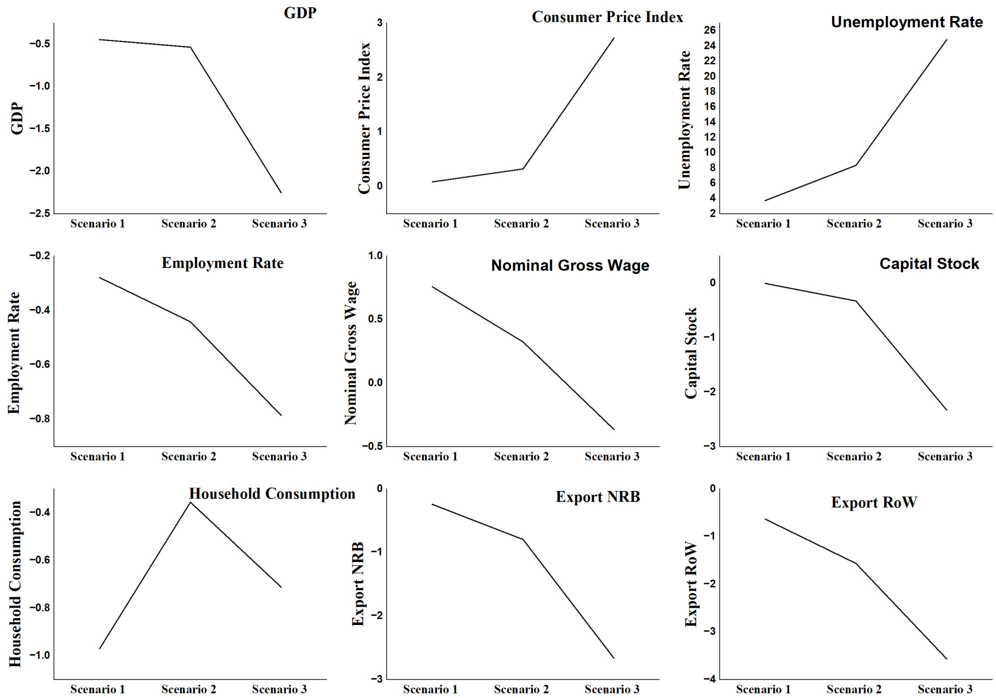


Fig. 4.3 Aggregate Sectoral change under 3 Scenarios

4.5.2 Sectoral effect of productivity reduction in agricultural

The 10% natural capital productivity loss in Egypt's agricultural sector reveals varying substantial effects on different sectors of the Economy, highlighting the degree of change to output prices, exports, and employment.

Regarding output prices, agriculture prices increase by 4.47%. The output price increment cascades through the sectors reliant on agricultural outputs, with the food and beverage, Hotel, and restaurant sectors most impacted, as well as the Education, health, and other services sectors.

On the export side, the impacts are highly negative across all sectors, demonstrating a reduction in export volume due to decreased agricultural productivity and damage to the competitiveness of Egyptian products. It has been shown that agriculture is the most severely affected sector, with exports falling by 8.37%. This is followed by the food and Beverage, textile, and other manufacturing sectors, each experiencing an export reduction ranging between 0.48% and 2.21%. As global prices remain unchanged, the increase in output prices across various sectors further exacerbates the challenge of maintaining competitiveness in the international market. With higher production costs, Egyptian exporters face a competitive price challenge for their products compared to counterparts from other countries.

The effect on employment is also evident, as declines have been observed in various economic sectors. Agriculture suffers the most, with an extensive 3% loss in employment, followed by the wholesale trade, Electricity, Gas, and water, and Transport sectors, each of which experienced an employment reduction ranging from 0.42% to 0.56%. These reductions imply a challenge to the labour market arising from diminishing agricultural productivity and its subsequent effects on employment-intensive sectors. As natural capital in agriculture is depleted, there is a notable shift in the capital-labour substitution dynamic within the Economy. The decline in agricultural productivity necessitates reallocating resources, with firms substituting labour for capital to maintain production levels. This shift is particularly pronounced in sectors heavily reliant on agricultural inputs, such as wholesale trade and transport, where labour-intensive activities are widespread. Consequently, the observed reductions in employment underscore the structural adjustments within the labour market as it responds to changes in the availability of natural capital and productivity in the agricultural sector.

Generally, the 10% reduction in natural capital productivity in Egyptian agriculture resonates throughout the Economy, leading to increased output prices, reduced export volumes, and declining employment across various sectors. The significant reductions in agricultural exports, predominantly in the agricultural sector itself, highlight the vulnerability of Egyptian export-oriented industries to natural capital depletion in the agricultural sector. These findings underscore the importance of sustainable agricultural practices and adaptation strategies in mitigating the adverse economic impact of Climate change-induced natural capital loss in Egypt.

Table 4.4 A long-run Sectoral effect of a 10% decline in the Natural Capital productivity in agriculture

Sectors	Long Run Sector effect		
	Output Price	Export	Employment
Agriculture	4.469	-8.373	-2.998
Fishing	0.239	-0.476	-0.840
Mining and Quarrying	0.174	-0.347	-0.514
Food & Beverages	1.125	-2.212	-0.777
Textiles and Wearing Apparel	0.311	-0.619	-0.574
Wood and Paper	0.412	-0.819	-0.670
Petroleum, Chemical and Non-Metallic Mineral Products	0.194	-0.387	-0.607
Metal Products	0.182	-0.362	-0.593
Electrical and Machinery	0.190	-0.380	-0.479
Transport Equipment	0.186	-0.372	-0.417
Other Manufacturing	0.224	-0.447	-0.472
Recycling	0.194	-0.387	-0.385
Electricity, Gas and Water	0.186	-0.372	-0.559
Construction	0.219	-0.436	-0.459
Maintenance and Repair	0.210	-0.418	-0.480
Wholesale Trade	0.201	-0.401	-0.550
Retail Trade	0.220	-0.439	-0.412
Hotels and Restaurants	0.368	-0.733	-0.431
Transport	0.208	-0.416	-0.557
Post and Telecommunications	0.210	-0.418	-0.453
Financial Intermediation and Business Activities	0.214	-0.427	-0.479
Public Administration	0.242	-0.481	-0.139
Education, Health and Other Services	0.242	-0.483	-0.339
Private Households	0.237	-0.472	-0.380
Others	0.204	-0.407	-0.549

The *figure* 4.4 below illustrates the central scenario, which reflects Egypt's current capacity for climate change mitigation. It captures the country's ongoing efforts and limitations in addressing climate-related challenges, providing a baseline for evaluating potential policy interventions and adaptation strategies. In this context, a 10% loss in agricultural productivity can have profound and far-reaching impacts on various sectors of the economy. This reduction in productivity leads to increased costs for agricultural products, which, in turn, drives up prices in the food and beverage sector as producers pass on the higher costs to consumers. The agricultural export sector is directly affected, with a likely decrease in export volumes due to reduced output, which will impact trade balances and economic stability. Employment in the agricultural sector may decline as farmers struggle with lower productivity and profitability, leading to potential job losses and economic hardship for workers. Additionally, sectors reliant on agricultural inputs, such as food processing and manufacturing, may experience disruptions in production and increased costs, which in turn further affect employment and economic performance. These interconnected effects underscore the critical importance of maintaining agricultural productivity to ensure economic stability.

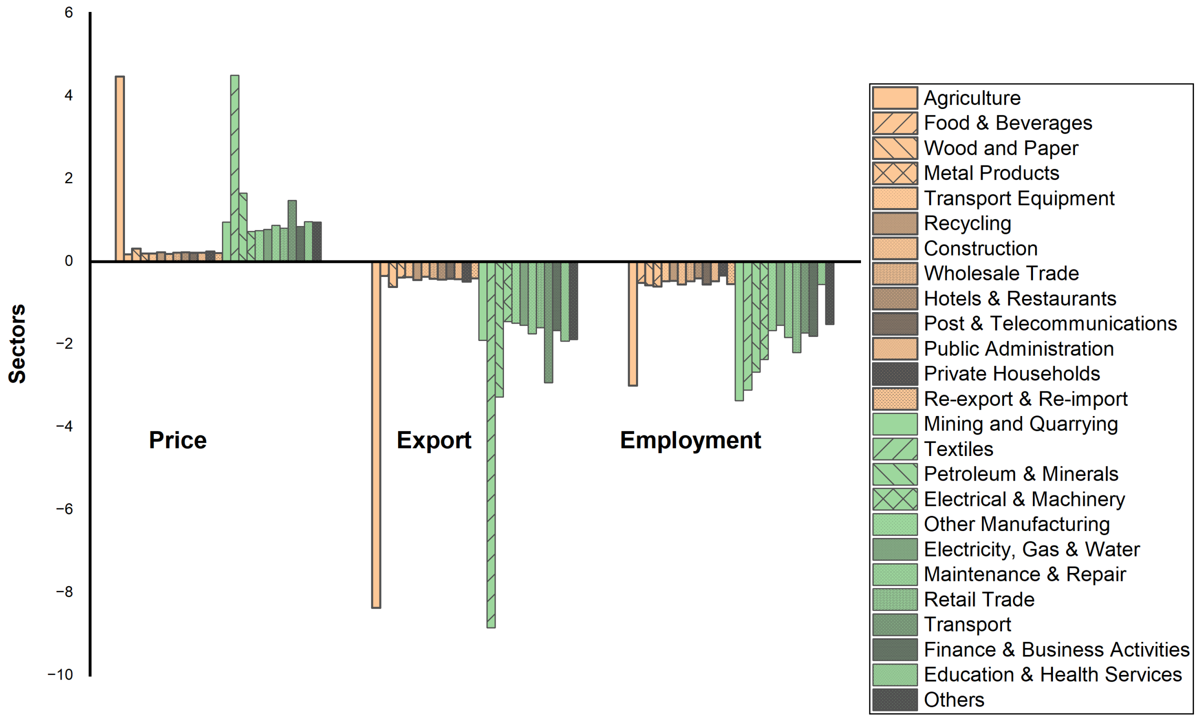


Fig. 4.4 Long Run Effect of Sectoral changes under central scanerio

4.5.3 Sensitivity Analysis of Armington Elasticity

The sensitivity analysis of Armington elasticity in response to a 10% reduction in natural capital productivity within the Egyptian agricultural sector provides valuable insights into the potential implications of various economic indicators. As the Armington elasticity σ increases from 0.5 to 5, a distinct trend effect emerges across all aggregate sectors. These elasticity ranges were chosen to represent realistic scenarios for different types of goods and sectors, such as agricultural products having different elasticity than manufactured goods. Lastly, examining these values is a thorough process that helps us assess the stability and robustness of the model. If the model consistently produces reasonable and stable results across this range, confidence in its reliability increases. This thorough examination ensures a detailed and robust understanding of how substitution between domestic and foreign goods affects economic outcomes under various scenarios.

The results in *Table* 4.5 show the significant impact of changes in Armington elasticity on GDP and the consumer price index (CPI) following the decline in natural capital productivity in the agricultural sector. As the elasticity of substitution increases, indicating a higher degree of substitutability between domestic and imported goods, there is a consistent decline in GDP across all values. This decline ranges from 0.44% when the elasticity σ is 0.5 to 0.71% when σ equals 5. This trend underscores the sensitivity of GDP to changes in consumer preferences and the relative size of the price increase resulting from reduced agricultural productivity.

In terms of exports to the Nile River Basin (NRB) and the Rest of the World (RoW), there is a substantial reduction as the Armington elasticity rises. The export to NRB declines from 0.80% to 0.78%, while the export to RoW decreases from 1.58% to 1.53%. Similarly, the overall Egyptian export dropped, ranging from 1.57% at $\sigma = 0.5$ to 1.53% at $\sigma = 5$, demonstrating a significant reduction in Egypt's overall export volumes.

Table 4.5 Sensitivity Analysis of Armington Elasticity

Sectors	Armington Elasticity (σ)				
	$\sigma = 0.5$	$\sigma = 1.0$	$\sigma = 2.0$	$\sigma = 3.0$	$\sigma = 5.0$
GDP	-0.442	-0.472	-0.533	-0.592	-0.711
Consumer Price Index	0.329	0.328	0.325	0.323	0.318
Unemployment Rate	6.791	7.319	8.374	9.426	11.516
Employment	-0.357	-0.385	-0.441	-0.496	-0.606
Nominal Gross Wage	0.329	0.328	0.325	0.323	0.318
Real Gross Wage	0.000	0.000	0.000	0.000	0.000
Labour Supply	0.000	0.000	0.000	0.000	0.000
Capital Stock	-0.229	-0.261	-0.325	-0.388	-0.514
Household Consumption	-0.330	-0.338	-0.356	-0.373	-0.407
Export NRB	-0.803	-0.800	-0.794	-0.788	-0.776
Export ROW	-1.576	-1.571	-1.561	-1.551	-1.531
Overall Export	-1.570	-1.566	-1.556	-1.546	-1.526

Notes: A sensitivity analysis of Armington elasticity has been carried out to determine how the major macroeconomic sectors respond to changes to their two levels above and below the current level.

4.6 Conclusion

In this chapter, we utilised a CGE to assess the economy-wide impacts of climate change-induced agricultural productivity losses in Egypt's agricultural sector. Our analysis reveals significant effects on Egyptian macroeconomic variables, including a 0.53% reduction in GDP, a 0.33% increase in the consumer price index, and a notable 8.4% rise in the unemployment rate compared to the base scenario. These findings underscore the severity of the economic downturn resulting from a 10% reduction in natural capital's productivity in the agricultural sector, representing a departure from where the country would have been without the shock. With its robust methodology, this research is a valuable resource for policymakers, economists, and researchers interested in climate change and its effects on macroeconomic variables. These effects are intricately linked to the depletion of natural capital, particularly in terms of water availability, which has a direct impact on agricultural productivity. The consequences extend beyond the agricultural sector, with knock-on effects observed across related industries, including food processing, transportation, and retail. Agriculture is a significant pillar of Egypt's Economy, contributing approximately 12% to the national GDP and 20% to total exports (Kassim et al., 2018). The impact of global pollution on Egypt's climate situation, including erratic rainfall patterns and rising temperatures, further intensifies these challenges and underscores the urgent need for sustainable practices and adaptation strategies to mitigate the devastating economic consequences.

The analysis delves into the sectoral effects of reduced natural capital productivity, revealing significant impacts on output prices, exports, and employment across various economic sectors. Agriculture experiences a substantial price increment of 4.47%, reflecting the reduced supply of agricultural products due to climate-induced challenges. This results in cascading effects on other sectors, with food, beverage, Hotel and restaurant, Education, health, and other services also experiencing noticeable price hikes. The reduction in agricultural productivity affects domestic consumption patterns and leads to a decline in Egyptian global competitiveness, particularly in agricultural exports. The sensitivity analysis, particularly Armington elasticity, further highlights the complex interplay of economic factors amidst climate-induced challenges, emphasising the necessity of a comprehensive policy framework. The CGE model provides a comprehensive framework for understanding the interconnection between climate change and the Economy, which underlines the essence of an integrated policy response to climate change.

The simulation results highlight the vulnerability of Egypt's Economy to climate-induced loss of natural capital in the agricultural sector. The adverse impacts on GDP, unemployment, consumer price index, and export volumes underscore the urgent need for proactive policy measures. With rising temperatures and erratic rainfall patterns, climate change is primarily responsible for these challenges. These environmental factors lead to soil erosion, salinisation, and desertification, depleting essential soil nutrients and moisture retention capacity. Insufficient water usage and climate-related water shortages have a significant impact on the agricultural sector, which heavily relies on irrigation (Furtak and Wolińska, 2023). The excessive depletion and pollution of water sources reduce water availability, which in turn adversely impacts crop yields and soil quality. To address these issues, promoting climate-resilient farming practices, investing in efficient irrigation systems, and supporting farmers in adopting eco-friendly farming practices are essential to mitigate the economic repercussions of resource depletion and build a more resilient agriculture sector.

To improve Egypt's trade performance in the face of climate-induced challenges, it is imperative to adopt a multifaceted approach that mitigates the impacts of climate change on agricultural productivity. Prioritising investments in research and development for renewable energy and climate adaptation technologies will be crucial. These efforts can lower production costs and enhance the resilience of the agricultural sector, thereby improving international competitiveness. Promoting sustainable agricultural practices, such as using climate-resilient crop varieties and efficient irrigation systems, will help preserve natural capital and optimise resource use. By addressing these climate-related challenges, Egypt can reinforce its agricultural output, stabilise trade volumes, and secure a more robust position in the global market.

The CGE model clarifies the complex relationship between the environment and the Egyptian macroeconomy, particularly in the context of adverse climate scenarios (Berthe et al., 2023). As a modelling framework, it offers a structured approach to understanding how changes in environmental factors, such as water reduction, resonate through the economy. By simulating these scenarios, the CGE model allows us to assess how variations in natural capital productivity impact key macroeconomic indicators, including GDP, CPI, and unemployment rates. This capability is particularly valuable, as it enables an empirical exploration of these relationships, providing insights that can inform policy decisions and adaptive strategies to mitigate climate risks.

Chapter 5

Conclusions

5.1 Thesis' Summary and Key Findings

This thesis examines the adverse impacts of climate change on the economies of NRB countries, with a focus on price volatility, virtual water flows in international trade, and the economic consequences of water scarcity. The study utilises secondary data from reputable sources for each chapter, addressing the challenges posed by the lack of replicable data in the developing world. To overcome these challenges, alternative sources such as FAO, NOAA, Eora, World Bank, and IMF were employed, along with a few datasets collected from NRB, including the national income account. The research employs various analytical methodologies, including econometrics, multi-regional input-output analysis, and Computable General Equilibrium, demonstrating a comprehensive exploration of economic analysis methods.

This research is structured around three core areas, each addressing specific gaps identified in the existing literature. Together, they contribute new insights to the broader academic debate. First, the study examines the multifaceted impacts of weather shocks on domestic food prices in East Africa, making a significant contribution to the existing literature by incorporating behavioural market mechanisms and building on the foundational work of Bellemare (2015) and Kakpo et al. (2022), which primarily emphasised production-side effects, the study introduces a trader anticipation model. This model captures how market agents adjust expectations in response to climate signals, revealing that food prices respond non-linearly to weather anomalies. Anticipated effects, particularly under erratic rainfall and rising temperatures, amplify price volatility, especially for staple crops such as maize, teff, and sorghum. For instance, a one standard deviation decline in seasonal rainfall can trigger price spikes of up to 12% during drought years, with the effects most severe in regions with poor storage infrastructure and fragmented markets. The study also explores the role of export restriction policies, extending the insights of Anderson and Nelgen (2012) by examining their interaction with climatic conditions. Regression results show that while export restrictions alone can increase food price volatility by up to 30%, their coordination with favourable rainfall or domestic support measures—such as targeted subsidies or public grain reserves can mitigate price spikes by approximately 5%. This highlights that the effectiveness of such policies is highly context-dependent and contingent on concurrent climate conditions, a nuance often overlooked in earlier analyses. Moreover, the findings align with recent evidence from the Global Report on Food Crises (2025), which underscores how climate extremes and policy missteps are jointly driving acute food insecurity across the region (FSIN and GNAFC, 2025). Similarly, recent panel data from Uganda confirms that weather shocks significantly undermine food security, particularly among smallholder households, reinforcing the need for integrated climate and market stabilisation strategies (Hübler et al., 2025). These insights collectively suggest that food price dynamics in East Africa are shaped not only by supply shocks but also by speculative trader behaviour and policy responses, necessitating a more holistic approach to food system resilience.

The second part of the study assesses virtual water flows in the Nile River Basin (NRB) using a multi-regional input-output (MRIO) framework extended with water accounts, addressing a critical gap left by global-level analyses such as Hoekstra and Chapagain (2007) and Mekonnen and Hoekstra (2011). While these foundational studies have shaped the virtual water discourse, they often overlook basin-specific vulnerabilities and asymmetries. By focusing on the NRB, this research reveals that the region remains a net exporter of virtual water to Europe, Asia, and North America, despite facing acute water scarcity. This challenges the optimistic assumption in earlier literature that trade inherently mitigates local water stress, instead advocating for a more region-sensitive and sustainability-oriented trade policy. The study further distinguishes between green, blue, and gray water types, emphasising the underestimated opportunity costs of blue water use in agriculture. This distinction reinforces the importance of incorporating water sustainability into international trade agreements. Empirical findings indicate that over 50% of the NRB's virtual water footprint is exported through trade in water-intensive commodities such as cereals, vegetables, and livestock. Upstream countries, such as Ethiopia, disproportionately contribute to these exports, reflecting both their agricultural potential and the lack of coordinated regional water governance. A 10% increase in virtual water exports from the NRB results in an estimated 0.8% increase in regional water stress, as more water is allocated to the production of export-oriented agricultural goods. This exacerbates local scarcity, particularly in upstream countries such as Ethiopia and South Sudan, where water-intensive production is highest and infrastructure is limited. The finding highlights the trade-off between export-driven growth and sustainable water use in transboundary basins. Recent studies support these findings. For instance, Abtew (2025) highlights how the hydro-politics of green, blue, and virtual water in the Nile Basin are increasingly central to debates over equitable water sharing, especially in the context of the Grand Ethiopian Renaissance Dam. Similarly, new evidence from the Nile Basin Initiative underscores the strategic importance of balancing virtual water exports with domestic water security, particularly under climate stress and population growth (Sallam, 2014). These insights suggest that strengthening intra-regional agricultural trade and improving water-use efficiency are essential for reducing dependency on volatile global markets and enhancing long-term water resilience in the NRB.

The third component of the study investigates the economy-wide impacts of climate change-induced agricultural productivity losses in Egypt using a dynamic CGE model. This approach builds on earlier macroeconomic analyses by Hertel et al. (2010) and Solomon et al. (2021), but advances the literature by explicitly embedding water as a direct production factor within the Egyptian SAM, a dimension often abstracted away in prior models. By jointly modelling water scarcity and productivity shocks, the study reveals that agricultural output contraction, declining household incomes, rising unemployment, and deteriorating trade balances are significantly intensified. Unlike traditional CGE models that assume uniform sectoral impacts, this research uncovers substantial intra-sectoral heterogeneity, with water-intensive sectors experiencing disproportionate losses. Scenario simulations aligned with IPCC projections show that a 5% to 20% decline in agricultural productivity driven by salinisation, heat stress, and reduced water availability in the Nile Delta could reduce Egypt's GDP by between 0.5% and 2.25% annually. Over a decade, cumulative GDP losses are projected to range from $10billionto47$ billion. These shocks also contribute to inflationary pressures through rising food prices and widen Egypt's trade deficit. However, the study demonstrates that strategic investments in climate-resilient agriculture, such as drought-tolerant crop varieties and improved irrigation infrastructure, can substantially mitigate these economic losses. These findings are consistent with recent global reviews, such as Yuan et al. (2024), which emphasise the direct and indirect pathways through which climate change affects agricultural systems, including altered precipitation patterns and increased frequency of extreme weather events. Additionally, Tanveer and Kalim (2024) highlights the nonlinear and region-specific impacts of climate change on agricultural productivity, reinforcing the need for tailored adaptation strategies. Together, these insights affirm the urgency of integrating water sustainability and climate resilience into Egypt's economic planning.

Across the three components of this research, the study contributes novel theoretical models, basin-specific empirical evidence, and dynamic economy-wide simulations that deepen our understanding of how climate change affects food markets, water resources, and macroeconomic stability. Nonetheless, several research gaps remain. Future studies should explore micro-level trader behaviour under varying climate information scenarios, refine MRIO analyses by disaggregating virtual water flows across global regions, and develop dynamic CGE models capable of capturing the cumulative and progressive nature of climate impacts. Policy recommendations include establishing market early warning systems, incorporating virtual water metrics into regional trade negotiations, and prioritising adaptive agricultural investments to build long-term economic resilience.

5.2 Policy Recommendation

A critical and comprehensive policy recommendation emerging from this thesis is the establishment of an NRB Climate-Economy Resilience Pact, spearheaded by NRB countries, to address the multidimensional impacts of climate change on food price volatility, virtual water flows, and agricultural productivity losses. This pact should integrate climate, trade, and water governance policies under a shared regional strategy, reflecting the intertwined nature of economic and ecological vulnerabilities explained by this research. The thesis critically addresses a significant gap in policy and literature: the absence of a coordinated mechanism to monitor and regulate grain trade behaviours in East Africa, particularly the role of speculative activities and weather-induced trader anticipation in destabilising staple food markets. While prior studies, for example Minot (2014); Tadesse et al. (2014), have highlighted food price volatility, they have largely neglected the micro-behavioural dimensions of traders responding to climate variability, an insight this thesis contributes through econometric analysis.

Therefore, a central policy recommendation is the creation of a regional food price intelligence and early warning system, supported by real-time climate and trade data, to monitor speculative patterns and ensure transparent and competitive grain markets. Such a platform should be coupled with regulatory reform targeting trader cartels and oligopolistic structures, utilising digital technologies like blockchain to track food movements and transactions. This will reduce price shocks, strengthen market fairness, and protect vulnerable populations from food insecurity.

In terms of virtual water, the thesis exposes a critical imbalance in global trade, where NRB countries are net exporters of water-intensive and low-value-added agricultural commodities to high-income regions, depleting their scarce water resources. Existing studies for instance Allan (2003); Hoekstra and Chapagain (2008) have identified the concept of virtual water but fail to engage with its implications in internal African trade or global climate agreements. This research fills that void by applying MRIO models to quantify these flows and demonstrate their economic impacts. Based on this, it is imperative that virtual water accounting be embedded into national and regional trade agreements, guiding both internal African commerce and global negotiations. NRB countries must adopt a water-sensitive trade policy, promoting the import of water-intensive goods from water-abundant regions and reducing dependency on exporting such goods themselves. This policy shift would help preserve ecological capital, realign trade with sustainability goals, and strengthen long-term water security.

To cushion economies against climate-induced agricultural productivity losses evident from the CGE analysis of Egypt, governments must implement coordinated, long-term adaptation strategies that reach beyond the farm level. While existing literature, such as Nelson et al. (2010) and Hertel et al. (2010), often overlooks the broader macroeconomic consequences of climate shocks, this study fills that gap by quantifying the cascading effects on GDP, employment, trade, and household income. Our findings underscore the need for cross-sectoral action: investing in water-saving technologies, scaling up climate-resilient seeds, and strengthening support for smallholder farmers. A key policy recommendation is the establishment of a National Agricultural Adaptation Council to integrate planning across ministries, direct climate finance to vulnerable sectors, and embed economic resilience strategies into Egypt's Nationally Determined Contributions (NDCs). This approach protects rural livelihoods and stabilises national economies amid rising climate uncertainty. Moreover, NRB countries must take a more assertive and unified stance in international climate change negotiations, particularly at UNFCCC conferences and other global forums. The thesis highlights that, although African countries are among the least responsible for global emissions, they bear a disproportionate share of climate impacts, particularly in the water and food systems. To correct this inequity, NRB countries should advocate for recognising virtual water imbalances and climate-induced economic losses in climate finance mechanisms. They should push for compensatory measures, including climate adaptation funding, technology transfers, and preferential access to resilient agricultural innovations. These positions should be supported by empirical evidence, such as that presented in this thesis, which demonstrates GDP losses, employment disruptions, and risks of food insecurity.

Ultimately, the thesis emphasises the importance of transforming agriculture into a climate-resilient sector, particularly in countries like Egypt, where agriculture plays a pivotal economic role. This transformation requires targeted public investments in agricultural R& D, support to smallholder farmers, climate-resilient infrastructure, and capacity-building for adaptive farming practices. A regional Agricultural Climate Innovation Fund, co-financed by national governments and international donors, could drive these interventions.

In summary, the thesis fills key gaps in the understanding of the economic effects of climate change on the NRB and provides evidence-backed, actionable, and regionally relevant policy recommendations. These range from regulating grain market behaviour and incorporating virtual water into trade policy to enhancing the voice of NRB in global climate negotiations, framing climate resilience as both an environmental concern and an issue of economic sovereignty and social justice.

5.3 Future Research Directions

This thesis has laid the groundwork for understanding the adverse effects of climate change on the economies of NRB countries; however, several areas require further investigation to build on these findings and address the remaining gaps.

Firstly, the analysis of food price volatility in East Africa focused on the role of trader anticipation. Future research should investigate additional domestic factors that contribute to regional food price volatility and economic stability. Investigating how the grain market structure influences food price volatility due to weather shocks could provide valuable insights. Comparative analysis of market concentration and its impact on price surges would be beneficial. Additionally, assessing the long-term effects of climate change trends on food prices in Africa is crucial. Modelling the projected impacts of changing rainfall patterns can help forecast future risks and identify potential adaptation needs to maintain price stability.

Secondly, the study of virtual water flows highlighted the significant role of international trade in water resource management. Future research should delve deeper into the impact of global trade arrangements on national and international water policies. Specifically, examining how water scarcity influences international trade dynamics in water-scarce countries could provide critical insights. Studies should strategically incorporate virtual water flow experiences analysis in global and regional contexts to develop effective water policy frameworks.

Thirdly, while this thesis focused on the agricultural sector, the broader economic impacts of climate change on water resources need further exploration. Future research should investigate the effects of climate change on sectors such as tourism, labour productivity, migration, and the rigidity of economic structural transformation in Africa. Understanding how global warming affects these areas will provide a more comprehensive view of climate change's economic implications.

Finally, climate-economic modelling must be advanced by incorporating high-frequency climate data and predictive analytics to improve the responsiveness of CGE and MRIO frameworks. Interdisciplinary approaches that combine economics, climate science, and policy design will also be crucial for developing adaptive strategies that reflect the region's complex vulnerabilities.

References

Abawari, Y. M. (2011). Conflict and cooperation among the nile basin countries with special emphasis on the nile basin initiative (nbi). *Journal of African and International Relations*, 5(2):14–19.

Abbott, P. and Borot de Battisti, A. (2011). Recent global food price shocks: Causes, consequences and lessons for african governments and donors. *Journal of African Economies*, 20(suppl_1):i12–i62.

Abd-Elhamid, H. and Abd-Elaty, I. (2017). Application of a new methodology (trad) to control seawater intrusion in the nile delta aquifer, egypt. In *Proceedings of the Solutions to Water Challenges in MENA Region Proceedings of the Regional Workshop, Cairo, Egypt*, pages 25–30.

Abeysekara, W. C. S. M., Siriwardana, M., and Meng, S. (2024). Economic consequences of climate change impacts on south asian agriculture: A computable general equilibrium analysis. *Australian Journal of Agricultural and Resource Economics*, 68(1):77–100.

Abtew, W. (2025). The hydro-politics of green, blue, virtual water and water footprint in the nile basin. In *Nile Water Conflict and the Grand Ethiopian Renaissance Dam*, pages 119–131. Springer.

Adjemian, M. K. (2012). Quantifying the wasde announcement effect. *American Journal of Agricultural Economics*, 94(1):238–256.

Aerts, S., Stracca, L., and Trzcinska, A. (2024). Measuring economic losses caused by climate change. Centre for Economic Policy Research (CEPR), published on 2024-10-02.

Ahmad, B., Badar, H., Gjølberg, O., and Mehdi, M. (2024). Price volatility and food security: Measurement and implications. *Food Security in the Developing World*, 12(2):165–189.

Ahmed, M. T. and Hefny, M. (2001). Climate change and tourism an egyptian perspective mohamed tawfic ahmed* and manal hefny suez canal university ismailia, egypt. Ismailia, Egypt.

Ahmed, S. A., Diffenbaugh, N. S., and Hertel, T. W. (2009). Climate volatility deepens poverty vulnerability in developing countries. *Environmental Research Letters*, 4(3):034004.

Aker, J. (2010). Information from markets near and far: Mobile phones and agricultural markets in niger. *American Economic Journal: Applied Economics*, 2:46–59.

Allan, G., Comerford, D., and McGregor, P. (2018). Towards incorporating natural capital into a computable general equilibrium model for scotland.

Allan, G., De Fence, J., Eromenko, I., Lim, A., Gilmartin, M., McGregor, P. G., Swales, J. K., and Turner, K. (2008a). *The impact on the Scottish economy of reducing greenhouse gas emissions in Scotland: Illustrative findings from an experimental computable general equilibrium model for Scotland: Final Report October 2008*. The Scottish Government.

Allan, G. and Gilmartin, M. (2011). The regional employment impacts of renewable energy expenditures: The case for modelling. Working Paper 11-29, University of Strathclyde.

Allan, G. J., Bryden, I., McGregor, P. G., Stallard, T., Swales, J. K., Turner, K., and Wallace, R. (2008b). Concurrent and legacy economic and environmental impacts from establishing a marine energy sector in scotland. *Energy Policy*, 36(7):2734–2753.

Allan, J. (1998). Watersheds and problemsheds: Explaining the absence of armed conflict over water in the middle east. *Middle East Review of International Affairs*, 2:49.

Allan, J. A. (1994). Overall perspectives on countries and regions. *Rogers, P. and Lydon, P. Water in the Arab World: perspectives and prognoses, Harvard University Press, Cambridge, Massachusetts*, pages 65–100.

Allan, J. A. (2003). Virtual water eliminates water wars? a case study from the middle east. pages 137–145.

Allan, J. A. et al. (1993). Fortunately there are substitutes for water otherwise our hydro-political futures would be impossible. *Priorities for water resources allocation and management*, 13(4):26.

Alsharhan, A. S., Rizk, Z. E., Alsharhan, A. S., and Rizk, Z. E. (2020). Water resources and water demands in the uae. *Water Resources and Integrated Management of the United Arab Emirates*, pages 757–791.

An, Q., Wu, S., Li, L., and Li, S. (2021). Inequality of virtual water consumption and economic benefits embodied in trade: a case study of the yellow river basin, china. *Water Policy*, 23(6):1445–1467.

Andersen, P. P. (2015). *The Political Economy of Food Price Policy*. Oxford University Press.

Anderson, K. (2009). *Distortions to Agricultural Incentives*. World Bank, Washington, DC.

Anderson, K. and Nelgen, S. (2012). Trade barrier volatility and agricultural price stabilization. *World Development*, 40(1):36–48.

Arjen, Y. H. and Ashok, K. C. (2007). The water footprints of morocco and the netherlands: Global water use as a result of domestic consumption of agricultural commodities. *Science Direct*.

Arjen, Y. H. and Ashok, K. C. (2008). Globalization of water sharing the planet's freshwater resources. *Blackwell Publishing*.

Armington, P. S. (1969). A theory of demand for products distinguished by place of production (une théorie de la demande de produits différenciés d'après leur origine)(una teoría de la demanda de productos distinguiéndolos según el lugar de producción). *Staff Papers-International Monetary Fund*, pages 159–178.

Arndt, C., Tarp, F., and Thurlow, J. (2015). The economic costs of climate change: a multi-sector impact assessment for vietnam. *Sustainability*, 7(4):4131–4145.

Asafu-Adjaye, J. (1996). Revitalising growth in papua new guinea's agricultural sector. *Agricultural systems*, 51(3):299–316.

Ashton, P. J. (2002). Avoiding conflict over africa's water resources. *A journal of Human Environment, Ambio*, 31(3):236–242.

Assefa, T., Yimer, F., and Tefera, A. (2021). Climate change impacts on farming communities: Advocating adaptation strategies to mitigate vulnerability. *Climate Risk Management*, 25:45–55.

Aulerich, N. M., Irwin, S. H., and Garcia, P. (2014). Bubbles, food prices, and speculation: evidence from the cftc's daily large trader data files. In *The economics of food price volatility*, pages 211–253. University of Chicago Press.

Awange, J. (2021). Nile river basin and its challenges. In *The Nile Waters: Weighed from Space*, pages 21–51. Springer.

Babatunde, K., Begum, R., and Said, F. (2017). *Application of computable general equilibrium (CGE) to climate change Mitigation Policy: A system review*. Elsevier.

Baecher, G. (2000). The nile basin: Environmental transboundary opportunities and constraints analysis. *United State Agency for International Development, Washington D.C.*

Bailey, R. (2015). How do we protect global food supplies from extreme weather? https://www.weforum.org/stories/2015/09/how-do-we-protect-global-food-supplies-from-extreme-weather/. Accessed: 2025-05-03.

Banerjee, O., Cicowiez, M., Rios, A. R., and De Lima, C. Z. (2021). Climate change impacts on agriculture in latin america and the caribbean: an application of the integrated economic-environmental modeling (ieem) platform.

Baptista, D., Farid, M., Fayada, D., Kemoe, L., Lanci, L., Mitra, P., and Unsal, F. (2022). Climate change and chronic food insecurity in sub-saharan africa. In *International Monetary Fund (IMF)*.

Bellemare, M. F. (2015). Rising food prices, food price volatility, and social unrest. *American Journal of agricultural economics*, 97(1):1–21.

Benson, C. and Clay, E. (1994). *The Impact of Drought on the Sub-Saharan African Economies: A preliminary Examination*. Overseas Development Institute Regent's College Inner Circle, Regent's Park London.

Berck, P., Robinson, S., and Goldman, G. (1990). *The use of computable general equilibrium models to assess water policy*. CUDARE Working Paper.

Berthe, A., Kubursi, A., Arain, M. A., and Janes, A. (2023). The comparative analysis of carbon pricing policies on canadian northwest territories' economy under different climate change scenarios. *Energies*, 16(22):7471.

Bhanumurthy, N., Dua, P., and Kumawat, L. (2013). Weather shocks and agricultural commodity prices in india. *Climate Change Economics*, 4:135.

Bhat, S., Zaidi, A., and Khan, M. (2020). Role of plant growth-promoting rhizobacteria (pgpr) in enhancing plant productivity and alleviating salinity stress. *Soil Biology and Biochemistry*, 78:51–59.

Björklund, G., Connor, R., Goujon, A., Hellmuth, M., Moriarty, P., Rast, W., Warner, K., Winpenny, J., Hoekstra, A., Wiberg, D., et al. (2012). Demographic, economic and social drivers. In *The United Nations World Water Development Report 3*, pages 29–40. Routledge.

Bollerslev, T. (1986). Generalized autoregressive conditional heteroskedasticity. *Journal of econometrics*, 31(3):307–327.

Boretti, A. and Rosa, L. (2019). Reassessing the projections of the world water development report. *npj, Clean Water*.

Bowen, C. N. (2019). *Climate shocks, food price stability and international trade: evidence from 76 maize markets in 27 net-importing countries*. Environmental Research Ltters.

Brooks, K. (2018). Rising absolutely, declining relatively: agriculture, climate change, and job creation in africa. *Agrekon*, 57(3-4):181–197.

Brown, A. and Matlock, M. (2011). A review ofwater scarcity indices and methodologies. *The Sustainability Consortium*.

Burke, M., Hsiang, S. M., and Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature*, 527(7577):235–239.

Calzadilla, A., Zhu, T., Rehdanz, K., Tol, R. S., and Ringler, C. (2013). Economywide impacts of climate change on agriculture in sub-saharan africa. *Ecological Economics*, 93:150–165.

Canta, J. J. P., Alava, F. R., Escobedo, A. E. G., Liza, Y. F. A., Espinoza, R. F. R., and Chujutalli, M. R. (2023). Water retentivity and environmental impact assessment in the headwaters of the chambira micro-watershed, san martin region. *Case Studies in Chemical and Environmental Engineering*, 8:100375.

Celmi, M., Valverde, A., and Carhuapoma, P. (2021). Managing glacial lakes in peru to address water scarcity issues under future climate change scenarios. *Environmental Science and Policy*, 70:56–67.

Cenacchi, N. (2014). Drought risk reduction in agriculture: A review of adaptive strategies in east africa and the indo-gangetic plain of south asia. *IFPRI Discussion Paper*, 01372.

Chalise, S. and Naranpanawa, A. (2016). Climate change adaptation in agriculture: A computable general equilibrium analysis of land-use change in nepal. *Land use policy*, 59:241–250.

Chambers, M. and Bailey, R. (1996). A theory of commodity price fluctuations. *Journal of Political Economy*, 104:924–957.

Chapagain, A., Aldaya, M. M., Mekonnen, M. M., and Hoekstra, A. Y. (2011). The water footprint assessment manual: Setting the global standard. Technical report.

Chapagain, A. and Hoekstra, A. (2004). Water footprints of nations', research report series no. 16. Delft. UNESCO-IHE.

Chapagain, A. K., Hoekstra, A. Y., and Savenije, H. H. (2006). Water saving through international trade of agricultural products. *Hydrology and Earth System Sciences*, 10(3):455–468.

Chapoto, A. and Jayne, T. S. (2009). The impacts of trade barriers and market interventions on maize price predictability: Evidence from eastern and southern africa. (102). Available at AgEcon Search: https://ageconsearch.umn.edu/record/56798.

Chavas, J.-P., Hummels, D., and Wright, B. (2014). *The Economics of food price volatility.* University of Chicago Press.

Chen, Z.-M. and Chen, G. (2013). Virtual water accounting for the globalized world economy: National water footprint and international virtual water trade. *Ecological indicators*, 28:142–149.

Chittaranjan, R., McInnes, D., and Sanderson, M. (2018). Virtual water its implications on agriculture and trade. *Water International.*

Choi, Y.-W. and Eltahir, E. A. (2023). Near-term climate change impacts on food crops productivity in east africa. *Theoretical and Applied Climatology*, 152(1):843–860.

Clionadh, R., Hyun, J., and Dominic, K. (2015). *An investigation of the relationships between conflict, food price and climate across Africa.* Global Environmental Change.

Coady, W., Kosali, S., and Ricardo, A.-G. (2018). *Designing Difference in Difference Sudies.* Best Practices for Public Health Policy Research.

Coffel, E., Keith, B., Lesk, C., and Horton, R. B. (2019). Future hot and dry years worsen nile basin water scarcity despite projected precipitation increases. *Earth Future.*

Connolly, K. (2018). Examining the potential economic impacts of scottish offshore wind developments. Ph.D. thesis, Department of Electronic and Electrical Engineering.

Cutler, H. and Davies, S. (2010). The economic consequences of productivity changes: A computable general equilibrium (cge) analysis. *Regional Studies*, 44(10):1415–1426.

Daly, H. E. (1968). On economics as a life science. *Journal of political economy*, 76(3):392–406.

Dasgupta, M. K. and Chakrabarty, C. (2009). Commodities derivative hedging: Portfolio and effectiveness. *Commodity Insights Yearbook.* Details such as volume, issue, and page numbers are not available.

Daviron, B., Nango Dembele, N., Murphy, S., and Rashid, S. (2011). Price volatility and food security. a report by the high level panel of experts on food security and nutrition of the committee on world food security.

Davis, S, J. and Caldeira (2010). Consumption-based accounting of co2 emission. *Proceedings of the National Academy of Science*.

Deaton, A. and Laroque, G. (1996). Competitive storage and commodity price dynamics. *Journal of Political Economy*, 896-923:104.

Deaton, A. and Laroque, G. (2003). Commodity prices and growth in africa. *The Journal of Economic Perspectives*, 17(3):23–40.

Deconinck, S. (2017). Security as a threat to development: the geopolitics of water scarcity in the nile river basin. *Royal high institute of Defence - Brussels*.

Degefu, D. M. and He, W. (2016). Water bankruptcy in the mighty nile river basin. *Sustainable Water Resources Management*, 2:29–37.

Dehn, J., Gilbert, C. L., and Varangis, P. (2005). Agricultural commodity price volatility. *Managing Economic Volatility and Crises: A Practitioner's Guide*, 1:137–185.

Dell, M., Jones, B. F., and Olken, B. A. (2012). Temperature shocks and economic growth: Evidence from the last half century. *American Economic Journal: Macroeconomics*, 4(3):66–95.

Dellink, R., Lanzi, E., and Chateau, J. (2017). Long-term economic growth projections in the shared socioeconomic pathways. *Global Environmental Change*, 42:200–214.

Delzeit, R., Beach, R., Bibas, R., Britz, W., Chateau, J., Freund, F., Lefevre, J., Schuenemann, F., Sulser, T., Valin, H., et al. (2020). Linking global cge models with sectoral models to generate baseline scenarios: Approaches, opportunities and pitfalls. *Journal of Global Economic Analysis*, 5(1):162–195.

Demeke, M., Pangrazio, G., and Maetz, a. M. (2011). Country responses to turmoil in global food markets: The nature and preliminary implications of the policies pursued in the 2006–08 episode'. In Prakash, A., editor, *Safeguarding Food Security in Volatile Global Markets*. Rome. Food and Agriculture Organization (FAO).

Demeke, M., Pangrazio, G., Maetz, M., et al. (2008). Country responses to the food security crisis: Nature and preliminary implications of the policies pursued. *Rome, Agricultural Policy Support Service, FAO*, pages 1–2.

Dennis, K. (2003). Effects of structural adjustment program on agriculture. a paper presented to makerere university.

Deschenes, O. and Greenstone, M. (2007). The economic impacts of climate change: evidence from agricultural output and random fluctuations in weather. *American Economic Review*, 97:354–385.

Diao, X., Dinar, A., Roe, T., and Tsur, Y. (2008). *A general equilbrium analysis of conjuctive ground and surface water use with an application to Morocco.* Agricultural Economics.

Dilley, M. (1997). Climatic factors affecting annual maize yields in the valley of oaxaca, mexico. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 17(14):1549–1557.

Dolan, F., Lamontagne, J., Link, R., Hejazi, M., Reed, P., and Edmonds, J. (2021). Evaluating the economic impact of water scarcity in a changing world. *Nature communications*, 12(1):1915.

Dongyu, D. and Houngbo, G. F. (2021). *Progress on change in water-use efficiency: Global status and acceleration needs for SDG indicator 6.4. 1, 2021.* Food & Agriculture Org.

Donkor, S. (2006). Water in africa: management options to enhance survival and growth. *S.I., UN Economic Commission for Africa.*

Dwyer, G., Loke, P., Appels, D., Stone, S., and Peterson, D. (2005). Integrating rural and urban water markets in south east australia: Preliminary analysis. In *Productivity Commision OECD Conference Paper*.

Easterling, W. E., Aggarwal, P. K., Batima, P., Brander, K. M., Lin, E., Howden, S. M., Kirilenko, A., Morton, J., Soussana, J.-F., Schmidhuber, J., Tubiello, F. N., and Newton, P. C. (2007). Food, fibre and forest products. *Climate Change 2007: Impacts, Adaptation* *and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)*, pages 273–313.

Edame, G., Anam, B., Fonta, W., and Duru, E. (2011). Climate change, food security and agricultural productivity in africa: Issues and policy directions policy directions. *International Journal of Humanities and Social Science*.

El-Ramady, H. R., El-Marsafawy, S. M., and Lewis, L. N. (2013). Sustainable agriculture and climate changes in egypt. *Sustainable Agriculture Reviews: Volume 12*, pages 41–95.

Elbadawi, I., Ghura, D., and Uwujaren, G. (1992). Wh structural adjustment has not succeeded in sub-saharan africa. In *WPS 1000*. World Bank, Washington DC.

Elshennawy, A., Robinson, S., and Willenbockel, D. (2016). Climate change and economic growth: An intertemporal general equilibrium analysis for egypt. *Economic Modelling*, 52:681–689.

Elzoughbi, K. (2022). Egypt – water and environment. Country Commercial Guide, International Trade Administration, U.S. Department of Commerce.

FAO, IFAD, IMF, OECD, UNCTAD, WFP, World Bank, WTO, and UN HLTF (2011). Price volatility in food and agricultural markets: Policy responses. Inter-agency report for the G20, prepared by FAO, IFAD, IMF, OECD, UNCTAD, WFP, World Bank, WTO, and UN HLTF.

FAO and IHE Delft (2020). Water accounting in the nile river basin: FAO WaPOR water accounting reports. Technical report, Food and Agriculture Organization of the United Nations, Rome.

Fatima, A., Farid, M., Safdar, K., Fayyaz, A., Ali, S. M., Adnan, S., Nawaz, M., Munir, H., Raza, N., and Zubair, M. (2020). Loss of agro-biodiversity and productivity due to climate change in continent asia: a review. *Plant ecophysiology and adaptation under climate change: mechanisms and perspectives I: general consequences and plant responses*, pages 51–71.

Feng, K., Chapagain, A., Suh, S., Pfister, S., and Hubacek, K. (2011). Comparison of bottom-up and top-down approaches to calculating the water footprints of nations. *Economic Systems Research*, 23:371–85.

Feng, K., Davis, S., Sun, L., Li, X., and Guan, D. (2013). Outsourcing co2 within china. *Proceedings of the National Academy of Sciences*.

Feng, K. and Hubacek, K. (2015a). 10 a multi-region input–output analysis of global virtual water flows. In *Handbook of research methods and applications in environmental studies*, page 225.

Feng, K. and Hubacek, K. (2015b). *A multi-region input–output analysis of global Virtual water flows*.

Feng, K., Siu, Y. L., Guan, D., and Hubacek, K. (2012). Assessing regional virtual water flows and water footprints in the yellow river basin, china: A consumption based approach. *Applied geography*, 32(2):691–701.

Figus, G. (2017). Evaluating the impact of pro-environmental energy policy in scotland and the uk: the case of increased efficiency in household energy use.

Figus, G., Lecca, P., McGregor, P. G., and Turner, K. (2017). Energy efficiency as an instrument of regional development policy? trading-off the benefits of an economic stimulus and energy rebound effects. Strathclyde Discussion Paper in Economics 17-02, University of Strathclyde, Department of Economics.

Fonta, W., Edame, G., Anam, B. E., and Duru, E. (2011). Climate change, food security and agricultural productivity in africa: Issues and policy directions.

Fox, J., Fishback, P., and Rhode, P. (2011). *The effects of weather shocks on crop prices in unfettered markets: The united states prior to the farm programs.. The Economics of Climate Change: Adaptations Past and Present*. University of Chicago Press.

Fraser of Allander Institute (2022). Scoping the potential use of macroeconomic models to assess energy policy in the uk. Technical report, University of Strathclyde.

Freitas, W. (2020). In the future there will be more rain, but less water, in the nile basin. Retrieved 08 06, 2022, from.

FSIN and GNAFC (2025). Global report on food crises. https://www.fsinplatform.org/grfc2025. Rome. Accessed: 31 May 2025.

Fuglie, K., Dhehibi, B., El Shahat, A. A. I., and Aw-Hassan, A. (2021). Water, policy, and productivity in egyptian agriculture. *American Journal of Agricultural Economics*, 103(4):1378–1397.

Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D. S., Dai, H., Hijioka, Y., and Kainuma, M. (2017). Ssp3: Aim implementation of shared socioeconomic pathways. *Global Environmental Change*, 42:268–283.

Furtak, K. and Wolińska, A. (2023). The impact of extreme weather events as a consequence of climate change on the soil moisture and on the quality of the soil environment and agriculture – a review. *CATENA*, 231:107378.

Gad, W. A. (2017). Water scarcity in egypt: causes and consequences. *IIOAB J*, 8(4):40–47.

Gamal, G., Samak, M., and Shahba, M. (2021). The possible impacts of different global warming levels on major crops in egypt. *Atmosphere*, 12(12):1589.

García-León, D., Casanueva, A., Standardi, G., Burgstall, A., Flouris, A. D., and Nybo, L. (2021). Current and projected regional economic impacts of heatwaves in europe. *Nature communications*, 12(1):5807.

Gerard, F. (2011). Managing food price volatility for food security and development.

Gilbert, C. and Morgan, W. (2010). *Has food price volatility risen?. Department of Economics Working Papers 1002*. Department of Economics, University of Trento, Italia.

Gilmartin, M. and Allan, G. (2015). Regional employment impacts of marine energy in the scottish economy: A general equilibrium approach. *Regional Studies*, 49(2):337–355.

Giordani, P. E., Rocha, N., and Ruta, M. (2012). Food prices and the multiplier effect of export policy.

Gleick, P. H. (1996). Basic water requirements for human activities: Meeting basic needs. *Water international*, 21(2):83–92.

Gollin, D., Lagakos, D., Ma, X., and Mandi, S. (2025). To maintain productivity, u.s. agriculture needs major investment in research. https://www.nber.org/papers/w33529. NBER Working Paper No. 33529, February 2025.

Goodman, D. (2000). More reservoirs or transfers? a computable genral equilibrium anlysis of projected water shortage in the arkansas river basin. *Journal of Agricultural and Resource Economics*.

Gosling, S. N. and Arnell, N. W. (2016). A global assessment of the impact of climate change on water scarcity. *Climatic Change*, 134:371–385.

Gouel, C. (2013). *Food price volatility and domestic stabilization policies in developing countries*. Number W18934. National bureau of economic research.

Grey, D., Blackmore, D., Kelman, J., Muller, M., and Sadoff, C. (2013). Water security in one blue planet: twenty-first century policy challenges for science. *Philosophical Transactions of the Royal Society of London*.

Gujarati, D. and Porter, D. (2004). Basic econometrics, 4th edn, the macgraw hill. *New York*.

Guo, J. and Tanaka, T. (2020). Examining the determinants of global and local price passthrough in cereal markets: evidence from dcc-gjr-garch and panel analyses. *Agricultural and Food Economics*, 8:1–22.

Haddad, E., Lahr, M., Elshahaway, D., and Vassallo, M. (2016). Regional analysis of domestic integration in egypt: An integrregional cge approach. *Journal of Economic Structures*.

Haddadin, M. (2003). Exogenous water: A conduit to globalization of waterresources. in: A.y. hoekstra (ed.), virtual water trade: Proceedings of the international expert meeting on virtual water trade, value of water research report series. *UNESCO-IHE, Delft*, pages 159–169.

Haddout, S., Hoguane, A., Priya, K., and Ljubenkov, I. (2020). Water shortages and pandemics in africa. *The Round Table*, 109(4):480–481.

Hallegatte, S., Bangalore, M., Bonzanigo, L., Fay, M., Kane, T., Narloch, U., Rozenberg, J., Treguer, D., and Vogt-Schilb, A. (2016). *Shock waves: Managing the impacts of climate change on poverty.* World Bank Publications, Washington, DC.

Handler, A. (1990). Usa corn yields, the el niñmo and agricultural drought: 1867–1988. *International Journal of climatology*, 10(8):819–828.

Harari, M. and La Ferrara, E. (2013). Conflict, climate and cells: A disaggregated analysis. *Centre for Economic Policy Research*, 100(9277):53–63.

Harrigan, F., McGregor, P. G., Dourmashkin, N., Perman, R., Swales, K., and Yin, Y. P. (1991). Amos: A macro-micro model of scotland. *Economic Modelling*, 8(4):424–479.

He, X. (2022). Political and economic determinants of export restrictions in the agricultural and food sector. *Agricultural Economics*, 53(3):439–453.

Healy, F. (1984). *A Tool for Social Research.* Wadsworth Publishing Company. Statistics.

Hertel, T. and Liu, J. (2019). *Implications of Water Scarcity for Economic Growth.* Department of Agricultural Economics, Purdue University.

Hertel, T. W., Burke, M. B., and Lobell, D. B. (2010). The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, 20(4):577–585.

Hirwa, H., Peng, Y., Zhang, Q., Qiao, Y., and Leng, P. (2020). Virtual water transfers in africa: Assessing topical condition of water scarcity, water savings, and policy implications. *Sience Direct.*

Hirwa, H., Peng, Y., Zhang, Q., Qiao, Y., Leng, P., Tian, C., Yang, G., Muhirwa, F., Diop, S., Kayiranga, A., et al. (2022). Virtual water transfers in africa: Assessing topical condition of water scarcity, water savings, and policy implications. *Science of the Total Environment*, 835:155343.

Hoegh Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I. A., Diedhiou, A., Djalante, R., Ebi, K. L., Engelbrecht, F., et al. (2018). Impacts of 1.5 c global warming on natural and human systems.

Hoekstra, A. (2003). Virtual water trade: Proceedings of the international expert meeting on virtual water trade, delft, the netherlands value of water research report series. *UNESCO-IHE, Delft*.

Hoekstra, A. and Chapagain, A. (2007). Water footprints of nations: Water use by people as a function of their consumption pattern. 21:35–48.

Hoekstra, A. and Chapagain, A. (2008). Globalization of water: Sharing the planet's freshwater resources. *Blackwell, Oxford*.

Hoekstra, A., Chapagain, A., Mekonnen, M., and Aldaya, M. (2011). The water footprint assessment manual: Setting the global standard. *Routledge, Washington, DC.*

Hoekstra, A. and Hung, P. (2002). A quantification of virtual water flows between nations in relation to international crop trade. *IHE DELFT: Value of water Research Report*, 11.

Hoekstra, A. and Mekonnen, M. M. (2014). Water conservation through trade: the case of kenya. *Twente Water Centre, University of Twente, Enschede, the Netherlands*.

Hopwood, D. and Holt, P. M. (2020). Egypt agriculture and fishing. https://www.britannica.com/place/Egypt/Agriculture-and-fishing. Retrieved May 15, 2022.

Hubacek, K., Feng, K., Siu, Y., and Guan, D. (2012). Assessing regional virtual water flows and water footprints in the yellow river basin, china: A consumption based approach. *Appl. Geogr*.

Hubacek, K. and Sun, L. (2001). A scenario analysis of china's land use and land cover change: incorporating biophysical information into input–output modeling. *Structural Change and Economic Dynamics*, 12:367–97.

Hübler, M., Ogenrwoth, B., Walusimbi, R., Ssali, P., Bonabana, J., and Kyamanywa, S. (2025). The impact of weather shocks on food security in uganda: A panel regression analysis. *Food Security*, pages 1–22.

Huchet, B. (2011). *Agricultural commoddity price volatility. An overview. OECD Food, Agriculture and Fisheries Papers 52*. OECD Publishing.

Iizumi, T. (2014). Impacts of el niño southern oscillation on the global yields of major crops. *Nature Communications*, 5. article number: 3712.

Ingram, W. (2021). *Smart Meters for Rural Water Supply in Sub-Saharan Africa*. Phd thesis, University of Exeter. Accessed via University of Exeter repository.

IPCC (2007). Contribution of working group ii to the fourth assessment report of the intergovernmental panel on climate change. *Cambridge University Press, Cambridge, United Kingdom*.

Isard, W., Bassett, K., Choguill, C., Furtado, J., Izumita, R., Kissin, J., Romanoff, E., Seyfarth, R., and Tatlock, R. (1968). On the linkage of socio-economic and ecologic systems. *Papers of the Regional Science Association*, 21:79–99.

Ismail, A. A. H. (2020). Future vision for agricultural investment in egypt. *Plant Archives*, 20(2):2187–2195.

Ismail, S., Rahman, A., and Yusuf, M. (2021). Techno-socio-economic analysis of fog-to-water solutions in indonesia: Highlighting water scarcity's impact on livelihoods. *Journal of Cleaner Production*, 94:123–134.

ITC (2004). Pc-tas version 1997–2001, harmonized system. cd-rom. *International Trade Centre, Geneva*.

Jaume, F.-G., Decker, C., and Hall, J. (2014). *THE ECONOMIC IMPACTS OF DROUGHTS: A FRAMEWORK FOR ANALYSIS*. Environmental Change Institute, University of Oxford, Oxford University Centre for the Environment, South Parks Road, Oxford.

Jayne, T. S., Zulu, B., and Nijhoff, J. J. (2006). Stabilizing food markets in eastern and southern africa. *Food policy*, 31(4):328–341.

J.Cohen, J. M. (2009). The global food criss: Governance challange and opportunities. In *The Centre for International Governance Innovation (CIGI*. and Wilfrid Laurier University Press.

Jia, R. and Gotz, L. (2014). Weather shocks, sweet potatoes and peasant revolts in historical china; regional price effects of extreme weather events and wheat export controls in russia and ukraine. *The Economic Journal; Journal of Agricultural Economics*, 124; 67:92–118 741–763.

Kahsay, T. N., Kuik, O., Brouwer, R., and Van Der Zaag, P. (2017). The economy-wide impacts of climate change and irrigation development in the nile basin: a computable general equilibrium approach. *Climate Change Economics*, 8(01):1750004.

Kakpo, A., Mills, B. F., and Brunelin, S. (2022). Weather shocks and food price seasonality in sub-saharan africa: Evidence from niger. *Food Policy*, 112:102347.

Kalkuhl, M. and Wenz, L. (2020). The impact of climate conditions on economic production. evidence from a global panel of regions. *Journal of Environmental Economics and Management*, 103:102360.

Kane, G., Joel, A., and Mabah, T. (2015). Determinants of food price volatility in cameroon. In *Paper submitted to the "8th Journées de recherches en sciences"*.

Karla, M. (2011). The food crises and political instability in north africa and middle east. new england complex system institute.

Kassim, Y., Mahmoud, M., Kurdi, S., and Breisinger, C. (2018). An agricultural policy review of egypt. *International Food Policy Research Institute: Middle East And North Africa*.

Keppenne, C. L. (1995). An enso signal in soybean futures prices. *Journal of Climate*, 8(6):1685–1689.

Khalifa, H. H. (2014). Assessment of climate change impacts on livestock in egypt. https://ams.confex.com/ams/ICB2014/webprogram/Paper253465.html. Retrieved 05 15, 2022.

Khalil, S. and Hamzawy, A. (2025). Egypt's challenges and opportunities in climate-related finance and governance. Published on March 13, 2025. Accessed on May 6, 2025.

Khan, M. A., Tahir, A., Khurshid, N., Husnain, M. I. u., Ahmed, M., and Boughanmi, H. (2020). Economic effects of climate change-induced loss of agricultural production by 2050: A case study of pakistan. *Sustainability*, 12(3):1216.

Khokhar, T. (2017). Chart: Globally, 70% of freshwater is used for agriculture. https://blogs.worldbank.org/en/opendata/chart-globally-70-freshwater-used-agriculture. World Bank Data Blog. Accessed: 2024-0-01.

Korotayev, A. and Zinkina, J. (2015). East africa in the malthusian trap? *Journal of developing societies*, 31(3):385–420.

Koudou, A. N. (2012). Role of freshwater resources in sustainable economic development in 21st century: Exploratory study.

Kriegler, E., C, O., S, H., T, K., J, L., H, M., and T, a. W. (2012). The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathwaysglob. *Environ. Change*, 22:807–22.

Kummu, M., Guillaume, J., Moel, H., Eisner, S., Florke, M., Porkka, M., Siebert, S., Veldkamp, T., and Ward, P. (2016). The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. *Scientific Reports*.

Kurukulasuriya, P., Mendelsohn, R., Hassan, R., Benhin, J., Diop, M., Eid, H., and Maddison, D. (2006). Will african agriculture survive climate change? *World Bank Economic review*, 20(3):367–388.

Lai, J., Li, Y., Chen, J., Niu, G.-Y., Lin, P., Li, Q., Wang, L., Han, J., Luo, Z., and Sun, Y. (2022). Massive crop expansion threatens agriculture and water sustainability in northwestern china. *Environmental Research Letters*, 17(3):034003.

Lecca, P., McGregor, P. G., and Swales, J. K. (2013). Forward-looking and myopic regional computable general equilibrium models: How significant is the distinction? *Economic modelling*, 31:160–176.

Lecca, P., Swales, K., and Turner, K. (2011). An investigation of issues relating to where energy should enter the production function. *Economic Modelling*, 28(6):2832–2841.

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., and Lo, L. (2012). International trade drives biodiversity threats in developing nations. *Nature*, 486:109–12.

Leontief, W. (1936). Quantitative input and output relations in the economic system of the united states. *The Review of Economic and Statistics*.

Leontief, W. (1970). Environmental repercussions and the economic structure: an input–output approach. *Review of Economics and Statistics*.

Letson, D. and McCullough, B. (2001). Enso and soybean prices: Correlation without causality. *Journal of Agricultural and Applied Economics*, 33(3):513–521.

Levine, R. R. (1991). Cross-country studies of growth and policy: Methodological, conceptual. In *Policy, Research, and External Affairs Working Paper Series 608*. World Bank.

Liliane, T. N. and Charles, M. S. (2020). Factors affecting yield of crops. *Agronomy-climate change & food security*, page 9.

Link, P. M., Piontek, F., Scheffran, J., and Schilling, J. (2012). On foes and flows: vulnerabilities, adaptive capacities and transboundary relations in the nile river basin in times of climate change. *L'Europe en formation*, 365(3):99–138.

Liu, J., Hertel, T., and Taheripour, F. (2016). Analyzing future water scarcity in computable general equilibrium models. *Water Economics and Policy*, 2(04):1650006.

Liu, J., Yang, H., Gosling, S. N., Kummu, M., Flörke, M., Pfister, S., Hanasaki, N., Wada, Y., Zhang, X., Zheng, C., et al. (2017). Water scarcity assessments in the past, present, and future. *Earth's future*, 5(6):545–559.

Liu, J., Zehnder, A., and Yang, H. (2009). Global consumptive water use for crop production: the importance of green water and virtual water. *Water Resources Research*.

Liu, X. (2012). By sector water consumption and realted economic analysis integrated model and its application in hai river basin, china. *Journal of Water Resource and Protection*, 4:264–76.

Liu, Y., Li, N., Zhang, Z., Huang, C., Chen, X., and Wang, F. (2020). Climate change effects on agricultural production: The regional and sectoral economic consequences in china. *Earth's Future*, 8(9):e2020EF001617.

Lobell, D., He, Y., and G., R. (2025). To maintain productivity, u.s. agriculture needs major investment in research. https://news.stanford.edu/stories/2025/03/investment-research-us-agriculture-productivity-slowdown.

Lofgren, H., Harris, R. L., and Robinson, S. (2002). *A standard computable general equilibrium (CGE) model in GAMS*, volume 5. Intl Food Policy Res Inst.

Lord, M. (1999). The elasticities approach to egypt's balance of payments and equilibrium exchange rate.

Lukas, K., Matthias, K., and Irfan, M. (2017). Food price volatility in developing countries: The role trade and policy. *Foodsecure Working Paper*, 57.

Ma, W., Opp, C., and Yang, D. (2020). Past, present, and future of virtual water and water footprint. *Water*, 12(11):3068.

Maddala, G. (1992). Limited dependent and qualitative variables in econometrics. In *United States of America*. Cambridge University press.

Mahlakeng, M. K. (2023). *Water Scarcity and Conflict in African River Basins*.

Mahmoud, M. (2019). Impact of climate change on the agricultural sector in egypt. *Conventional Water Resources and Agriculture in Egypt*, pages 213–227.

Maite, M., Pedro Martínez-Santos, A., and Ramón Llamas, M. (2009). Incorporating the water footprint and virtual water into policy: Reflections from the mancha occidental region, spain. *Springerlink*.

Mancosu, N., Snyder, R. L., Kyriakakis, G., and Spano, D. (2015). Water scarcity and future challenges for food production. *Water*, 7(3):975–992.

Mankin, E. (2020). Scientists predict more rain but less water for the millions of people in the nile basin. Retrieved May 05, 2022, from.

Mantlana, B., Rumble, O., and Gilder, A. (2022). Unfccc cop27 coalitions in the unfccc: A case study of egypt as host of unfccc cop27. *Carbon & Climate Law Review*, 16(3).

Marilyne, H.-B. (2011). Agricultural commodity price volatility. *OECD Food, Agriculture and Fisheries Working Papers*, 52.

Marshall, S. (2011). The water crisis in kenya: Causes, effects and solutions. *Global Majority E-Journal*, 2(1):31–45.

Marta, K., Matthias, K., Shweta, S., and Jan, B. (2015). Modelling indian wheat and rice sector policies. Zentrum für Entwicklungsforschung (ZEF).

Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J., Maycock, T., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B. (2021). Summary for policymakers. In Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J., Maycock, T., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., editors, *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, pages 3–32. Cambridge University Press, Cambridge, UK and New York, NY, USA. See Figure SPM.8.

Matthews, A. (2010). Prespectives on addressing market instability and income risk for farmers. In *Joint AES and SFER Conference on the common Agricultural policy post 2013*, Edinburgh.

McGrath, M. (2012). Huge water resource exists under africa. *Science Environment, BBC News*.

McKenzie, A. (2008). Pre-harvest price expectations for corn: The information content of usda reports and new crop futures. *American Journal of Agricultural Economics*, 90:315–335.

Mekonnen, M. and Hoekstra, A. (2010a). The green, blue and gray water footprint of crops and derived crop products', value of water research report series no. 47. *UNESCO-IHE*.

Mekonnen, M. and Hoekstra, A. (2010b). The green, blue and gray water footprint of farm animals and animal products', value of water research report series no. 48. *NESCO-IHE, Delft*.

Mekonnen, M. and Hoekstra, A. (2011a). National water footprint accounts: the green, blue and gray water footprint of production and consumption', value of water research report series no. 50. *UNESCO-IHE, Delft*.

Mekonnen, M. and Hoekstra, A. (2011b). The water footprint of electricity from hydropower', value of water research report series no. 51. *UNESCO-IHE, Delfat*.

Mekonnen, M. M. and Hoekstra, A. Y. (2011). The green, blue and gray water footprint of crops and derived crop products. *Hydrology and earth system sciences*, 15(5):1577–1600.

Mekonnen, M. M. and Hoekstra, A. Y. (2015). Global gray water footprint and water pollution levels related to anthropogenic nitrogen loads to fresh water. *Environmental Science and Technology*.

Mekonnen, M. M. and Hoekstra, A. Y. (2016). Four billion people facing severe water scarcity. *Science advances*, 2(2):e1500323.

Melesse, M. B. and Demissie, Y. (2024). Hydrology and droughts in the nile: A review of key findings and implications. *Water*, 16(17):2521.

Michael, B. B., Carlo, B., Jens, K., Karina, W., and Niels, D. (2016). A regional approach to climate adaptation in the nile basin. *Water Resources Assessment and Seasonal Prediction*.

Miller, R. E. and Blair, P. D. (2009a). *Input-output analysis: foundations and extensions*. Cambridge University Press.

Miller, R. E. and Blair, P. D. (2009b). *Input–Output Analysis: Foundations and Extensions*. Cambridge university press.

Minot, N. (2014). Food price volatility in sub-saharan africa: Has it really increased? *Food Policy*, 45:45–56.

Morabito, M., Crisci, A., and Giunti, G. (2020). Economic cost of heat-related productivity loss for agricultural workers: Emphasizing mitigation importance. *Agricultural Economics*, 55:23–32.

Moss, R. (2010). The next generation of scenarios for climate change research and assessment nature.

Mostafa, S. M., Wahed, O., El-Nashar, W. Y., El-Marsafawy, S. M., Zeleňáková, M., and Abd-Elhamid, H. F. (2021). Potential climate change impacts on water resources in egypt. *Water*, 13(12):1715.

MRIO, W. (2023). World input-output model: Country-wise data. https://worldmrio.com/countrywise/. Accessed: 10/07/2023.

Mubenga-Tshitaka, J.-L., Dikgang, J., Muteba Mwamba, J. W., and Gelo, D. (2023). Climate variability impacts on agricultural output in east africa. *Cogent economics & finance*, 11(1):2181281.

Mukherjee, C., White, H., and Wuyts, M. (2013). *Econometrics and data analysis for developing countries*. Routledge.

Muth, J. (1991). Rational expectations and the theory of price movements. *Econometrica*, page 315–335.

Naylor, R. and Falcon, W. (2010). Food security in an era of economic volatility. *Population and Development Review*, 36(4):693–723.

Naylor, R. L., Falcon, W. P., Rochberg, D., and Wada, N. (2001). Using el nino/southern oscillation climate data to predict rice production in indonesia. *Climatic Change*, 50:255–265.

Nazareth, M. S., Gurgel, A. C., and Da Cunha, D. A. (2022). Economic effects of projected decrease in brazilian agricultural productivity under climate change. *GeoJournal*, 87(2):957–970.

Nelson, G. C., Rosegrant, M. W., Koo, J., Robertson, R., Sulser, T., Zhu, T., Ringler, C., Msangi, S., Palazzo, A., Batka, M., et al. (2009). *Climate change: Impact on agriculture and costs of adaptation*, volume 21. Intl Food Policy Res Inst.

Nelson, G. C., Rosegrant, M. W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., Sulser, T. B., Ringler, C., et al. (2010). *Food security, farming, and climate change to 2050: scenarios, results, policy options*, volume 172. Intl Food Policy Res Inst.

Network, W. F. (2003). Virtual water trade: Proceedings of the international expert meeting. *Water Footprint Network, IHE DELFT*, page 14.

OECD., K. (2018). Oecd science, technology and innovation outlook 2018. https://www.oecd.org/en/publications/oecd-science-technology-and-innovation-outlook-2018_sti_in_outlook-2018-en.html. Accessed: 2025-04-01.

Ogundari, K. and Onyeaghala, R. (2021). The effects of climate change on african agricultural productivity growth revisited. *Environmental Science and Pollution Research*, 28(23):30035–30045.

Oki, T. and Kanae, S. (2004). Virtual water trade and world water resources. *Water Science and Technology*, 49:203–209.

Okoth, P. G. (2007). The nile river question and the riparian states: Contextualising uganda's foreign policy interests. *African Sociological Review*.

Omar, M. E. D. M., Moussa, A. M. A., and Hinkelmann, R. (2021). Impacts of climate change on water quantity, water salinity, food security, and socioeconomy in egypt. *Water Science and Engineering*, 14(1):17–27.

O'Neill, B. (2016). The shared socioeconomic pathways (ssps) and their extension and use in impact, adaptation and vulnerability studies.

Osborne, T. (2004). Market news in commodity price theory: Application to the ethiopian grain market. Online.

Osman, R., Ferrari, E., and McDonald, S. (2016). Water scarcity and irrigation efficiency in egypt. *Water Economics and Policy*, 2(04):9–16.

Oyiga, B. (2011). *Implication of Climate change on crop yield and food accessibility in Sub-Saharan Africa*. International Term Paper.

Padder, F. A. and Bashir, A. (2023). Scarcity of water in the twenty-first century: Problems and potential remedies. *Medalion Journal: Medical Research, Nursing, Health and Midwife Participation*, 4(1):1–5.

Parkash, A. (2011). Why volatility matters. In Prakash, A., editor, *Safeguarding food security in volatile global markets*, page 3–26. FAO, ROme, Itily.

Paudel, B., Adhikari, S., and Sharma, S. (2023). Addressing challenges posed by covid-19, climate change, and agricultural conflicts: Strategies to ensure global food security. *Global Food Security*, 17:56–66.

Peters, G., Minx, J., Weber, C., and Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. U. S. A.*

Polakovic, G. (2021). Water dispute on the nile river could destabilize the region. *University of Southern California News*, 13.

Porteous, O. (2017). Empirical effects of short-term export bans: The case of african maize. *Food Policy*, 71:17–26.

Prell, C., Feng, K., Sun, L., and Geores, M. (2014). The global economic gains and environmental losses of us consumption: a world-systems and input–output approach. *Social Forces*, 93:405–28.

Pörtner, H.-O., Roberts, D. C., Dupuis, M. M. M., Masson-Delmotte, H. Z., Zhai, P., Aldrian, E., Campos, R. S. C., and Mach, K., editors (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK and New York, NY, USA.

Rabie, T. (2020). *Potential climate change impacts on livestock and food security nexus in Egypt.* Springer, Cham.

Rapsomanikis, G. et al. (2009). The 2007-2008 food price swing: Impact and policies in eastern and southern africa.

Rees, W. (1992). Ecological footprints and appropriated carrying capacity:what urban economics leaves out. *Environment and Urbanization*, 4:121–130.

Reilly, J., Baethgen, W., Chege, F., Erda, L., Iglesias, A., Kenny, G., and Lingren, P. (1996). Agriculture in a changing climate: impacts and adaptations in: R. In Watson, M., Moss, R., and Dokken, D., editors, . *Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK.

Reuter, K., Juhn, D., Portela, R., and Venter, J. (2016). Natural capital accounting across the gaborone declaration for sustainability in africa: A desktop scoping. Technical report, Report prepared for the Gaborone Declaration for Sustainability in Africa, Gaborone, Botswana.

Richard, W. H. (2020). Climate change in east african agriculture: Rencent trends, current projections, crop-climate suitability and prospects for improved climate model information.

Robinson, E., Whyte, K., Álvaro Lario, Hussain, S., Challinor, A., Vos, R., Matthews, A., Paredes, X. J., Dasgupta, S., and Otero, M. (2024). Experts: What is causing food prices to spike around the world? https://www.carbonbrief.org/experts-what-is-causing-food-prices-to-spike-around-the-world/. Published on 19 June 2024. Accessed on 3 May 2025.

Robinson, S., Cattaneo, A., and El-Said, M. (1998). Estimating a social accounting matrix using cross entropy methods. *IFPRI, Discussion Paper*, (33).

Robles, M., Torero, M., and von Braun, J. (2009). When speculation matters. (PL Study 40). Prepared for the Commodity Futures Trading Commission (CFTC) Public Roundtable on Commodity Markets.

Rockström, J., Falkenmark, L., and Karlberg, H. H. (2009). ‘future water availability for global food production: the potential of green water for increasing resilience to global change. *Water Resource Research*, W00A12:45.

Rosenzweig, C. and Parry, M. (1994). *Potential Impacts of Climate Change on World Food Supply: Data Sets from a Major Crop Modeling Study*. Goddard Institute for Space Studies, Columbia University, New York.

Ruf, T. (1993). The history of agricultural development. *The agriculture of Egypt*, 3:188.

Sachs, J., Panatayou, T., and Peterson, A. (1999). *Developing Countries and the Control of Climate Change: A Theoretical Perspective and Policy Implications, CAER II Discussion Paper*. Harvard Institute for International Development.

Sadoff, C. W., Borgomeo, E., and de Waal, D. (2017). Turbulent waters: Pursuing water security in fragile contexts. *World Bank*.

Sallam, O. M. (2014). Water footprints as an indicator for the equitable utilization of shared water resources:(case study: Egypt and ethiopia shared water resources in nile basin). *Journal of African Earth Sciences*, 100:645–655.

Sawyer, D., Ness, R., Lee, C., and Miller, S. (2022). Damage control: Reducing the costs of climate impacts in canada.

Schlenker, W. (2024). Policy change needed now to avoid climate-driven global food crisis. https://www.hks.harvard.edu/faculty-research/policycast/policy-change-needed-now-avoid-climate-driven-global-food-crisis.

Semeraro, T., Cicco, V., and Palermo, G. (2023). Climate change impact on agroecosystems: Potential adaptation strategies and the role of new technologies. *Agronomy*, 14:789–799.

Seo, N. and Mendelsohn, R. (2008). Measuring impacts and adaptations to climate change: a structural ricardian model of african livestock management. *Agricultural Economics*, 38(2):151–165.

Serageldin, I. (2001). Living water: Wwf freshwater conservation actions in asia/pacific. {https://wwfeu.awsassets.panda.org/downloads/water.pdf},.

Shaaban, I. and Ramzy, Y. (2010). The impact of climate change on tourism in egypt as perceived by both policymakers and and tourism managers. *WIT Transactions on Ecology and the Environment*.

Sharef, A. J. S. (2019). Integrated water resource managementfor in khalifan river basin.

Sharma, R. (2011). Food export restrictions: Review of the 2007-2010 experience and consideration. *Commodity and Trade Policy Research Working Paper*, 32.

Shihao, S., Ni, H., Lin, X., and Chen, a. G. (2023). Evaluation of water saving and economy impact for tax reform policy using cge model with integrated multiple types of water.

Shiklomanov, I. A. (1991). The world's water resources. In *Proceedings of the international symposium to commemorate*, volume 25, pages 93–126. Unesco.

Smith, M. P. and Favell, A. (2006). *The human face of global mobility: International highly skilled Migartion in Europe, North America and the Asia-Pacific*, volume 8. Transaction Publishers.

Solomon, R., Simane, B., and Zaitchik, B. F. (2021). The impact of climate change on agriculture production in ethiopia: application of a dynamic computable general equilibrium model. *American Journal of Climate Change*, 10(1):32–50.

Song, Y., Zhang, B., Wang, J., and Kwek, K. (2022). The impact of climate change on china's agricultural green total factor productivity. *Technological Forecasting and Social Change*, 185:122054.

Sultan, R., Ahmed, N., and Ali, S. (2022). Climate-smart agriculture in pakistan: Strengthening agricultural resilience. *Agricultural Systems*, 90:99–109.

Sumartono, E., Mulyasari, G., and Sukiyono, K. (2021). Assessment model impact of climate change on potential production for food and energy needs for the coastal areas of bengkulu, indonesia. *Agro Bali: Agricultural Journal*, 4(2):159–169.

Summer, D. (1989). Are harvest forecasts news? usda announcements and futures market reactions. *American Journal of Agricultural Economics*, 71:1–8.

Sun, Y., Zhu, S., Wang, D., Duan, J., Lu, H., Yin, H., Tan, C., Zhang, L., Zhao, M., Cai, W., et al. (2024). Global supply chains amplify economic costs of future extreme heat risk. *Nature*, 627(8005):797–804.

Tadesse, G., Algieri, B., Kalkuhlc, M., and Braunc, J. (2014). Drivers and triggers of international food price spikes and volatility. *Food policy*, 47:117–128.

Taheripour, F., Tyner, W. E., Sajedinia, E., Aguiar, A., Chepeliev, M., Corong, E., De Lima, C. Z., and Haqiqi, I. (2020). *Water in the balance: The economic impacts of climate change and water scarcity in the Middle East.* World Bank.

Tanveer, Z. and Kalim, R. (2024). An empirical analysis of climate transition: A global outlook of agriculture productivity. *Journal of Economic Studies*, 51(4):777–796.

Tariku, T. B. and Gan, T. Y. (2018). Regional climate change impact on extreme precipitation and temperature of the nile river basin. *Climate Dynamics*, 51(9):3487–3506.

Tesfamicheal, W., Thomas, B., Mekbib, G., and Troost, C. (2017). Impacts of climate variability and food price volatility on household income and food security of farm households in east and west africa. In *International Institute of Tropical Agriculture (IITA), Nageria*.

The Water Project (2022). Water and poverty: How access to clean water alleviates poverty. https://thewaterproject.org/why-water/poverty. Accessed: 2025-03-15.

The World Bank (2021). Average precipitation in depth (mm per year). https://data.worldbank.org/indicator/AG.LND.PRCP.MM. Accessed: 2024-10-29.

Tian, G., Han, X., Zhang, C., Li, J., and Liu, J. (2020a). Virtual water flows embodied in international and interprovincial trade of yellow river basin: A multiregional input-output analysis. *Sustainanbility*.

Tian, G., Han, X., Zhang, C., Li, J., and Liu, J. (2020b). Virtual water flows embodied in international and interprovincial trade of yellow river basin: A multiregional input-output analysis. *Sustainability*, 12(3):1251.

Toulmin, C. (2013). Africa's food crisis: Growing crops sustainably. https://www.theguardian.com/global-development/poverty-matters/2013/apr/18/africa-food-crisis-growing-crops-sustainably. Accessed on 2023-10-28.

Trostle, R. et al. (2008). Global agricultural supply and demand: factors contributing to the recent increase in food commodity prices. *USDA Economic Research Service Report*.

Turpie, J., Winkler, H., Spalding-Fecher, R., and Midgley, G. (2002). Economic impacts of climate change in south africa: a preliminary analysis of unmitigated damage costs. *Energy and Development Research Centre, University of Cape Town, Cape Town*, pages 1–58.

Turvey, C. G. (2001). Weather derivatives for specific event risks in agriculture. *Applied Economic Perspectives and Policy*, 23(2):333–351.

Ubilava, D. (2012). El niño, la niña, and world coffee price dynamics. *Agricultural Economics*, 43(1):17–26.

Ubilava, D. (2013). El nino south oscillation and its effects on world vegetable oil pricing: Assessing asymmetries using smooth transition models. *Australian Journal of Agricultural and Resource Economics*, 57(2):273–297.

UNDP (2015). . human development report: Beyond scarcity: Power, poverty and the global water crisis. *New York, NY: Palgrave Macmillan.*

UNFCCC, U. (2017). *Intended Nationally Determined Contributions as per United Nation Framework Convention on Climate Change*. The Arab Republic of Egypt.

Van Schaik, L. and Dinnissen, R. (2014). Terra incognita: Land degradation as underestimated threat amplifier. *Clingendael Report. Wasssenaar: Netherlands Institute of International Relations.*

Velazquez, E. (2006). An input–output model of water consumption: Analysing intersectoral water relationships in andalusia. *Ecological Economics*, 56:226–40.

Vogel, D. (2009). *Trading up: Consumer and environmental regulation in a global economy.* Harvard University Press.

Vorosmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B. (2000). Global water resources: vulnerability from climate change and population growth. *science*, 289(5477):284–288.

Vuuren, D. (2011). Representative concentration pathways an overview climate change.

Wackernagel, M. and Rees, W. (1996). Our ecological footprint: Reducing human impact on the earth. *New Society Publishers, Gabriola Island, B.C., Canada.*

Wang, D., Jenkins, K., Forstenhäusler, N., Lei, T., Price, J., Warren, R., Jenkins, R., and Guan, D. (2021). Economic impacts of climate-induced crop yield changes: evidence from agri-food industries in six countries. *Climatic Change*, 166(3):30.

Wang, Y., Xiao, H., and Lu, M. (2009). Analysis of water consumption using a regional input-output model: Model development and application to zhangye city, northwestern china. *Journal of Arid Environment*, 73:894–00.

Washington, R. and Pearce, H. (2012). Climate change in east african agriculture: recent trends, current projections, crop-climate suitability, and prospects for improved climate model information. *CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). Copenhagen, Denmark. Available online at: www. ccafs. cgiar. org.*

Wattanakuljarus, A. (2006). The nationwide economic and environmetal impact of tourism: A computable general equilibrium approach for thailand. In *Economy and Environment Program for Southeast Asia (EEPSEA*.

Wei, J., Lei, Y., Liu, L., and Yao, H. (2023). Water scarcity risk through trade of the yellow river basin in china. *Ecological Indicators*, 154:110893.

Weinzettel, J., Hertwich, E., Peters, G., Steen-Olsen, K., and Galli, A. (2013). Affluence drives the global displacement. *Global Environmental Change*, 23:233–8.

WHO (2017). Progress on drinking water , sanitation and hygiene. launch version july 12 main report progress on drinking water , sanitation and hygiene. *WHO Library Cataloguing in Publication Data.*

Wiebe, K., Lotze-Campen, H., Sands, R., Tabeau, A., Mensbrugghe, and der, a. D. (2015). *Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios.* Environ. Res.

Wiedmann, T. (2009). A review of recent multi-region input–output models used for consumption-based emission and resource accounting. *Ecol. Econ.*

Wiedmann, T., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., and Kanemoto, K. (2013). The material footprint of nations. *Proceedings of the National Academy of Sciences.*

Willenbockel, D., Elshennawy, A., and Robinson, S. (2013). Climate change and economic growth: An intertemporal general equilibrium analysis for egypt. Technical report, EcoMod.

William, C. (2007). Global warming and agriculture impact estimates by country. Retrieved 06 05, 2022.

Williams, E., Ayres, R., and Heller, M. (2002). The 1.7 kilogram microchip: Energy and material use in the production of semiconductor devices. *Environmental Science and Technology.*

World-Bank (2016). *Shock Waves: Managing the Impacts of Climate Change on Poverty.* The World Bank, Washington, DC.

WorldBank (2015). Annual freshwater withdrawals as a percentage of total renewable resources. Accessed: 2024-11-05.

Worldometers (2019). Current world population. Available at: https://www.worldometers.info/world-population/ [Accessed 12 September 2019].

Wosenie, M. D., Verhoest, N., Pauwels, V., Poesen, J., Adgo, E., Deckers, J., and Nyssen, J. (2015). The water balance of lake tana. In *TropiLakes 2015: Tropical lakes in a changing environment: water, land, biology, climate and humans: excursion guide pre-conference excursion*, pages 54–60. Bahir Dar University.

Wossen, T., Berger, T., Haile, M. G., and Troost, C. (2018). Impacts of climate variability and food price volatility on household income and food security of farm households in east and west africa. *Agricultural systems*, 163:7–15.

Xia, W., Degefu, D. M., Yuan, L., LiaoZaiyi, He, W., An, M., and Zhang, Z. (2019). Assessment of water footprints of consumption and production in transboundary river basins at country-basin mesh-based spatial resolution. *Environmental Research and Public Health.*

Yang, H., Wang, L., Abbaspour, K., and Zehnder, A. (2006). Virtual water trade: An assessment of water use efficiency in the international food trade. *Hydrology and Erth System Sciences.*

Yang, Y. E., Son, K., Hung, F., and Tidwell, V. (2020). Impact of climate change on adaptive management decisions in the face of water scarcity. *Journal of Hydrology*, 588:125015.

Yates, D. N. and Strzepek, K. M. (1998). An assessment of integrated climate change impacts on the agricultural economy of egypt. *Climatic Change*, 38(3):261–287.

Yoffe, S. B. and Wolf, A. T. (2002). Water, conflict and cooperation: Geographical perspectives. *Cambridge Review of International Affairs*, 12(2):197–213.

Yuan, X., Li, S., Chen, J., Yu, H., Yang, T., Wang, C., Huang, S., Chen, H., and Ao, X. (2024). Impacts of global climate change on agricultural production: A comprehensive review. *Agronomy*, 14(7):1360.

Zeitoun, M. and Allan, J. A. (2008). Applying hegemony and power theory to transboundary water analysis. *Water policy*, 10(S2):3–12.

Zeitoun, M., Allan, J. T., and Mohieldeen, Y. (2010). Virtual water 'flows' of the nile basin, 1998–2004: A first approximation and implications for water security. *Global Environmental Change*, 20(2):229–242.

Zhang, L., Feng, S., Zhan, E., and Zhang, Z. (2024). How does virtual water influence the water stress pattern in africa? a research perspective from the perspectives of production and trade. *Science of The Total Environment*, page 174244.

Zhang, Y., Zhang, J., Tang, G., Chen, M., and Wang, L. (2016). Virtual water flows in the international trade of agricultural products of china. *Sci. Total Environ.*

Zhao, X., van der Mensbrugghe, D. Y., Keeney, R. M., and Tyner, W. E. (2020). Improving the way land use change is handled in economic models. *Economic modelling*, 84:13–26.

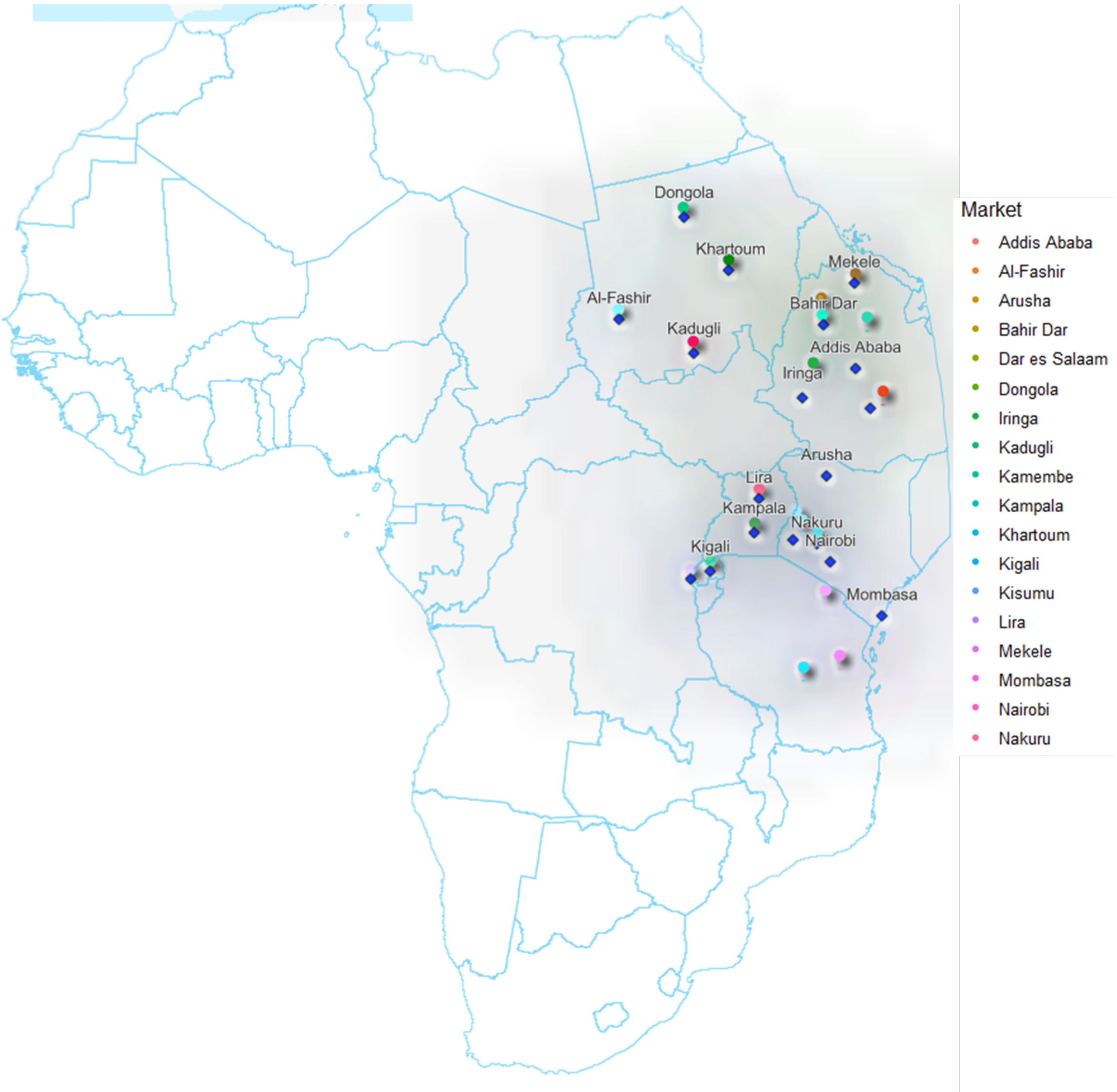
Zhou, B., Li, Y., and Ali, T. (2024). Sector-level inter-provincial virtual water trade in china: Implications for regional water stress. *Sustainability*, 16(9):3666.

Zisopoulou, A., Nikolaidis, N., and Karalis, A. (2021). Physical water scarcity in agriculture and its economic interpretation: Complexities in translating physical variables into economic terms. *Water Resources Research*, 57:1–14.

Appendix A

Chapter 2 Appendix

Fig. A.1 East African Commodity Market and nearby Weather Station

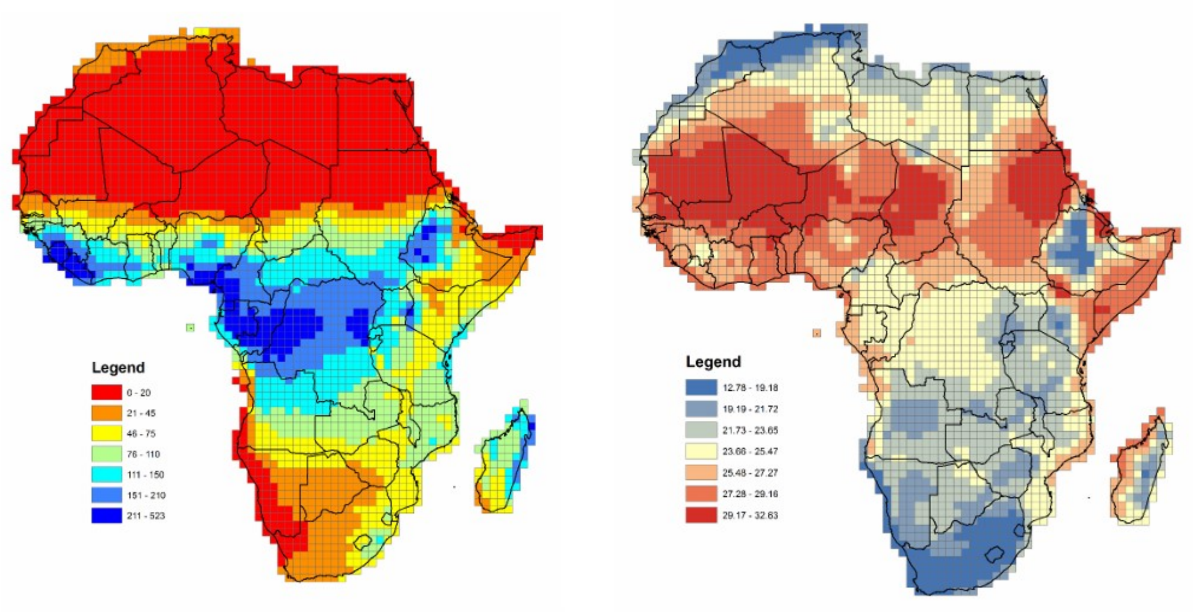


Notes: The *Map* shows the selected East African markets near weather stations. The blue rectangle represents the weather station, while the location symbols, marked in different colours, indicate the 18 markets chosen to track food price trends in six East African countries.

Table A.1 Grain Markets and Weather Stattions

Country	Market	Metrological stations around the crops' production farm				
		Beans	Maize	Sorghum	Wheat	Rice
Ethiopia	Addis Ababa		Bako		Sinana	
	Bahir Dar		Gondar		Gojjam	
	Mekelle		Mekelle		Enderta	
Kenya	Kisumu	Kitale	Kitale			
	Mombasa	Eldoret	Eldoret			
	Nairobi	Kitale	Kitale			
	Nakuru	Nakuru	Nakuru			
Rwanda	Kigali		Kigali			Kigali
	Kimironko		Kimironko			Kimironko
Sudan	Khartoum			Khartoum	Khartoum	
	Al-Fashir			Al-Fashir	Al-Fashir	
	Dongola			Dongola	Dongola	
	Kadugli			Kadugli	Kadugli	
Tanzania	Arusha	Arusha	Arusha			
	Daresalaam	Daresalaam	Daresalaam			
	Iringa	Iringa	Iringa			
Uganda	Kampala	Kampala	Kampala			Kampala
	Lira	Lira	Lira			Lira

Fig. A.2 Average Rainfall and Temperature in Africa



(a) Average Yearly Rainfall (in mm), 1997-2011 **(b)** Average Yearly Temperature (in °C), 1997-2011

Notes: Map a and b: illustrate Africa's average rainfall and temperature provided by Harari and La Ferrara (2013), in both cases, the Nile River Basin countries are experiencing high temperatures and low precipitation.

Fig. A.3 Food price trend in 6 countries in East Africa

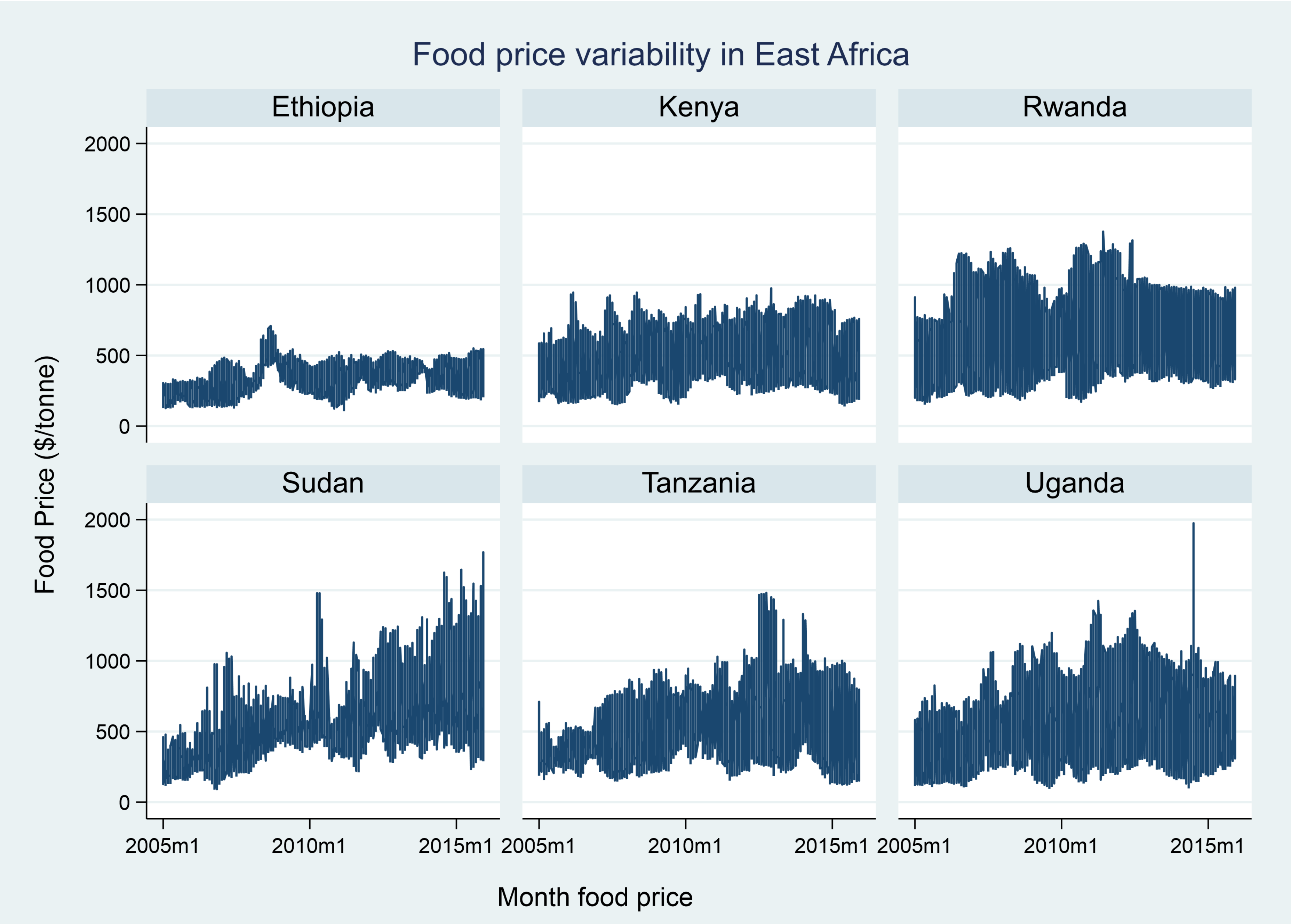


Fig. A.4 Food price trend in 18 markets in East Africa

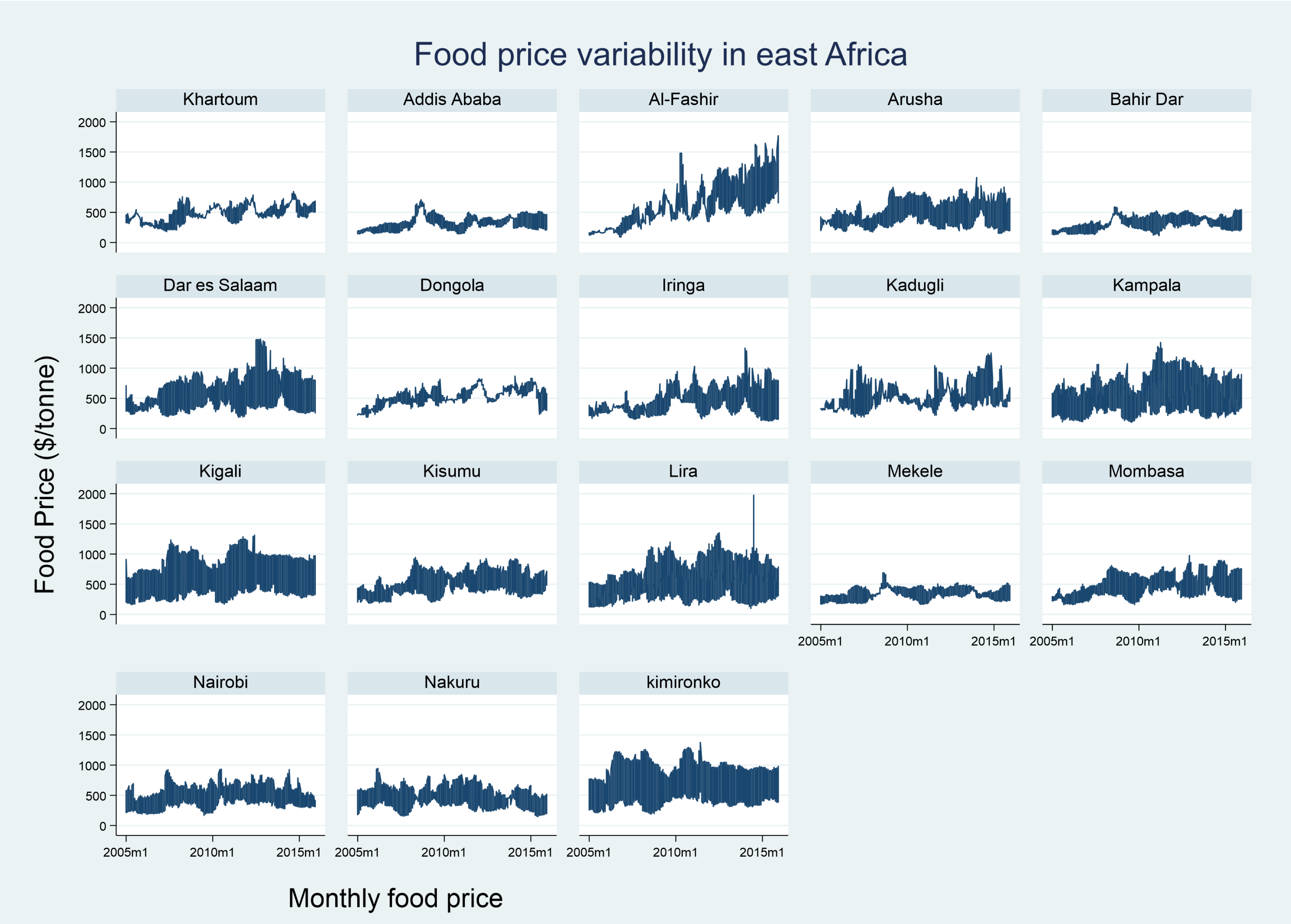
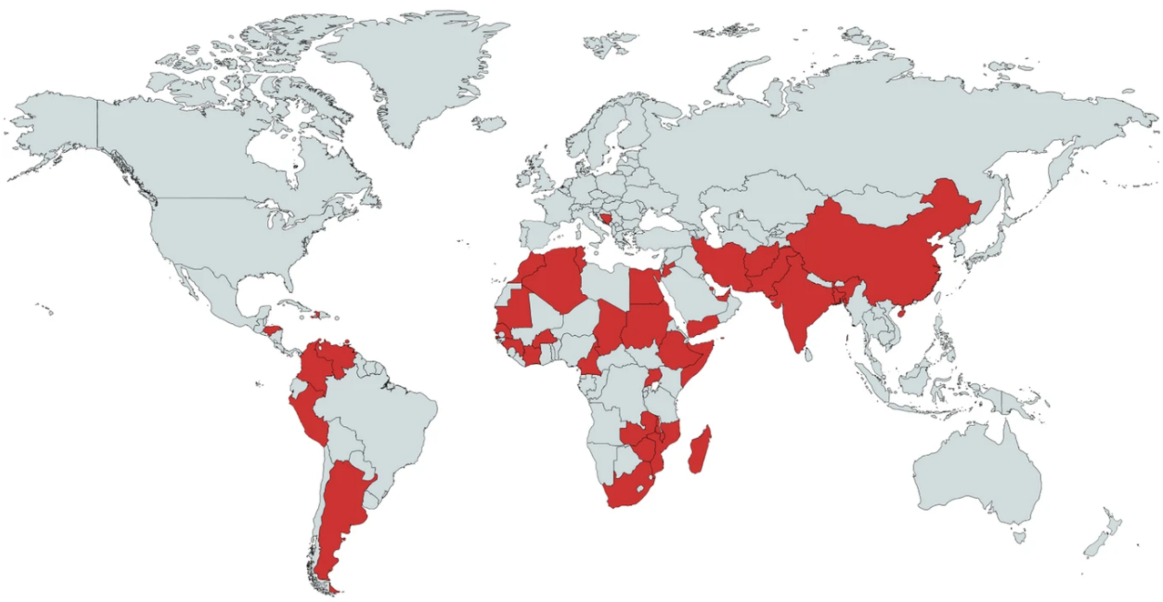


Fig. A.5 Global food price volatilities



Notes: As global food price volatility decreased after 2009, access to food, particularly in low-income countries, has worsened. According to the study by Guo and Tanaka (2020) illustrated in *Figure* (A.5), this deterioration is highlighted by a red region on the map where food prices continue to soar. In contrast, stability has been observed in most of the world's economies. These factors have contributed to heightened societal and political instability in various regions, with limited access to nutritious food exacerbating inequalities and fueling unrest.

Table A.2 ANOVA Test for Maize prices

Source	Partial SS	DF	MS	F	Prob > F
Model	30,724,942	98	313,519.82	37.10	0.0000
Country	1,500,181.4	2	750,090.68	88.76	0.0000
Market	4,170,966.4	6	695,161.07	82.26	0.0000
year	12,857,281	10	1,285,728.1	152.15	0.0000
Country # year	2,688,674	20	134,433.7	15.91	0.0000
Market # year	7,476,173.2	60	124,602.89	14.75	0.0000
Residual	9,202,561	1,089	8,450.4692		
Total	39,927,503	1,187	33,637.324		

Table A.3 ANOVA test for Wheat prices

Source	Partial SS	DF	MS	F	Prob > F
Model	10,636,720	153	69,521.047	25.18	0.0000
Country	1,210,003.7	4	302,500.93	109.54	0.0000
Market	481,902.23	9	53,544.693	19.39	0.0000
year	2,582,873.7	10	258,287.37	93.53	0.0000
Country # year	1,999,647	40	49,991.175	18.10	0.0000
Market # year	2,251,517.1	90	25,016.857	9.06	0.0000
Residual	4,677,873.3	1,694	2,761.4364		
Total	15,314,594	1,847	8,291.6045		

Table A.4 ANOVA test for Rice Prices

Source	Partial SS	DF	MS	F	Prob > F
Model	15,132,728	43	351,923.91	34.48	0.0000
Country	1,334,388.4	1	1,334,388.4	130.73	0.0000
Market	265,315.82	2	132,657.91	13.00	0.0000
year	8,638,798.3	10	863,879.83	84.64	0.0000
Country # year	2,013,331.8	10	201,333.18	19.72	0.0000
Market # year	2,656,152.7	20	132,807.64	13.01	0.0000
Residual	4,940,247.3	484	10,207.122		
Total	20,072,975	527	38,089.137		

Table A.5 ANOVA results for Sorghum Prices

Source	Partial SS	DF	MS	F	Prob > F
Model	9,228,835.2	43	214,624.07	26.33	0.0000
Market	1,167,371.4	3	389,123.8	47.73	0.0000
year	4,354,682.5	10	435,468.25	53.42	0.0000
mkt # year	3,706,781.3	30	123,559.38	15.16	0.0000
Residual	3,945,783.5	484	8,152.4452		
Total	13,174,619	527	24,999.276		

Table A.6 ANOVA results for Beans Prices

Source	Partial SS	DF	MS	F	Prob > F
Model	49,497,806	76	651,286.92	64.29	0.0000
Country	1,084,477.1	1	1,084,477.1	107.05	0.0000
Market	5,023,668.7	5	1,004,733.7	99.18	0.0000
year	13,439,254	10	1,343,925.4	132.66	0.0000
Country # year	839,980.77	10	83,998.077	8.29	0.0000
Market # year	13,485,158	50	269,703.17	26.62	0.0000
Residual	8,580,309.7	847	10,130.236		
Total	58,078,115	923	62,923.202		

Table A.7 Effect of different variables on crop markets and years, separated by negative and positive impacts

Crop	**Desc. Var**	**Negatively - effect**	**Positively - effect**
beans	Country	Tanzania and Uganda	Ethiopia, Kenya, Rwanda, & Tanzania
Maize	Country	Uganda	Rwanda & Tanzania
Rice	Country	Rwanda	
Sorg	Country		
Wheat	Country		
beans	Market	Kisumu, Mombasa, & Nairobi	Kampala
Maize	Market	Kisumu, Mombasa, & Nairobi	Kampala
Rice	Market		
Sorg	Market		
Wheat	Market		
beans	Year	2013, 2015	2006, 2009, 2010, 2011
Maize	Year		2008, 2009, 2011-15
Rice	Year		2006-2015
Sorg	Year	2006-2007	2009-2015
Wheat	Year		2007-2015
beans	Country # Year	Tanzania 2007-15	Ken-2006, Rwa 2006-15
Maize	Country # Year	Ken 2007-15, Tan 2007-09, 2011-15	and Tan 2006 & 10
Rice	Country # Year	Uganda 2006-10	Uganda 2011-15
Sorg	Country # Year		
Wheat	Country # Year		
beans	Market # Year	Kampala 2005-15	Dares Salaam 2005-15
Maize	Market # Year	Arusha 2005-15	Dares Salaam 2005-15
Rice	Market # Year	Kigali 2006-10	Al-Fashir & Dongola 2005-15
Sorg	Market # Year	Kadugali 20011-15	Al-Fashir, Dongola, and Kadugali 2005-15
Wheat	Market # Year		

Table A.8 Interactions involving covariates and environmental factors in East Africa

Interaction term	**Explanations**
Country # Year	The interaction between country and Year in East Africa reveals insights into regional price volatility trends. Analysing data from 2005 to 2015 reveals fluctuating commodity prices and exchange rates, which are influenced by economic policies and external shocks. Emerging nations within the region often experience heightened volatility linked to currency fluctuations and geopolitical instability. This emphasises the complex relationship between national economic conditions and regional market dynamics. Importantly, it emphasises the need for adaptive risk management strategies tailored to local contexts to mitigate the impact of price volatility effectively.
Market # Year	In East Africa, the interaction between market dynamics and time reveals evolving patterns of price volatility influenced by technological advancements, regulatory shifts, and changing consumer preferences from 2005 to 2015. Notably, high-tech sectors exhibit heightened volatility during periods of rapid innovation, which starkly contrasts with the stability in traditional markets driven by established consumer bases. This stark contrast highlights the need for agile market strategies that anticipate and respond to volatility drivers, which are essential for maintaining resilience and a competitive advantage in dynamic economic environments.
Export Restriction # Temperature	The interaction between export restrictions and temperature fluctuations in East Africa has a significant impact on agricultural livelihoods and economic stability. Governments may impose export bans on staple crops during extreme heat to secure local food supplies. However, these measures can strain international trade and increase local market volatility, which in turn impacts farmers' incomes and consumer prices. This highlights the delicate balance between ensuring food security and sustainable trade practices, emphasising the need for adaptive policies to manage climate risks and support resilient agricultural economies.
Export Restriction # Rainfall	In East Africa, export restrictions in response to rainfall variability have a direct impact on agricultural productivity and economic resilience. Government-imposed export controls, implemented during erratic rainfall conditions ranging from droughts to floods, aim to secure local food supplies and stabilise prices. However, these controls can disrupt regional trade dynamics, hindering economic growth that relies on agricultural exports. This highlights the challenge of balancing food security with trade obligations, emphasising the need for integrated policies that support sustainable agriculture and effectively manage climate risks.

Sources: The concept of variable interaction for the analysis was derived from various sources, including (Abbott and Borot de Battisti, 2011; Chapoto and Jayne, 2009; Gouel, 2013; Jayne et al., 2006)

Appendix B

Chapter 3 Appendix

Table B.1 Virtual Water Flow in the NRB 2007 (10^6 m^3)

Country	Withdrawal	Internal WFP	Import				Export				Net Inflow
			NRB	RoA	RoW	Total	NRB	RoA	RoW	Total	
Burundi	5,790.89	4,299.45	147.46	21.94	44.40	213.80	16.48	55.00	1,419.97	1,491.45	-1,277.65
DR Congo	26,706.75	22,503.88	372.41	1,415.78	361.18	2,149.36	78.62	140.79	3,983.47	4,202.87	-2,053.51
Egypt	62,673.90	40,316.07	22,312.92	431.26	3,594.25	26,338.42	52.90	531.32	21,773.60	22,357.83	3,980.59
Eritrea	2,777.89	2,405.15	115.64	11.23	29.00	155.87	5.68	20.75	346.30	372.74	-216.87
Ethiopia	77,498.14	5.58	87.74	115.73	235.44	438.91	204.93	699.25	76,588.38	77,492.56	-77,053.65
Kenya	27,434.01	21,274.22	5,843.66	822.79	1,205.09	7,871.55	261.64	139.37	5,758.77	6,159.78	1,711.77
Rwanda	7,558.75	6,751.58	327.60	40.88	79.35	447.83	15.61	34.77	756.79	807.17	-359.34
Sudan	58,072.25	27.30	1.34	2.03	3.99	7.36	1,220.29	4,952.80	51,871.87	58,044.96	-58,037.60
Uganda	35,538.62	19,129.01	400.39	181.24	322.80	904.43	5,692.33	225.92	10,491.36	16,409.61	-15,505.18
Tanzania	38,943.39	12,291.58	240.11	385.44	502.18	1,127.74	820.10	640.05	25,191.66	26,651.81	-25,524.08
NRB	342,994.60	129,003.82	29,849.29	3,428.32	6,377.66	39,655.27	8,368.59	7,440.03	198,182.16	213,990.79	-174,335.51

Table B.2 Virtual Water Flow in the NRB 2015 (10^6 m^3)

Country	Withdrawal	Internal WFP	Import				Export				Net Inflow
			NRB	RoA	RoW	Total	NRB	RoA	RoW	Total	
Burundi	5,790.89	4,643.31	31.56	28.80	46.09	106.45	16.38	50.75	1,080.46	1,147.59	-1,041.13
DR Congo	26,706.75	23,464.74	337.60	2,017.12	403.95	2,758.68	81.75	125.41	3,034.86	3,242.01	-483.34
Egypt	62,673.90	41,096.43	859.95	356.20	3,074.42	4,290.57	76.80	535.72	20,964.95	21,577.47	-17,286.91
Eritrea	2,777.89	2,375.27	6.77	11.58	28.57	46.92	7.87	26.12	368.63	402.63	-355.71
Ethiopia	77,498.14	6.26	73.51	136.63	272.49	482.63	424.62	1,551.61	75,515.65	77,491.88	-77,009.24
Kenya	27,434.01	22,973.50	7,556.60	1,053.83	1,511.21	10,121.64	217.14	104.66	4,043.42	4,365.22	5,756.42
Rwanda	7,558.75	6,860.93	293.82	72.32	121.69	487.84	12.91	30.97	653.94	697.82	-209.98
Sudan	58,072.25	51,640.48	66.14	13.94	44.44	124.53	37.72	169.11	6,224.95	6,431.78	-6,307.25
Uganda	35,538.62	19,990.61	339.73	189.01	302.27	831.02	7,547.64	190.60	7,809.77	15,548.01	-14,716.99
Tanzania	38,943.39	13,123.67	121.31	345.29	400.17	866.78	1,113.06	766.35	23,940.32	25,819.72	-24,952.95
NRB	342,994.60	186,175.19	9,687.00	4,224.73	6,205.31	20,117.04	9,535.88	3,551.30	143,636.94	156,724.13	-136,607.09

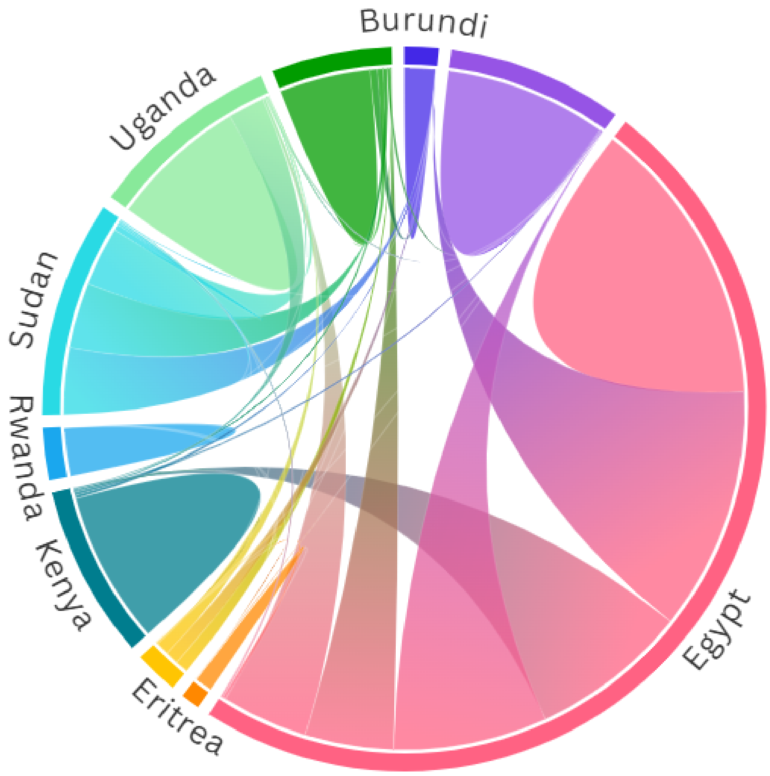
Table B.3 Global Virtual Water Consumption per capita distribution 2007

Consumption trend	Unit	NRB	RoA	ASI	Europe	NAM	OCE	SAM
Domestic Consumption	Absolute (10^6 m^3)	137,372.41	435,795.37	3,678,452.37	1,052,955.06	984,669.67	92,999.07	889,784.42
	Per capita (m^3)	798.68	541.36	903.57	2,135.81	2,948.11	2,657.12	2,341.54
Virtual water export	Absolute (10^6 m^3)	205,622.19	257,507.46	374,471.99	126,495.23	200,394.55	71,376.43	219,510.39
	Per capita (m^3)	1,195.48	319.89	91.99	256.58	599.98	2,039.33	577.66
Virtual water import	Absolute (10^6 m^3)	9,686.32	27,352.60	399,154.25	564,597.65	342,578.06	23,602.87	88,406.50
	Per capita (m^3)	56.32	33.98	98.05	1,145.23	1,025.68	674.37	232.65
Water footprint (WF)	Absolute (10^6 m^3)	-58,563.46	205,640.51	3,703,134.63	1,491,057.48	1,126,853.18	45,225.51	758,680.53
(Top-down approach)	Per capita (m^3)	-340.49	255.45	909.64	3,024.46	3,373.81	1,292.16	1,996.53
Direct water use	Absolute (10^6 m^3)	8,890.89	10,992.14	195,010.02	51,534.27	38,646.99	1,566.43	41,231.23
	Per capita (m^3)	51.69	13.65	47.90	104.53	115.71	44.76	108.50

Table B.4 Global Virtual Water Consumption per capita distribution 2015

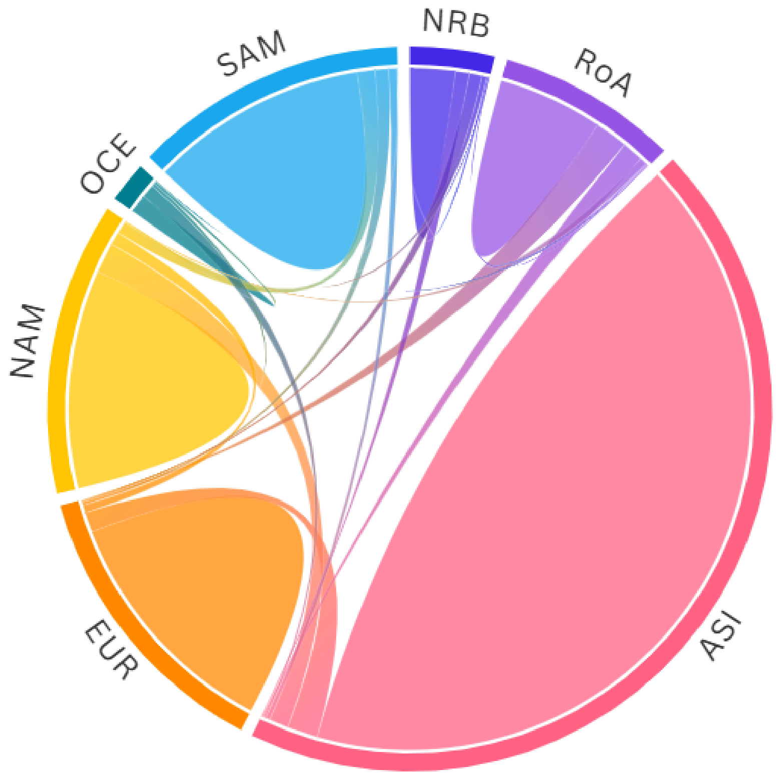
Consumption trend	Unit	NRB	RoA	ASI	Europe	NAM	OCE	SAM
Domestic Consumption	Absolute (10^6 m^3)	195,806.36	452,464.95	3,765,276.43	1,036,873.84	938,896.53	79,141.30	935,650.84
	Per capita (m^3)	761.89	479.31	855.74	2,040.29	2,551.35	1,978.53	2,271.00
Virtual water export	Absolute (10^6 m^3)	147,188.24	277,527.83	250,956.73	142,576.45	246,167.69	85,234.20	173,643.97
	Per capita (m^3)	572.72	293.99	57.04	280.55	668.93	2,130.86	421.47
Virtual water import	Absolute (10^6 m^3)	10,599.43	23,983.49	458,000.76	454,753.10	253,431.79	22,419.76	100,106.78
	Per capita (m^3)	41.24	25.41	104.09	894.83	688.67	560.49	242.98
Water footprint (WF)	Absolute (10^6 m^3)	59,217.55	198,920.62	3,972,320.47	1,349,050.50	946,160.62	16,326.86	862,113.64
(Top-down approach)	Per capita (m^3)	230.42	210.72	902.80	2,654.57	2,571.09	408.17	2,092.51
Direct water use	Absolute (10^6 m^3)	8,913.91	11,500.38	195,980.47	48,288.51	36,391.72	1,556.57	41,634.02
	Per capita (m^3)	34.68	12.18	44.54	95.02	98.89	38.91	101.05

Fig. B.1 Overall virtual water footprint in NRB



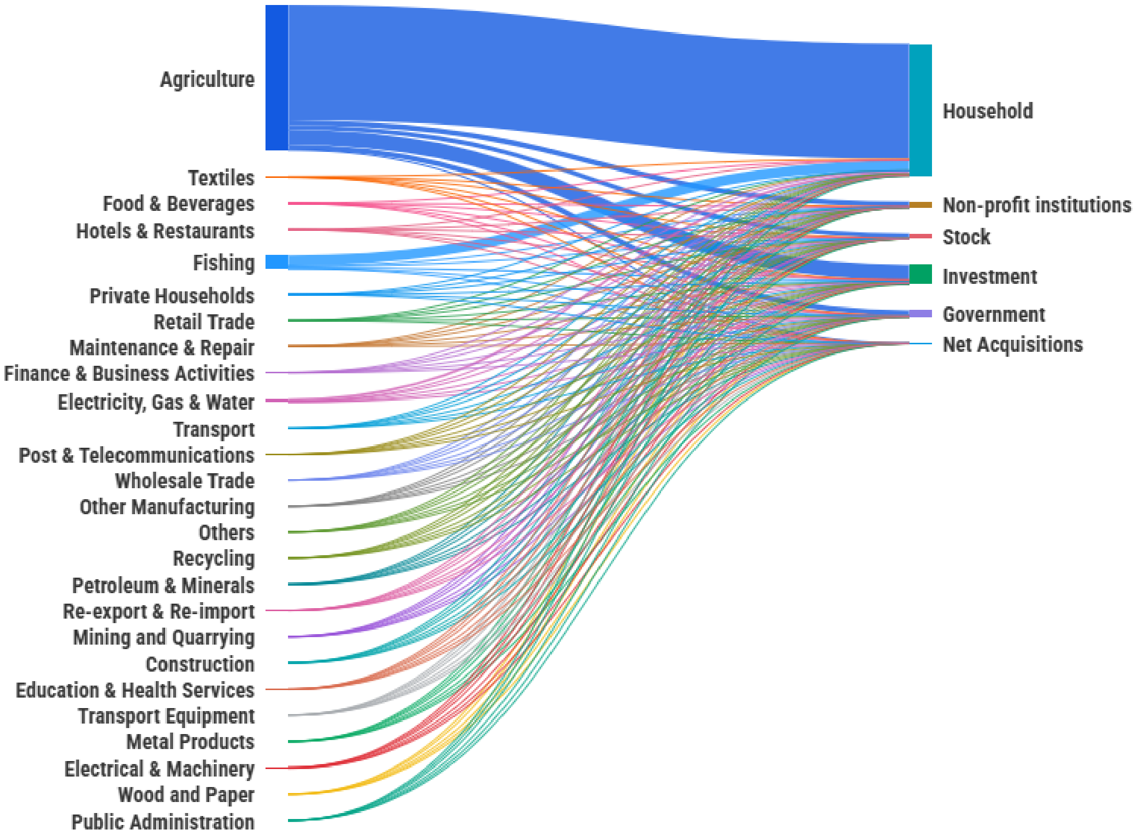
Note: This chord diagram illustrates the internal and external water footprints in the NRB region. The smaller diagonal lines between nations represent external water footprints, while the tick-coloured line in each country indicates the domestic water footprint. As depicted on the graph, Egypt only exhibits a substantial external water footprint, which, in this case, is exported to Kenya.

Fig. B.2 Overall virtual water footprint in the world



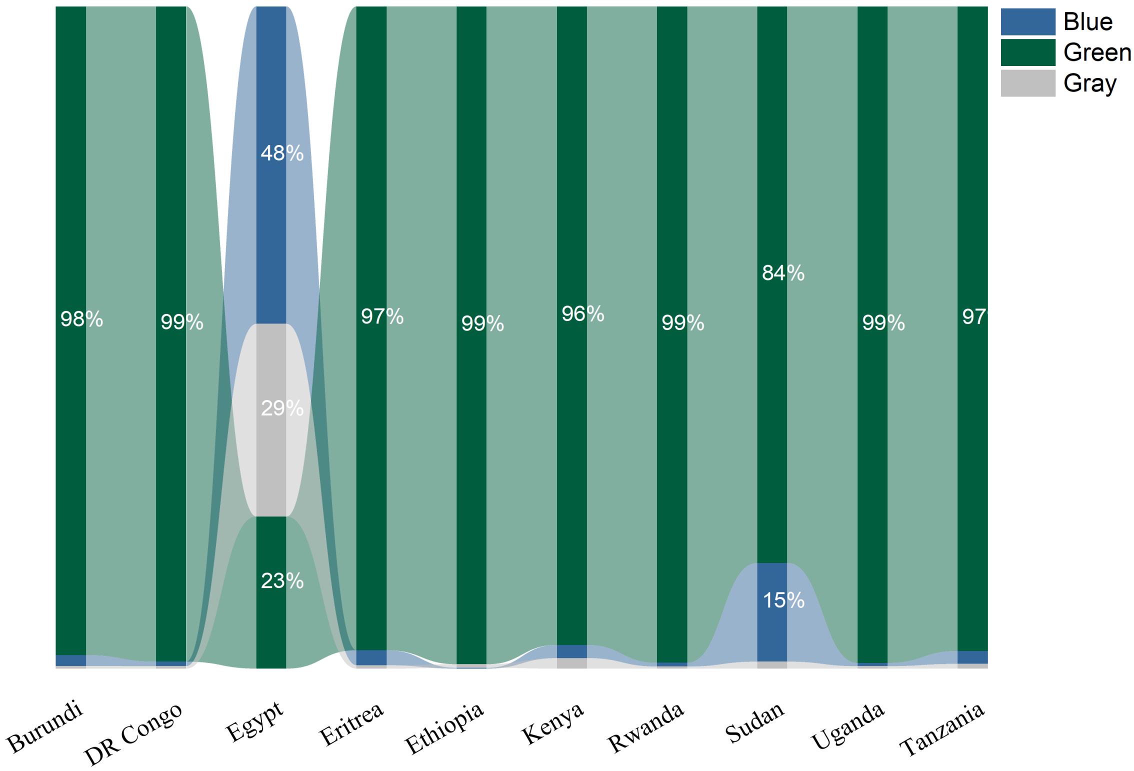
Note: This chord diagram illustrates the world's internal and external water footprints. The smaller diagonal lines that cross between regions represent external water footprints, while the tick-colored line in each region indicates the domestic water footprint. As depicted on the graph, Asia, South and Northern America, the Nile River Basin (NRB), and the Rest of Africa are well-connected in trade, exhibiting a substantial external water footprint globally.

Fig. B.3 Virtual Water Flow between Intermediate and Final Demand



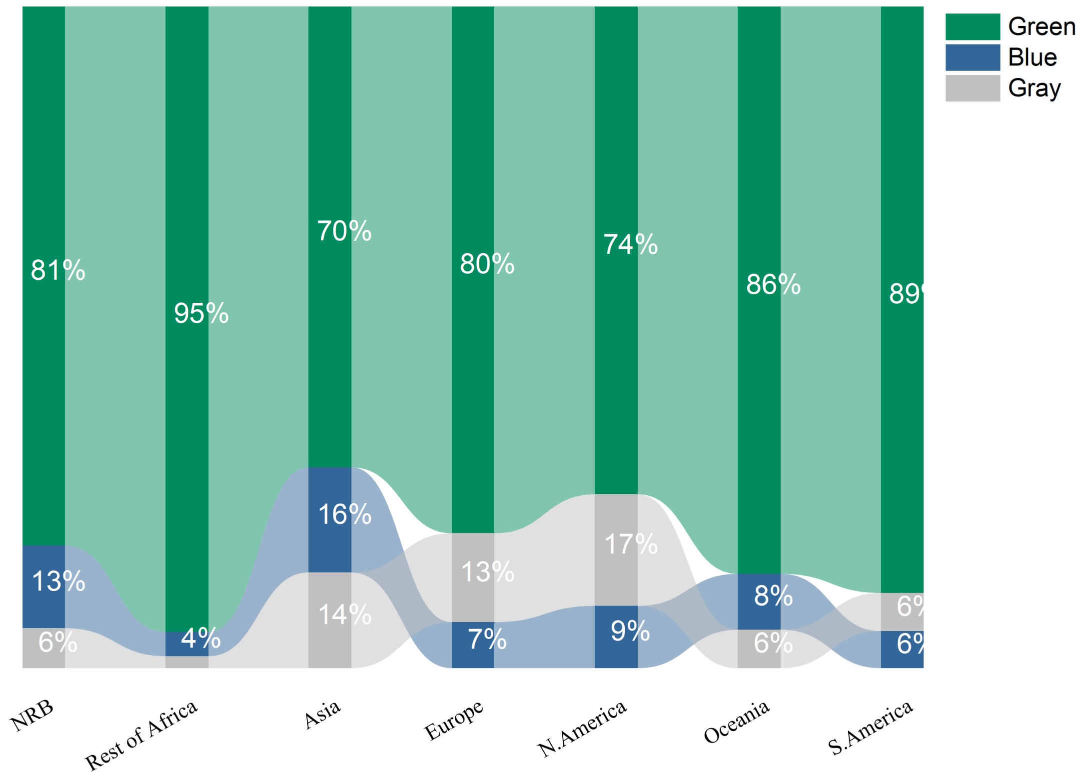
Note: This Sankey diagram illustrates the global virtual water flow between intermediate and final demand. Intermediate sectors consist of 26 sectors. Final demand sectors include households, investment, change in investment (stock), non-profit institutions, government, and net capital acquisitions. Agriculture is the primary source, contributing 78% of households' virtual water. The diagram illustrates the distribution of virtual water, primarily for household consumption, with the remainder allocated for investment and government use.

Fig. B.4 Green, Blue, and Gray Water in the NRB



Note: This graph shows the share of green, blue, and gray virtual water in Nile River Basin countries. Most countries rely heavily on green water (rain-fed agriculture), while Egypt and Uganda show higher shares of blue and gray water, indicating greater dependence on irrigation and water treatment.

Fig. B.5 Virtual Water Composition Across Continents



Note: This graph illustrates the share of green, blue, and gray virtual water across global regions. Green water, primarily from rainfall, dominates all regions, particularly in Africa, South America, and Oceania. Asia and North America show higher shares of blue and gray water, indicating greater reliance on irrigation and water treatment. The data highlights regional differences in agricultural water sources and environmental impact.

Table B.5 Water scarcity of NRB in 2007

Country	Virtual Water availability ($10^6\ m^3 yr^{-1}$)	Virtual Water Use ($10^6\ m^3\ yr^{-1}$)	Gross Virtual water import ($10^6\ m^3\ yr^{-1}$)	Gross Virtual water export ($10^6\ m^3\ yr^{-1}$)	Net virtual water import ($10^6\ m^3\ yr^{-1}$)	Water Scarcity (%)	Water self-sufficiency (%)	water Dependency (%)
Burundi	10.06	5.79	0.21	1.49	-1.28	58	95%	5%
DR of Congo	900.00	26.71	2.15	4.20	-2.05	3	91%	9%
Egypt	86.80	62.67	26.34	22.36	3.98	72	60%	40%
Eritrea	4.22	2.78	0.16	0.37	-0.22	66	94%	6%
Ethiopia	122.00	77.50	0.44	77.49	-77.05	64	99%	1%
Kenya	20.70	27.43	7.87	6.16	1.71	133	73%	27%
Rwanda	9.50	7.56	0.45	0.81	-0.36	80	94%	6%
Sudan	37.80	58.07	0.01	58.04	-58.04	154	79%	21%
Uganda	84.00	35.54	0.90	16.41	-15.51	42	95%	5%
Tanzania	39.00	38.94	1.13	26.65	-25.52	100	92%	8%
NRB	1314.08	342.99	39.66	213.99	-174.34	26	76%	24%

Notes: According to Mekonnen and Hoekstra (2016), water scarcity is categorized into three levels based on domestic water availability and the percentage of external water dependency, such as 20 - 40% Moderate water Scarcity, 40 - 100% Sever Water Scarcity, and Over 100% Extreme Water Scarcity.

Table B.6 Water scarcity of NRB in 2015

Country	Virtual Water availability ($10^6\ m^3 yr^{-1}$)	Virtual Water Use ($10^6\ m^3\ yr^{-1}$)	Gross Virtual water import ($10^6\ m^3\ yr^{-1}$)	Gross Virtual water export ($10^6\ m^3\ yr^{-1}$)	Net virtual water import ($10^6\ m^3\ yr^{-1}$)	Water Scarcity (%)	Water self-sufficiency (%)	water Dependency (%)
Burundi	10.06	5.79	0.11	1.15	-1.04	58	98%	2%
DR of Congo	900.00	26.71	2.76	3.24	-0.48	3	89%	11%
Egypt	57.50	62.67	4.29	21.58	-17.29	109	91%	9%
Eritrea	4.16	2.78	0.05	0.40	-0.36	67	98%	2%
Ethiopia	122.00	77.50	0.48	77.49	-77.01	64	99%	1%
Kenya	20.70	27.43	10.12	4.37	5.76	133	70%	30%
Rwanda	9.50	7.56	0.49	0.70	-0.21	80	93%	7%
Sudan	26.93	58.07	0.12	6.43	-6.31	216	100%	0%
Uganda	63.23	35.54	0.83	15.55	-14.72	56	96%	4%
Tanzania	39.00	38.94	0.87	25.82	-24.95	100	94%	6%
NRB	1253.08	342.99	20.12	156.72	-136.61	27	90%	11%

Notes: According to Mekonnen and Hoekstra (2016), water scarcity is categorized into three levels based on domestic water availability and the percentage of external water dependency, such as 20 - 40% Moderate water Scarcity, 40 - 100% Sever Water Scarcity, and Over 100% Extreme Water Scarcity.

Appendix C

Chapter 4 Appendix

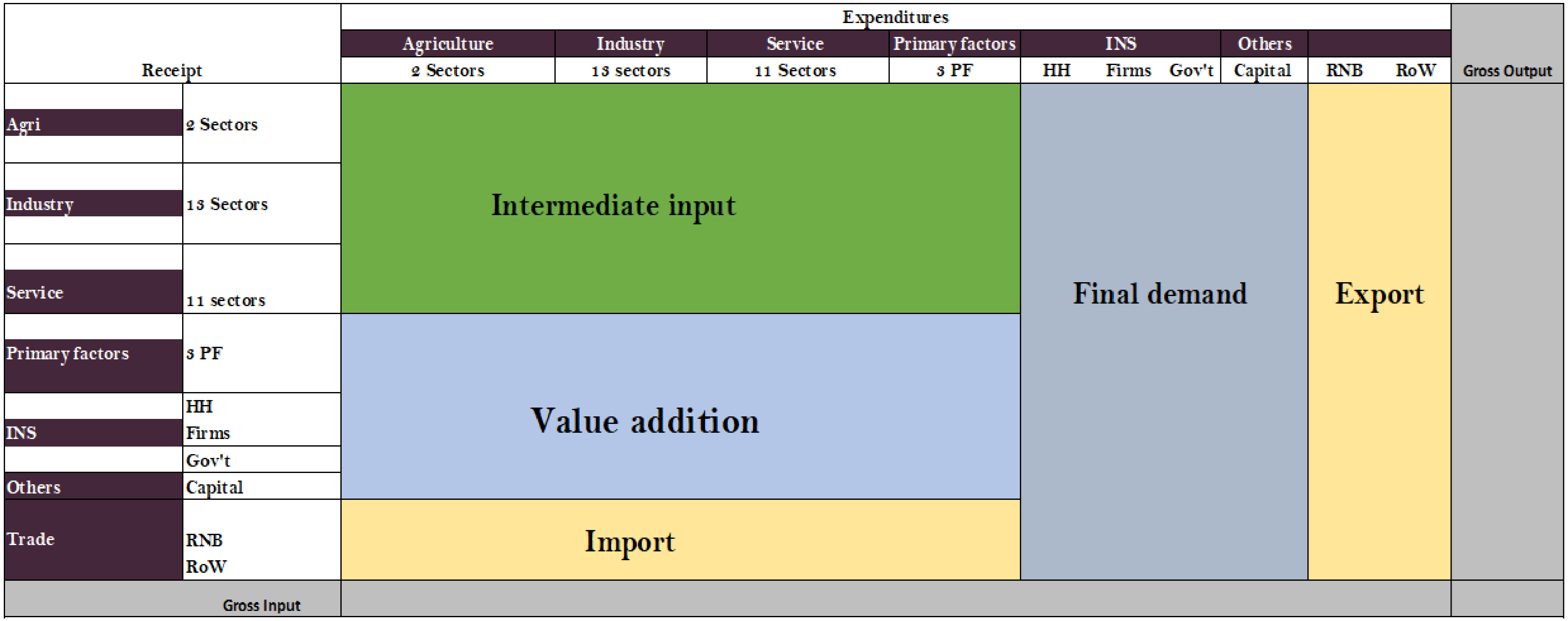


Fig. C.1 Structure of Egypt's WSAM

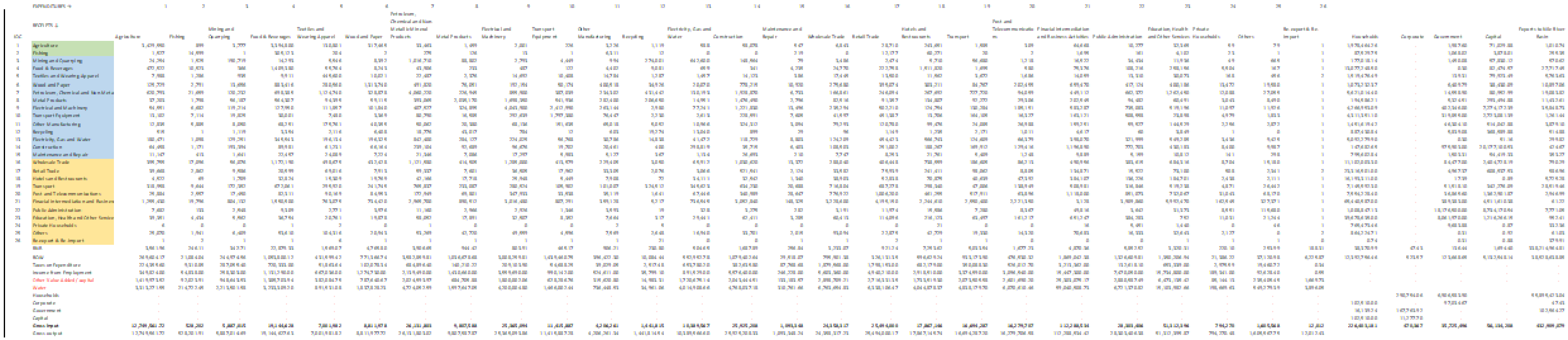


Fig. C.2 WSAM of Egypt

Table C.1 Elasticity of Substitution

Sectors	Armington Elasticity	CET Elasticity	Capital-Labour Elasticity	Water-Capital Elasticity	Wage Differential	Intermediate-Value Added Elasticity
	σ_V	σ_X	σ_F	σ_1	ϕ	σ_Z
Agriculture	2.00	2.00	0.30	0.30	1.00	0.30
Fishing	2.00	2.00	0.30	0.30	1.00	0.30
Mining and Quarrying	2.00	2.00	0.30	0.30	1.00	0.30
Food & Beverages	2.00	2.00	0.30	0.30	1.00	0.30
Textiles and Wearing Apparel	2.00	2.00	0.30	0.30	1.00	0.30
Wood and Paper	2.00	2.00	0.30	0.30	1.00	0.30
Petroleum, Chemical and Non-Metallic Mineral Products	2.00	2.00	0.30	0.30	1.00	0.30
Metal Products	2.00	2.00	0.30	0.30	1.00	0.30
Electrical and Machinery	2.00	2.00	0.30	0.30	1.00	0.30
Transport Equipment	2.00	2.00	0.30	0.30	1.00	0.30
Other Manufacturing	2.00	2.00	0.30	0.30	1.00	0.30
Recycling	2.00	2.00	0.30	0.30	1.00	0.30
Electricity, Gas and Water	2.00	2.00	0.30	0.30	1.00	0.30
Construction	2.00	2.00	0.30	0.30	1.00	0.30
Maintenance and Repair	2.00	2.00	0.30	0.30	1.00	0.30
Wholesale Trade	2.00	2.00	0.30	0.30	1.00	0.30
Retail Trade	2.00	2.00	0.30	0.30	1.00	0.30
Hotels and Restaurants	2.00	2.00	0.30	0.30	1.00	0.30
Transport	2.00	2.00	0.30	0.30	1.00	0.30
Post and Telecommunications	2.00	2.00	0.30	0.30	1.00	0.30
Financial Intermediation and Business Activities	2.00	2.00	0.30	0.30	1.00	0.30
Public Administration	2.00	2.00	0.30	0.30	1.00	0.30
Education, Health and Other Services	2.00	2.00	0.30	0.30	1.00	0.30
Private Households	2.00	2.00	0.30	0.30	1.00	0.30
Others	2.00	2.00	0.30	0.30	1.00	0.30

Table C.2 Water reduction simulation output

Sectors	S1a: Agricultural Productivity shocks 5%		S1b: Agricultural Productivity shocks 20%		S1c: Agricultural Productivity shocks 30%	
	Short Run	Long Run	Short Run	Long Run	Short Run	Long Run
Agriculture	-27.90	-10.46	-57.68	-48.89	-82.74	-64.23
Fishing	-4.99	-1.14	-22.97	-5.23	-31.83	-39.38
Mining and Quarrying	-0.42	-0.30	-2.03	-1.38	-129.36	-90.07
Food & Beverages	1.34	0.22	6.43	1.02	-33.50	-36.35
Textiles and Wearing Apparel	0.23	-0.01	1.08	-0.05	-128.37	-99.20
Wood and Paper	-0.61	-0.42	-2.90	-1.92	-32.49	-40.07
Petroleum, Chemical and Non-Metallic Mineral Products	-0.95	-0.47	-4.55	-2.17	-63.85	-60.00
Metal Products	-0.60	-0.46	-2.96	-2.12	-46.71	-50.64
Electrical and Machinery	-0.31	-0.37	-1.73	-1.68	-33.09	-37.12
Transport Equipment	-0.10	-0.35	-0.77	-1.59	-24.82	-30.50
Other Manufacturing	-0.29	-0.34	-1.55	-1.56	-45.82	-44.42
Recycling	0.48	-0.19	1.83	-0.87	-43.93	-35.32
Electricity, Gas and Water	-1.08	-0.59	-5.10	-2.72	-24.63	-34.53
Construction	-0.35	-0.28	-2.07	-1.29	-26.73	-33.37
Maintenance and Repair	-0.60	-0.49	-2.91	-2.23	-23.78	-32.33
Wholesale Trade	-0.59	-0.49	-3.01	-2.23	-27.63	-35.98
Retail Trade	-0.58	-0.48	-2.76	-2.21	-15.23	-26.21
Hotels and Restaurants	-0.38	-0.38	-1.75	-1.75	-18.33	-27.97
Transport	-1.03	-0.54	-4.95	-2.47	-36.78	-41.43
Post and Telecommunications	-0.57	-0.46	-2.77	-2.12	-21.69	-31.33
Financial Intermediation and Business Activities	-0.72	-0.49	-3.50	-2.24	-19.34	-30.39
Public Administration	1.41	0.13	5.95	0.58	-27.56	-25.21
Education, Health, and Other Services	-0.60	-0.42	-2.83	-1.92	-15.75	-25.66
Private Households	-0.69	-0.48	-3.21	-2.21	-15.16	-25.83
Others	-1.06	-0.57	-5.04	-2.59	-27.91	-36.89
Re-export & Re-import	-1.06	-0.50	-4.25	-2.35	-25.23	-36.89

Appendix C: AMOS Core Model Equations developed by (Harrigan et al., 1991)

Production Technology: CES productions function of Agricultural sectors

$$Y_{KW} = A(\alpha K^{-\rho 1} + (1-\alpha)W^{-\rho 1})^{\frac{-1}{\rho 1}} \tag{C.1}$$

$$Y = A(\beta Y_{kw}^{-\rho} + \beta(1-\beta)L^{-\rho 1})^{\frac{-m}{\rho 1}} \tag{C.2}$$

Where:

Y_{KW} - the composite capital

Y - the value added;

A - technical efficiency

m - represents the return to scale

α and β - shared parameters where $(0 < \alpha, \beta < 1)$

ρ and ρ_1 - shift parameters where $(\rho > -1, \infty > \rho_1)$

Production Technology: CES productions function of other sectors

$$Y_{JT} = C_J^Y \sigma_J^Z \left[\frac{p_{JT}^X}{p_{JT}^Y}\right]^{\sigma_J^Z} X_{JT} \tag{C.3}$$

$$VV_{IJT} = C_{IJ}^{V^\sigma} \left[\frac{p_{IT}^X}{p_{IT}^Q}\right]^{\sigma Z} X_{JT} \tag{C.4}$$

$$Y_{JT} = \left[\alpha_J (EK_{JT} KD_{JT})^{\rho Y} + \beta_J (EL_{JT} LD_{JT})^{\rho Y}\right]^{\frac{1}{\rho Y}} \tag{C.5}$$

$$LD_{JT} = [EL_{JT}{}^{\rho}\}_{\beta_J} \frac{p_{JT}^Y}{WF_T}\Bigg]^{\frac{1}{1-\rho\}}} Y_{JT} \tag{C.6}$$

$$RK_{JT} = P_{JT}^Y \alpha_J EK_{JT}{}^{\rho}\Big\} \left[\frac{Y_{JT}}{KD_{JT}}\right]^{1-\rho\}} \tag{C.7}$$

$Y_{JT}-$ value added

$P^{Y}_{JT}-$ Value-added price

C^{Y}_{J} - the calibrated coefficient for a unit of output

X_{JT} - gross output

P^{X}_{JT} - gross output price

VV_{IJT} - intermediate inputs

P^{Q}_{IT} - composite price

C^{V}_{IJ} - the calibrated coefficient for intermediate inputs I and J (Leontief)

EL_{JT} - labour augmenting technology

EK_{JT} - capital augmenting technology

LD_{JT} - labour demand

WF_{T} - firms' labour costs before tax

KD_{JT} - capital demand

RK_{JT} - rate of return on capital

$\alpha_{J}-$ calibrated CES parameter for capital

β_{J} - calibrated CES parameter for labour

σ^{Z}_{J} - elasticity between value added and intermediate

ρ^{Y}_{J} - substitution parameter for factors

Taxes on Production, Import and Production Subsidies

$$IBT_{IT} = BTAX_{I}X_{IT}P^{X}_{IT} \tag{C.8}$$

$$IMT_{JT} = \sum_{I} VM_{IJT}MTAX_{J}P^{M}_{JT} \tag{C.9}$$

$$SUBSY_{IT} = SUB_{I}X_{IT}P^{X}_{IT} \tag{C.10}$$

IBT_{IT} - indirect business tax

$BTAX_I$ - indirect business tax rate

$X_{IT}-$ gross output

P^X_{IT} - gross output price

IMT_{JT} - indirect import tax

$\sum_I VM_{IJT}$ - imported intermediate input from ROW

$MTAX_J$ - import tax rate

$P^M_{JT}-$ import price

$SUBSY_{IT}$ - production subsidy

SUB_I - subsidy rate

X_{IT} - gross output

P^X_{IT} - gross output price

Intermediate Demand

$$VV_{IJT} = \left(\delta^{VM}_{IJ}\left(\gamma^{VM}_{IJ}VM_{IJT}\right)^{\rho J} + \quad \delta^{VIR}_{IJ}\left(\gamma^{VIR}_{IJ}VIR_{IJT}\right)^{\rho Y}\right)^{\frac{1}{\rho !}} \tag{C.11}$$

$$VM_{IJT} = VIR_{IJT}\left[\frac{\delta^{VM}_{lJ}}{\delta^{VIR}_{lJ}}\frac{\gamma^{VM}_{IJ}}{\gamma^{VI}_{IJ}}\frac{PIR}{p^M_{IT}}\right]^{\frac{1}{1-\rho V}} \tag{C.12}$$

$$VIR_{IJT} = \left(\delta^{VI}_{IJ}\left(\gamma^{TI}_{IJ}VI_{IJT}\right)^{\rho U} + \delta^{VR}_{IJ}\left(\gamma^{TR}_{IJ}VR_{IJT}\right)^{\rho Y}\right)^{\frac{1}{\rho Y}} \tag{C.13}$$

$$VR_{IJT} = VI_{IJT}\left[\frac{\delta^{VR}_{IJ}}{\delta^{VT}_{IJ}}\frac{\gamma^{TR}_{IJ}}{\gamma^{TT}_{IJ}}\frac{p^I_{0I}}{p^R_{IT}}\right]^{\frac{1}{1-\rho I}} \tag{C.14}$$

$$TV_{JT} = \sum_I VV_{IJT} \tag{C.15}$$

$$TVR_{JT} = \sum_I VR_{IJT} \tag{C.16}$$

$$TVI_{JT} = \sum_I VI_{IJT} \tag{C.17}$$

$$TVM_{JT} = \sum_I VM_{IJT} \tag{C.18}$$

VM_{IJT} – ROW input

VI_{IJT} – RNRB input

VIR_{IJT} - intermediate input (RNRB + domestic)

P^{IR}_{IT} - price of RNRB + domestic composite good

P^{M}_{IT} - import price

ρ^{V}_{I} - substitution parameter

$\delta^{VR}_{IJ}, \delta^{VI}_{IJ}$ - share parameter

P^{I}_{0I}– RNRB price

P^{R}_{IT} - domestic good price

TV_{JT} - total intermediate inputs

TVR_{JT} - total regional intermediate input

TVI_{JT} - total imported intermediate from RNRB

TVM_{JT} - total imported intermediate goods from ROW

Goods market balance

$$X_{IT} + M_{IT} = \Sigma_J VV_{IJT} + Q^{H}_{IT} + E_{IT} + Q^{V}_{IT} + Q^{G}_{IT} + TUTOT_{IT} + STOCKTOT_{I} \quad \text{(C.19)}$$

X_{IT} - gross output

E_{IT} - exports

M_{IT} -imports

$\sum_J VV_{IJT}$ - total intermediate imports in sector i

Q^{H}_{IT} - household consumption

Q^{V}_{IT} - investment demand

Q^{G}_{IT} - government consumption

$TUTOT_{IT}$ - tourism consumption

$STOCKTOT_{I}$ - total stock

Export

$$X_{IT} = R_{IT} + E_{IT} \tag{C.20}$$

$$E_{IT} = E_{IT}^{REG} + E_{IT}^{INT} \tag{C.21}$$

$$E_{IT}^{REG} = SIMRUK_{IT} E_{0I}^{REG} \left(\frac{p_T^E}{p_{PT}^Q} \right)^{\sigma\sigma^X} \tag{C.22}$$

$$E_{IT}^{INT} = \text{SIMROW}_{IT}\, E_{0I}^{INT} \left(\frac{pF_T}{p_{IT}^Q} \right)^{\sigma_T^X} \tag{C.23}$$

$$R_{IT} = \sum_J VR_{IJT} + Q_{IT}^{HR} + Q_{IT}^{VR} + Q_{IT}^{GR} + TURREG_{IT} + STOCKREG_I \tag{C.24}$$

X_{IT}- gross output

E_{IT}- exports

R_{IT}-domestic goods

E_{IT}^{REG}- exports to RNRB

E_{IT}^{INT} - exports to ROW

$SIMRNRB_{IT}, SIMROW_{IT}$- simulation variable

E_{0I}^{INT}-exports to ROW in base year

E_{0I}^{EEG}- exports to RNRB in base year

σ_I^X- export elasticity

P_{IT}^Q-commodities price

P_{IT}^E- export price

$\sum_J VR_{IJT}$- total regional intermediate input in sector j

$TURREG_{IT}$-Tourists regional consumption

$STOCKREG_I$- Regional stock

Income and Output

$$LY_T = \sum_J LD_{JT} WF_T \tag{C.25}$$

$$KY_T = \sum_J KD_{JT} RK_{JT} \tag{C.26}$$

$$GRP_T = C_T + \sum_I Q^G_{IT} + \sum_I Q^V_Q + \sum_I TUTOT_{IT} + \sum_I E_{IT} - \sum_I M_{IT} \tag{C.27}$$

$$TRSNG_{DNGINS,DNGINS,T} = TRSNG_{0,DNGINS,DNGINSP} CPI_T \tag{C.28}$$

$$\begin{aligned} YNG^H_T = LY_T - NIEMPL_T + DSHR_{HH} KY_T + TRSNG_{HH,Firms,T} + \\ TRH_{HH,EGTGov} CPI_T + TRH_{HH,NRBGov} CPI_T \sum_{FINS} S_{HAM,FINS} * \varepsilon_T \end{aligned} \tag{C.29}$$

$$\begin{aligned} YNG^F_T = DSHR_{Firms} KY_T + TRSNG_{Firms,HH,T} + SAM_{Firms,EGTGov} CPI_T + \\ SAM_{Firms,NRBGov} CPI_T + NIEMPL_T + \sum_{FINS} SAM_{Firms,FINS} \varepsilon_T \end{aligned} \tag{C.30}$$

LY_T - labour income

$\sum_J LD_{JT}$ - total labour demand

WF_T - firms [2] labour costs before tax

KY_T - capital income

$\sum_J KD_{JT}$ - total capital demand

RK_{JT} - rate of return on capital

GRP_T - gross domestic product

C_T - household consumption

$\Sigma_I Q^G_{TT}$ - total government consumption

$\sum_I Q^V_{IT}$ - total investment

$\sum_I$ TUTOT $_{IT}$ - total stock

$\sum_I E_{IT}-$ total exports

$\sum_I M_{IT}$ - total imports

YNG^H - household income

NIEMPL L_T-Employers' NICs

CPI_T - consumer price index

ε_T-exchange rate

YNG^F - firms' income

TRSNG - transfers

TRH-Government transfers to households

DSHR - share of capital income

SAM - values as given in the Scottish SAM

FINS - foreign institutions

Household Taxes and Savings

$$SAV_T = \left(YNG_T^H - HTAX_T\right) MPSAV \tag{C.31}$$

$$HTAX_T = (LABTAX_{R_{NIHH}} + LABTAX_{R_{IT}} + LABTAX_{R_{OTH}}) * WHG_T \sum_I LD_{IT} + LABTAX_{R_P} TRH_{HH,EGYGOV} + \text{STAMP} + COUNCIL \tag{C.32}$$

$$NIEMPL_T = LABTAX\_R_{NIF} * WHG_T \sum_I LD_{IT} \tag{C.33}$$

$$VATREV_T = VATRATE * Q_{IH}^{OH} \tag{C.34}$$

SAV_T - household saving

MPSAV - household savings rate:

$$\frac{SAV_0}{\sum_H TOT_H}$$

YNG^{H} - household income

$HTAX_{T}$ - household tax paid

LABTAX X_{R} - effective labour tax rate by type

TRH- Government transfers to households

NIHH - employees' National insurance contributions

IT - income tax

OTH - other household taxes

NIF - employers' National insurance contributions

NIEMP L_{T} - total payments of employers' NICs

WHG_{T} - household gross wage

LD_{IT} - firms' labour demand

STAMP - Stamp duty

COUNCIL - Council tax

Q_{IH}^{0H} - household consumption

VATREV -Value added tax revenue

VATRATE - Value added tax rate

Firm Taxes

$$ETAX_{T} = DTRE\left(YNG_{T}^{F} - NIEMPL_{T}\right) \quad \text{(C.35)}$$

$$CTAX_{IT} = RK_{IT}KS_{IT}TKT_{IT} \quad \text{(C.36)}$$

$$\text{CTAXTOT}_{T} = \sum_{I} CTAX_{IT} \quad \text{(C.37)}$$

$ETAX_{T}$ - firm taxes (excluding corporation tax

YNG^{F} - firms' income

NIEMPL - firms' total expenditure on NICs

$DTRE$ - effective firm tax rate (excluding CT)

CTAX $_{IT}$ - corporation tax revenues by sector

RK_{IT} - interest rate

KS_{IT} - capital supply

TKT_{IT} - effective corporation tax rate

$\mathrm{CTAXTOT}_T$ - total corporation tax revenue

Foreign Debt

$$DEBT_T = (1 + IR - GINT_0)\, DEBT_{T-1} + BALPAY_{T-1} \tag{C.38}$$

In first period only:

DEBT_T=DEBT_0 (C.39)

In final period only:

$$-\,(IR - GINT_0)\, DEBT_T = BALPAY_T \tag{C.40}$$

$DEBT_T-$ foreign debt

IR - interest rate

GINT T_0 - variable in CALIB model

$DEBT_0$ - base year debt

$BALPAY_T$ - balance of payments

Prices, Wages and Balance of Payments

$$P^M_{IT} = \varepsilon_T P^{WM}_I \,(1 + MTAX_I) \tag{C.41}$$

$$P^Y_{JT} = \left[\ P^R_{JT}(1 - BTAX_J - SUB_J) - \textstyle\sum_I P^Q_{JT} CV_{IJ} \sigma^Z_J - P^M_{JT} CMT_J\ \right] \frac{1}{CY^Z_{JJ}} \tag{C.42}$$

$$UCK_T = P^{INV}_T (IR + \delta) \tag{C.43}$$

$$P^{CON}_T = \frac{\sum_{II} P^Q_{IT} Q^H_{0I}}{\sum_I P^Q_{0I} Q^H_{0I}} \tag{C.44}$$

$$CPI_T = \frac{\sum_I P^Q_{IT} Q^H_{HI}}{\sum_I Q^H_{0I}} \tag{C.45}$$

$$WHG_T = \frac{WHN_T}{(1 - (LABTAX\_R_{\mathrm{NIHH}} + LABTAX\_R_{IT} + LABTAX\_R_{OTH}))} \tag{C.46}$$

$$WF_T = WHG_T(1 + LABTAX\_R_{NIF}) \tag{C.47}$$

$$P^E_{IT} = \varepsilon_T P^{WE}_I (1 - TE_I) \tag{C.48}$$

$$P^X_{IT} = \frac{P^R_{TT} R_{IT} + E_{IT} P^E_{IT}}{R_{IT} + E_{IT}} \tag{C.49}$$

$$P^Q_{JT} = \frac{R_{JT} P^R_{JT} + P^M_{JT} M_{JT}}{R_{JT} + M_{TT}} \tag{C.50}$$

$$P^{IR}_{JT} = \frac{R_{JT} P^R_{JT} + P^I_{0J} MVI_{JT}}{MVI_{JT} + R_{JT}} \tag{C.51}$$

$$BALPAY_T = \sum_I M_{IT} + SAM_{ROW,Firms} + SAM_{RNRB,Firms} + SAM_{RNRB,Gov} + SAM_{ROW,Gov} - \left(\sum_{FINS} SAM_{Tur,FINS} + \sum_I E_{IT} + \sum_{\mathrm{FINS}} SAM_{Gov,FINS}\varepsilon_T + \sum_{\mathrm{DNGINS,FINS}} SAM_{\mathrm{DNGINS,FINS}}\,\varepsilon_T\right) \tag{C.52}$$

P^M_{IT} - import price

P^{WM}_I - world import price

$MTAX_I$ - import tax rate

ε_T - exchange rate

P_{JT}^{Y} - value added price

CY_J - calibrated coefficient for a unit of output

σ_I^Z - elasticity of substitution between value added and composite good

P_{JT}^{R} - regional output price

P_{JT}^{Q} - composite good price

CV_{IJ} - calibrated coefficient for intermediate inputs

CMT_J - share of import tariffs of total production

$BTAX_J$ - indirect business tax rate

SUB_J - subsidy rate

UCK_T - user cost of capital

$P_T^{INV\_}$ - price of investment good

IR - interest rate

δ - depreciation rate

P_T^{CON} - household consumption price

$Q_{IH}^{0\mathrm{OH}}$ - household consumption

WHG_T - household gross wage

WHN_T - household net wage

$LABTAX_R$ - effective direct labour tax rates by type

$P_{IT}^{E}-$ export price

P_I^{WE} - world export price

TE_I- export tax rate $(=0)$

P_{IT}^{X} - gross output price

P_{IT}^{R} - regional good price

R_{IT} - regional good

$E_{IT}-$ export

P_{IT}^{E} - price of export

P_{JT}^{IR} - regional and RNRB price

$P_{0J}^{I}-$ RNRB price

MVI_{JT} - total imports from RNRB

$BALPAY_T$ - balance of payments

$\sum_I M_{IT}-$ total imports

SAM - values as given in the Northern Irish SAM

$FINS$ - foreign institutions

DNGINS - domestic nongovernment institutions

Household Consumption

$$U = \sum_{t=0}^{\infty} \left(\frac{1}{1+\rho} \right)^t \frac{{C_T}^{1-\sigma} - 1}{1-\sigma} \tag{C.53}$$

$$\frac{C_T}{C_{T+1}} = \left[\frac{P_T^{CON}(1+\rho)}{P_{T+1}^{CON}(1+r)} \right]^{-\left(\frac{1}{\sigma}\right)} \tag{C.54}$$

$$Q_{IT}^H = HDEL_I \left[\frac{P_T^{CON}}{P_{IT}^Q} \right]^{SIGINV} C_T \tag{C.55}$$

$$Q_{IT}^H = \gamma_I^{QH} \left[\delta_I^{QHIR} Q_{IT}^{HIR} \rho_I^H + \delta_I^{QHM} Q_{IT}^{HM} \rho_I^H \right] \tag{C.56}$$

$$Q_{IT}^{HIR} = Q_{IT}^{HM} \left[\frac{\delta_I^{QHIR}}{\delta_I^{QHM}} \frac{P_{IT}^M}{P_{IT}^{IR}} \right]^{\frac{1}{1-\rho_I^H}} \tag{C.57}$$

$$Q_{IT}^{HIR} = \gamma_I^{HT} \left[\delta_I^{QHI} Q_{IT}^{HI} \rho_I^H + \delta_I^{QHR} Q_{IT}^{HR} \rho_I^H \right]^{\frac{1}{\rho_I^H}} \tag{C.58}$$

$$Q_{IT}^{HR} = Q_{IT}^{HI} \left[\frac{\delta_I^{QHR}}{\delta_I^{QHI}} \frac{P_I^{I0}}{P_{IT}^R} \right]^{\frac{1}{1-\rho_I^H}} \tag{C.59}$$

ρ - rate of time preference

r - interest rate

σ - Constant elasticity of marginal utility

Q_{IT}^H - household consumption by sector

$HDEL_I$ - consumption share

P_T^{CON} - consumption price

P_{IT}^Q - composite price

$SIGINV$ - elasticity substitution (0.3)

C_T- consumption

γ_I^{QH}- shift parameter

$\delta_I^{QHIR}, \delta_I^{QHM}, \delta_I^{QHI}, \delta_I^{QHR}$ - share parameters

Q_{IT}^{HIR}- domestic consumption

Q_{IT}^{HM}- household consumption of imports

ρ_I^H -elasticity

γ_I^{HT}-shift parameters

$Q_{IT}^{HI}-$ RNRB household consumption

Q_{IT}^{HR} - domestic household consumption

P_I^{I0} - RNRB good price (base year) $= 1$

P_{IT}^R - regional good price

Government Expenditure and Revenues

$$\begin{aligned} SGY_T = DSHR_{GOV}KY_T + \sum_I IBT_{IT} + \sum_I IMT_{IT} + HTAX_T + ETAX_T + \\ CTAXTOT_T + \sum_I SUBSY_{IT} + VATREV_T \end{aligned} \tag{C.60}$$

$$NRBGY_T = NRBGY_0 \tag{C.61}$$

$$\begin{aligned} GOVBAL_T = (GEXP_T P_T^{Gov} + SAM_{Firms,Gov}CPI_T + TRH_T CPI_T + SAM_{KFOR,Gov} + \\ SAM_{RNRB,Gov} + SAM_{RoW,Gov}) - (DSHR_{GOV}KY_T + \sum_I IBT_{IT} + \sum_I IMT_{IT} + \\ HTAX_T + ETAX_T + CTAXTOT_T + \sum_I SBSY_{IT}) \end{aligned} \tag{C.62}$$

$$P_T^{GOV} BF_T = [1 + IR - DIN + (\frac{CPI_T}{CPI_{T-1}} - 1)] P_{T-1}^{GOv} BF_{T-1} + GOVBAL_{T-1} \quad (C.63)$$

In first period only:

$$BF_T = BF_0 \quad (C.64)$$

In final period only:

$$-(IR - DIN) BF_T = GOVBAL_T \quad (C.65)$$

$$Q_{IT}^{G} = GDEL_I GEXP_T \quad (C.66)$$

$$Q_{IT}^{GM} = Q_{0I}^{GM} \quad (C.67)$$

$$Q_{IT}^{GR} = Q_{0I}^{G} - Q_{0I}^{GM} \quad (C.68)$$

$$P_T^{GOV} = \frac{\sum_I P_{IT}^{Q} Q_{0I}^{G}}{\sum_I P_{0I}^{Q} Q_{0I}^{G}} \quad (C.69)$$

$NRBGY_T$-UK government income

$NRBGY_0$ - UK government income in base year

$egyGY_T - NRBgovernmentincome$

DSHR_G O V$-capitalshareofgovernment$

KY_T$-capitalincome$

$\sum_I IBT_{IT}$ - indirect business tax revenues

$\sum_I IMT_{IT}$ - import tax revenues $(= 0)$

$HTAX_T$ - household tax revenues

$ETAX_T$ - firm tax revenues (excl. CT)

$CTAXTOT_T$ - CT revenues

$\sum_I SUBSY_{IT}$ - subsidies

$GOVBAL_T$ - government deficit

SAM - values as given in the Northern Irish SAM

GEXP - current government spending

P_T^{GOV} - government price index

BF_T - gov. borrowing

IR - interest rate

DIN - calibrated variable

Q_{IT}^G - government consumption

$GDEL_I$ - consumption share

Q_{IT}^{GM} - imports by government (=0)

P_{IT}^Q - composite price st

TKT,TK - effective corporation tax rate

RK_{0I}-return on capital

KS_{0I} - capital supply

Investment "Demand" (investment by sector of origin)

$$Q_{IT}^V = \sum_J KMATRIX_{IJ} JINV_{JT} \tag{C.70}$$

$$Q_{IT}^V = \gamma_I^{QV}[\delta_I^{QM}(Q_{IT}^{VM})^{\rho_I^V} + \delta_I^{QVIR}(Q_{IT}^{VIR})^{\rho_I^V}]^{\frac{1}{\rho_I^V}} \tag{C.71}$$

$$Q_{IT}^{VM} = Q_{IT}^{VIR}[\frac{\delta_I^{QM}}{\delta_I^{QVIR}}\frac{P_{IT}^{IR}}{P_{TT}^M}]^{\frac{1}{1-\rho_I^V}} \tag{C.72}$$

$$Q_{II}^{VIR} = \gamma_I^{QT}[\delta_I^{QVI}(Q_{IT}^{VI})^{\rho_I^V} + \delta^{\varrho VR}{}_I(Q_{IT}^{VR})^{\rho_I^v}]^{\frac{1}{\rho_I^V}} \tag{C.73}$$

$$Q_{IT}^{VR} = Q_{IT}^{VI}(\frac{\delta_I^{QVR}}{\delta_I^{QVI}}\frac{P_{0I}^I}{P_{IT}^X})^{\frac{1}{1-\rho_I^V}} \tag{C.74}$$

Q_{IT}^V - investment demand by sector

$KMATRLX$ - parameter linking investment by destination and origin

$JINV$ - Investment by destination (incl. adjustment costs and tax credits)

γ_I^{QV} - shift parameter

$\delta_I^{QM}\delta_I^{QVIR}$ - share parameters

Q_{IT}^{VM} - imported investment

Q_{IT}^{VIR} - investment (NRB and domestic)

P_{IT}^{IR} - domestic + RNRB price

P_{IT}^{M} - export price

γ_I^{QI} - shift parameter in Armington

Q_{IT}^{VI} - investment RNRB

Q_{IT}^{VR} - domestic investment

P_{0I}^{I} - RNRB price

P_{IT}^{X} - gross output price

γ_J^{QT} - shift parameter in HH CES

δ_I^{QVI} - share parameter

Investment and Capital Accumulation

$$KST_{JT} = \left(\frac{EK_{JT}^{\rho_J^Y}\alpha_J P_{JT}^Y}{UCK_T}\right)^{\frac{1}{1-\rho_J^Y}} Y_{JT} \tag{C.75}$$

$$JINV_{IT} = IND_{IT}\left(1 - BOP_{0I} + COP_{0I} - TAXC_I + \frac{ADJ}{2}\frac{IND_{IT}^2}{KS_{IT}}\right) \tag{C.76}$$

$$PINV_T = \frac{\sum_{IJ} PQ_{JT}(1-TKT_{IT})^{-1}KMATRIX_{IJ}}{\sum_{IJ} PQ_{J0}(1-TK_I)^{-1}KMATRIX_{IJ}} \tag{C.77}$$

IND_{IT} - (net) investment

KS_{IT} - capital supply

δ - depreciation

KST_{IT} - desired level of capital stock

$SPEED$ - speed of adjustment

$JINV$ - investment by destination (incl. adjustment costs and tax credits)

BOP_{0I} - calibrated parameter (rate of distortion or incentive to invest)

COP_{0I} - calibrated parameter (no economic meaning)

$TAXC_I$ - rate of tax credit to investment

ADJ - cost parameter

PQ_{JT} - composite price

$KMATRIX$ - parameter linking investment by destination and origin

$PINV_I$ - price of investment

TKT_{IT} - effective CT rate

$EK_{IT}-$ capital augmenting technical change

α_J- CES parameter for capital

ρ_I^Y - elasticity of substitution between labour and capital

P_{JT}^Y - value added price

UCK_T - user cost of capital

$Y_{JT}-$ value added

Labour Market Closures

Regional Bargaining (REGBARG):

$$\ln \frac{WHN_T}{CPI_T} = AWE - 0.113 \ln UN_T \tag{C.78}$$

National Bargaining (NATBARG):

$$WHG_T = WHG_0 \tag{C.79}$$

Real Wage Resistance (FIXRW):

$$\frac{WHN_T}{CPI_T} = \frac{WHN_0}{CPI_0} \tag{C.80}$$

WHN_T - household wage after tax

CPI_T - price level

AWE - calibrated parameter (based on real wage and unemployment in base)

UN_T - Northern Ireland unemployment rate

WHG_T - gross household wage

Capital Market Equilibrium

$$KS_{IT} = KD_{IT} \tag{C.81}$$

$$KS_{IT} = KS_{I,T-1}(1-\delta) + IND_{I,T-1} \tag{C.82}$$

In the first period only:

$$KS_{IT} = KS_{0I} \tag{C.83}$$

In the final period only:

$$KS_{IT}\delta = IND_{IT} \tag{C.84}$$

KS_{IT} - capital supply

KD_{IT} - capital demand

δ - depreciation of physical capital

$IND_{I(T-1)}$ - investment by sector of destination

Labour Supply and Migration

$$LS_T(1-UN_T) = \sum_J LD_{JT} \tag{C.85}$$

$$M^S_{I,T} = \sigma - 0.08\Big[\ln\left(UN^S_T\right) - \ln\left(UN^{NRB}_T\right)\Big] + 0.06\left[\ln\left(\frac{WHN^S_T}{CPI^S_T}\right) - \ln\left(\frac{WHN^{NRB}_T}{CPI^{NRB}_T}\right)\right] \tag{C.86}$$

LS_T- labour supply

LD_{JT}- labour demand

UN_T- unemployment rate

UN^S_T - Scotland unemployment rate

UN^{UK}_T- NRB unemployment rate

WHN_T^S- Scotland household wage after tax

WHN_T^{NRB}- household wage after tax

CPI_T^S-Scotland price level

CPI_T^{NRB}-NRB price level

$$MVI_{JT} = Q_{JT}^{VI} + Q_{JT}^{HI} + \sum_I VI_{IJT} \tag{C.87}$$

$$M_{IT} = \sum_J VI_{IJT} + \sum_J VM_{IJT} + Q_{IT}^{HM} + Q_{IT}^{HI} + Q_{IT}^{GM} + Q_{IT}^{VI} + Q_{IT}^{VM} + TURIMP_{IT} + STOCKIMP_I \tag{C.88}$$

$MVI_{JT}-$ import demand (RNRB goods)

Q_{IT}^{VI} - investment imported from RNRB

Q^{HI} - imports by households from RNRB

$\sum_I VI_{IJT}$ - intermediate input from RNRB

M_{IT} - total imports

$\sum_J VM_{IJT}$ - intermediate input from RNRB

Q^{HM} - imports by households from ROW

Q_{IT}^{GM} - government consumption of ROW imports

Q_{IT}^{VM} - investment imported from ROW

$TURIMP_{IT}$ - consumption of imports by tourists

$STOCKIMP$ - imported stock

Table C.3 – Model Sector List

Abbreviation	Full Sector Listing
AFF	Agriculture, forestry, and fishing
OTP	Other primary
FAD	Food and drink
TLW	Textile, Leather, Wood, Paper, Printing
CEP	Chemicals and Pharmaceutical
RCG	Rubber, Cement, Glass, Metals
ELM	Electrical Manufacturing
MOM	Mechanical and Other Manufacturing (incl. Repair)
ETD	Electricity, transmission, and distribution
GDS	Gas; distribution of gaseous fuels through mains; steam and air conditioning supply
WSW	Water, sewerage, and Waste
CON	Construction - Buildings
WRT	Wholesale and Retail Trade, Transportation and Storage, accommodation, food, and services
IAC	Information and Communication
FIN	Financial services, insurance, and services
RES	Real Estate, professional activities, R&D
PUB	Public Administration, Education, and Health
OTS	Other services