INTERNATIONAL MONETARY FUND

Investing in Climate Adaptation under Trade and Financing Constraints:

Balanced Strategies for Food Security

Chen Chen, Koralai Kirabaeva, Danchen Zhao

WP/24/184

2024
AUG

WORKING PAPER

 WP/24/184

IMF Working Paper
Fiscal Affairs Department and Institute for Capacity Development

Investing in Climate Adaptation under Trade and Financing Constraints: Balanced Strategies for Food Security

Prepared by Chen Chen, Koralai Kirabaeva, Danchen Zhao

Authorized for distribution by Dora Benedek and Mercedes Garcia-Escribano
August 2024

ABSTRACT: Financially constrained governments, particularly in emerging and developing economies, tend to face a fiscal trade-off between adapting to climate change impacts and pursuing broader development goals. This trade-off is especially relevant in the agriculture sector, where investing in adaptation is critical to ensure food security amidst climate change. International trade can help alleviate this challenge and reduce adaptation investment needs by offsetting agricultural production shortages. However, in the presence of trade fragmentation, the adaptive role of trade diminishes, exacerbating food insecurity and increasing investment needs for adaptation. In this paper, we present a model to guide policymakers in deciding on the cost-efficient balance between investing in adaptation in the agricultural sector versus in broader development under financing and trade constraints. We apply the model to Ghana, Egypt, and Brazil, to examine the adaptation-development trade-off and highlight factors that would potentially lower adaptation investment needs. These factors include trade openness, higher agricultural productivity and efficiency of adaptation spending, and reduced labor market distortions. The key takeaways from the model applications suggest that (i) promoting trade openness and accessing concessional finance for adaptation help tackle climate challenges and ensure food security in lower-income countries; and (ii) domestic structural reforms are necessary to facilitate adaptation investments and reduce investment needs, by improving labor market flexibility, adaptation efficiency, and agriculture productivity.

RECOMMENDED CITATION: Chen Chen, Koralai Kirabaeva, Danchen Zhao (2024) “Investing in Climate Adaptation under Trade and Financing Constraints: Balanced Strategies for Food Security” IMF WP/24/184

JEL Classification Numbers:	E13, F18, H54, O13, Q17, Q54, Q56
Keywords:	agriculture; investment; adaptation; trade; climate change
Author’s E-Mail Address:	cchen3@imf.org, kkirabaeva@imf.org, dzhao@nd.edu

WORKING PAPERS

Investing in Climate Adaptation under Trade and Financing Constraints:

Balanced Strategies for Food Security

Prepared by Chen Chen, Koralai Kirabaeva, and Danchen Zhao[1]

[1] The authors would like to thank Zamid Aligishiev, Karim Barhoumi, Hasan Dudu, Mercedes Garcia-Escribano, Mohammad Khabbazan, Christina Kolerus, Junko Mochizuki, Tewodaj Mogues, Ryota Nakatani, Bruno Versailles, Robert Zymek, and participants of seminars at IMF FAD and at ICD Climate and Inclusive Growth Divisions for valuable comments, and Sunalika Singh for excellent research assistance. The work has significantly benefited from feedback and comments from country teams of Brazil, Egypt, and Ghana. The views expressed herein are those of the authors and should not be attributed to the IMF, its Executive Board, or its management.

Contents

FIGURES

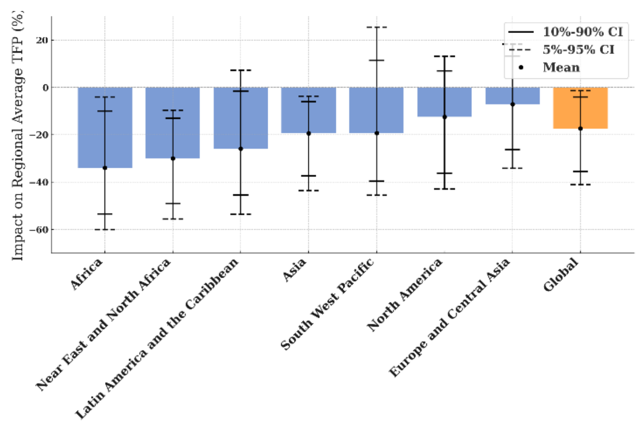
TABLES

1. Introduction

Motivation

Agriculture is one of the most vulnerable sectors to climate change. In many emerging and developing countries (EMDEs), it is a prominent sector for economic growth and provides supports to livelihoods, accounting for sizable shares of output and employment.[1] Beyond economic metrics, agriculture is fundamental for human survival because of the food it produces. In many lower-income countries, a considerable portion of agricultural output is devoted to subsistence consumption, providing a large share of the needed food in these regions.[2]

Figure 1. Impact of Anthropogenic Climate Change on Agriculture TFP,1961-2020



Data source: Ortiz-Bobea, 2021

Empirical evidence suggests that anthropogenic climate change has contributed to the loss of agricultural productivity (Ortiz-Bobea et al., 2021). Globally, over the past 60 years, climate change was responsible for 20 percent of agricultural productivity loss, with the average loss reaching almost 30 percent in EMDEs (Figure 1).[3] Projections indicate that, under a high-emission scenario, agricultural productivity in EMDEs could decline by an additional 16 percent from baseline levels, by the 2080s (Cline, 2007).

Investment in agriculture is crucial for reducing the damages caused by weather and climate-related shocks[4] and in maintaining food security more broadly. These investments typically correlate with enhanced food security (Figure 2), for instance, through improving productivity. In particular, investments in rural public goods, such as expansion of water access and technology development, are key drivers of agricultural productivity growth worldwide (Goyal and Nash, 2017).

Intensified climate shocks require additional spending for adaptation to prevent productivity from declining. Examples include deploying climate-proof technologies, enhancing climate resilience of road networks, and constructing irrigation systems in areas historically not prone to water shortages. Most developing countries rely on public finance to fund these investments. However, financing constraints, due to high debt levels,

[1] Despite the declining trend, agriculture still employs about 30 percent of low-middle-income countries' labor forces (World Bank Data, https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?locations=IN-XO, accessed in July 2024).

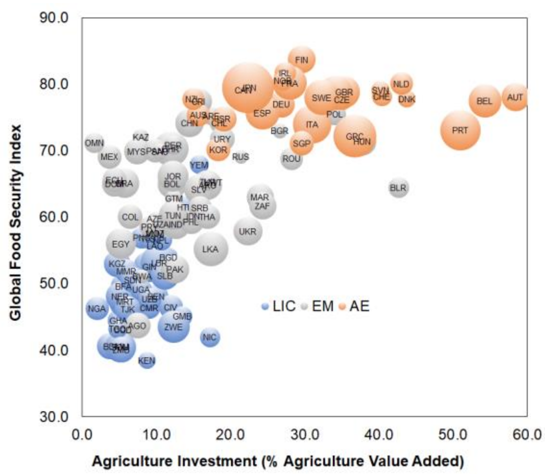
[2] For example, subsistence consumption provides on average 58 percent of rural households' calorie consumption in Africa (Sibhatu and Qaim, 2017)

[3] Climate change impacts on agriculture production are manifested on multiple fronts. Changes in temperature and precipitation shift cropping seasons and increase the risks of soil erosion, wildfires, and pests, all of which adversely affect productivities of the sector. Agricultural workers are exposed to more extreme weather conditions and increased health risks from pests and poor air quality. Livestock health and productivity suffer due to heightened heat and humidity. Coastal agricultural communities face risks from sea level rise and worsening coastal storms, exacerbating land loss and saltwater intrusion that threaten coastal agriculture.

[4] Below, we focus primarily on climate-related shocks, acknowledging that findings could be applicable in the context of managing weather-related shocks to food security.

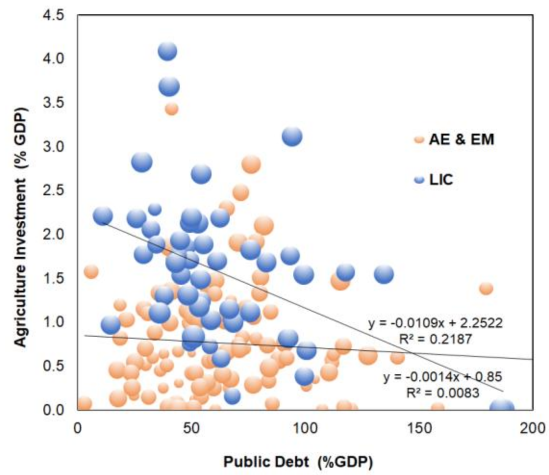
increasing borrowing costs,[5] as well as constrained access to international capital markets and lower revenue mobilization capacities, severely hinder a country's ability to invest in climate adaptation and sustainable development. As a result, sectors heavily dependent on public investment, such as agriculture, tend to be significantly underinvested, leading to increased vulnerability to shocks including those related to climate. As Figure 3 shows, low-income countries with higher levels of public debt often correspond to those that underinvest in their agriculture sector and are also highly vulnerable to climate change, thus requiring substantial investment for adaptation.

Figure 2. Agricultural Investment and Food Security Index, 2022



Note: Bubble size corresponds to **Debt to GDP level (2022).**
Global Food Security Index averages food affordability, availability, quality and safety, and sustainability and adaptation, with higher values. corresponding to higher security. Source: Economist Impact, Corteva
Agriculture Investment: Gross Fixed Capital Formation (Agriculture, Forestry and Fishing) as a share of Agriculture Value Added. Source: FAO.

Figure 3. Agriculture Investment and Public Debt, 2022



Note: Bubble size corresponds to **ND-GAIN Food and Agriculture Vulnerability sub-index**. Larger bubbles indicate higher vulnerability.
Source: ND-GAIN Index data, FAO, WEO

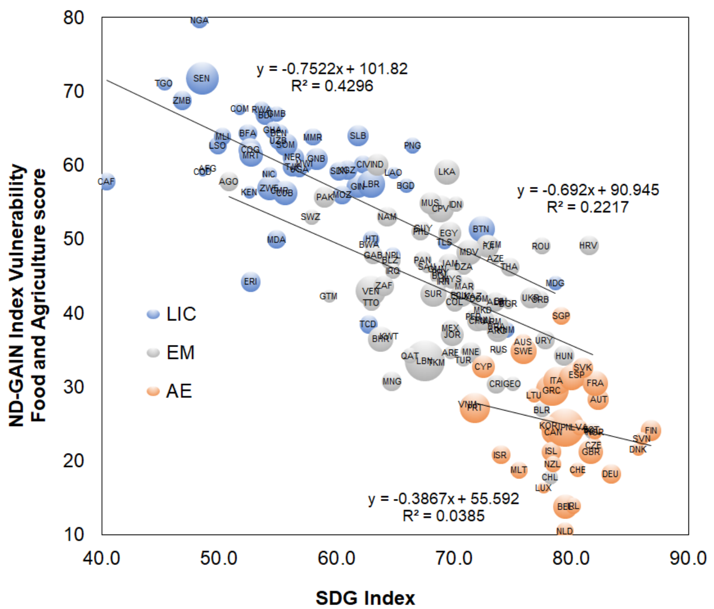
Development and adaptation are closely interconnected. As countries become more socially and economically developed, capacities to adapt also improve due to the stronger institutions, more advanced social services, infrastructure, and technologies. This relationship is particularly strong for EMDEs (Figure 4). Vice versa, successful adaptation helps shield development progress from effects of climate-related disruptions, improving resilience and sustainability of growth.

It is, however, also important to distinguish the two types of investment when it comes to financing. Trade-off between broad development investment and investing in adaptation to climate change is common in developing countries due to financing constraints. According to the principle of additionality, adaptation should not encompass primary development requirements (Aligishiev et al., 2022). Targeted adaptation capital aim to specifically reduce damages from climate change and is considered additional to standard development needs. As one of the key principles stipulated in the climate finance pledge, applying the principle of additionality ensures that funding for adaptation is not diverted from financing other development requirements.

[5] More than half of low-income developing countries are currently in or at high risk of debt distress, and about one fifth of emerging markets have sovereign bonds trading at distressed level (IMF, 2023).

Finding optimal balance between standard development and adaptation investments requires cost-efficiency. Investing in adaptation often incurs higher costs but does not always guarantee proportionate benefits. The decision depends on several factors, such as investment objectives, climate change uncertainties, and investment returns in general. Adaptation investment may not be warranted, if similar development outcomes could be efficiently achieved through standard development investments (within a specific timeframe), or if the impacts of climate change are not evident. On the other hand, because targeted adaptation capital is, by definition, specifically invested to reduce climate change damages, underinvesting in adaptation could mean higher cost for the economy once climate risks materialize.

Figure 4. Climate Change Vulnerability, SDG, and Public Debt to GDP, 2022



Note: Bubble size corresponds to **Debt to GDP level (2022).**
ND-GAIN Vulnerability measures a country's exposure, sensitivity and capacity to adapt to the negative effects of climate change, with higher values corresponding to higher vulnerability, 2021. Source: ND-GAIN Index data.
SDG Index indicate progress to the optimum SDG performance of 100, with higher values corresponding to more progress. Source: Sustainable Development Report, 2022

International trade plays a vital role in food security as well as in development. In addition to facilitating technology transfer and contributing to growth, trade in agricultural goods acts as a buffer to cushion against domestic production shocks, contributing to adequate food supply. Thus, it is one way to adapt to climate shocks and reduces the needs of investment. Conversely, higher trade barriers and export restrictions could undermine the adaptive roles of trade, especially in food importing countries. This adaptive role would diminish, however, in case of regional and global climate shocks. Meanwhile, it is worth noting that while international trade is crucial in helping countries cope with climate shocks, it can also be a source of risks. Increased reliance on imported food could negatively impact domestic farmers' income and employment opportunities, while more exports would help increase the income; trade openness also exposes agriculture to global market fluctuations and changes in trade policies.

All aspects considered, balanced strategies are needed to efficiently use resources and effectively address impacts of climate change on agriculture production and food security. An optimal adaptation strategy must balance broader development needs, taking into consideration financing constraints and the role of trade. These considerations are particularly important for lower-income countries, where subsistence farming is more prevailing and often has larger shares of agricultural output and employment, greater exposure to climate shocks, less adaptive capacity, larger development investment needs, and lower trade openness (Figure 5).

Overview of the Model

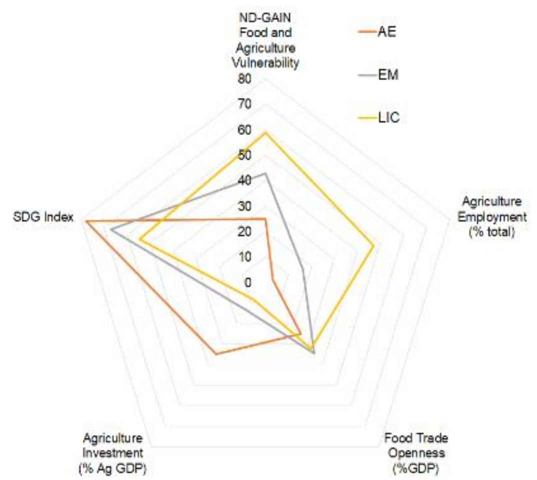
Despite the increased availability of country-level dynamic general equilibrium models, which help analyze different climate and development policies, there is still demand for a more stylized framework that can be easily tailored to a country-specific application. In this paper, we present a model designed to study balanced adaptation strategies and to identify an efficient level of investment for agricultural adaptation to ensure food security. The model is intentionally parsimonious, focusing on essential elements to build, and is capable of analyzing three key issues:

(1) *What is a cost-efficient mix of climate adaptation and standard development investments to ensure food security, for a country grappling with negative effects of climate change?*

(2) *What factors influence the investment needs for agricultural adaptation?*

(3) *What role does trade play in agricultural adaptation?*

Figure 5. Elements of Balanced Adaptation Investment Strategy, 2019



Source: ND-GAIN Index data, FAO, WEO, WB, Sustainable Development report

The model segments the economy into an agricultural sector and a non-agricultural sector. The preference of households is defined over distinct final agricultural and non-agricultural goods. A home country (HC) and the rest of the world (ROW) trade both goods, differentiated by the region of origin in accordance with the Armington assumption. As climate condition changes, agricultural productivity declines.

In the model, the government invests in two types of capital in the agricultural sector: development capital and adaptation capital. Development capital enhances production (for example, through acquiring machinery, investing in infrastructure, and facilitating exchange of knowledge and information), while adaptation capital (such as additional irrigation and developing more resilient crops) mitigate climate change damages. A resource-constrained government must balance adaptation investments with standard development investments to ensure food security in the face of climate change.

Applying the model to three country cases (Ghana, Egypt, and Brazil), we demonstrate that balanced investment and policy strategies allow countries to minimize output losses from climate shocks while using public financial resources efficiently. We show that:

- With financing constraints, a balanced investment strategy ensures cost-efficiency of public investment in offsetting climate change damages. Underinvesting in adaptation would require higher level of total investment to withstand climate-related shocks, maintaining food production and ensuring food security. On the other hand, excessive adaptation investment is wasteful, diverting funds needed for development.

- Trade openness is an effective adaptation strategy when agricultural production falls short, and it reduces adaptation investment needs, especially for food importers. For food exporters, higher trade costs mostly affect global food supply. As a result, trade fragmentation increases risks of food insecurity and leads to higher adaptation investment needs.

- Higher agriculture productivity, higher adaptation efficiency, and less labor market distortions reduce investment needs for adaptation by improving the productive allocation of capital. Corresponding structural reforms are especially important, yielding more benefits under trade fragmentation and/or larger climate-related shocks.

The remainder of the paper is organized as the following. Section 2 briefly discusses the literature based on which the model was built. Section 3 presents the model. Section 4 discusses the model applications to the selected country cases of Ghana, Egypt, and Brazil, including the model calibration and a series of comparative static exercises. Section 5 concludes and discusses relevant policy implications.

2. Literature Review

To investigate the interconnected issues among agricultural production, adaptation investment, financing constraints, and trade issues, we build our model based on four literature strands. Each strand of literature explores the interconnections among these elements, with different focus that determines the respective modeling approaches.

(1) Studies on finding an efficient balance between standard development investments and additional adaption investments across an economy (Agrawala et al., 2010; Millner and Dietz, 2014). This strand of literature focuses on the optimality of investment trajectories in a neoclassical growth setting. These models create channels for targeted adaptation capital to counteract climate change damages to the production, while development capital primarily functions as inputs to the production. Trade has not typically been part of the dynamics.

(2) Studies that identify required investments to offset food consumption loss induced by climate change (Nelson et al., 2009; Narain et al., 2011; Sulser et al., 2021). The assessments primarily rely on bottom-up estimations in a partial equilibrium setting, characterizing details of an agricultural sector through coupling crop and hydrology models at fine scales. Shocks, such as climate change, impact food supply, affecting price, market dynamics, and food security. Adaptation needs are estimated with the objective of achieving the desired damage reduction to food consumption. These studies do not attempt to pursue the optimality of investments.

(3) The IMF’s Dynamic General Equilibrium models that shed lights on the macro-fiscal implications of investing in infrastructure resilience to natural disasters, tailored to small open economies (such as the Debt, Investment, Growth and Natural Disasters model, by Marto et al, 2018). The approach has been frequently used by IMF country teams to quantify effects of adaptation investments and policy scenarios, such as combinations of additional financial inflows and reforms (for example, enhancing efficiency of fiscal spending). The model differentiates adaptation investment from standard development investment, with a notable assumption that adaptation capital, despite its higher cost, promotes development more effectively than standard development capital. Therefore, in defining adaptation, the notion of additionality has not been currently reflected.

(4) A relatively rich literature body that explores the impacts of climate change on the shifting comparative advantages of agricultural production across countries. Models of international trade provide backbones for this strand of literature. These studies investigate the geographic shift of agricultural production due to climate change. They help understand the welfare implications of such shifts (Costinot et al. 2016; Gouel and Labordeal., 2021, Nath, 2022), specifically, highlighting the welfare benefits of international trade in mitigating the cost of climate change, especially in developing countries (Nath, 2022). Adaptation strategies to reduce climate change damages are not commonly incorporated.

Table 1 summarizes the main characteristics of the representative models, featured by each literature strand mentioned above.

Table 1. Model Comparison

Literature Strand	Balancing development and adaptation investments	Costing investments in agricultural adaptation	Macro-fiscal implications of adaptation investments	Impacts of climate change on geographic shifts of agricultural production
Representative model	Millner and Dietz (2014)	Narain et al. (2011)	Marto et al (2018)	Nath (2022)
Optimality of Investments	Yes	No	No	No
International Trade	No	Yes	Yes	Yes
Ensuring Food Security	Not relevant	Yes	Not relevant	Yes
Financing Constraints	No	No	Yes	No
Reflection of *Additionality*	Yes	Yes	No	Not relevant

We build a neoclassic growth model with an explicit Ramsey problem, to provide guidance to governments on efficiently allocating finance for adaptation and achieving food security under climate change. Such model is not intended for forecasting; rather, it highlights structural dynamics, taking into consideration financing and trade constraints. The model focuses on agricultural production and food consumption, and it allows for a discussion about what role trade plays by leveraging literature on trade and welfare implications under climate change. It incorporates adaptation investment to facilitate a study on the interaction among trade, agricultural production, and adaptation.

3. Model

In this paper, we introduce a model that features two sectors and two countries in the world. Both Home Country (HC) and the Rest-of-the-World (ROW) include an agricultural sector and a non-agricultural sector. We model the slow-moving effects of climate change by capturing its impacts on agricultural productivity in HC, based on estimations from literature. The effects on the non-agricultural sector are indirect, manifesting through domestic and international trade dynamics.

International Trade

We first introduce the setting of international trade in our model, since the notations related to trade are going to be frequently referenced later in this section. The international trade in the model follows the Armington assumption that the goods produced in each sector by each economy are differentiated. Each economy simultaneously imports and exports both agricultural and non-agricultural goods.

Output, denoted by $Y_{i,j,k,t}$, represents final goods produced in sector k (either agriculture A or non-agriculture N), and shipped from country i (either HC 1 or the ROW 2) to country j (either HC 1 or the ROW 2), at time t.

We incorporate iceberg costs in trade, denoted by $\tau_{i,j,k}$ ($\tau_{i,j,k} > 1$), which reflect the costs incurred before goods reaching overseas markets. The model assumes that one unit of goods reaching oversea markets require $\tau_{i,j,k}$ units of goods to be produced and shipped. Iceberg costs may vary due to uncertainties involved in international trade. In the model, they capture impacts of multiple risk factors that potentially affect trade, including one-off shocks and cyclical or more persistent trends such as global economic fragmentation and climate change.

Households

Each country i is populated by a representative household of size $L_{i,t}$ at time t. Households derive their inter-temporal welfare from a population-weighted Constant Relative Risk Aversion (CRRA) function over a finite time horizon T. The welfare function is expressed as:

$$W = \Sigma_{t=0}^{T} \beta^t \left\{ L_{i,t} \frac{(U_{i,t})^{1-\alpha} - 1}{1-\alpha} \right\}, \qquad (1)$$

where parameter β is the discount rate and $1/\alpha$ represents the elasticity of intertemporal substitution.

The utility function at time t, $U_{i,t}$, applies to households in both countries and is expressed in a Stone-Geary form over *per-capita* non-agricultural consumption $c_{i,N,t}$ and agricultural consumption $c_{i,A,t}$, with a subsistence consumption $\bar{a}$, which defines the minimum level of food consumption required for each country. In a strict sense, this fixed level of minimum food consumption means that food security requirement does not depend on food prices or income.

$$U_{i,t} = \left(c_{i,A,t} - \bar{a}\right)^{\omega} c_{i,N,t}^{1-\omega}, \qquad (2)$$

where parameter ω represents the long-term Cobb-Douglas weight of agricultural consumption in the utility function.

Households in both countries seek to maximize their Stone-Geary utility functions separately, subject to their respective budget constraints:

$$c_{i,A,t} P_{i,A,t} + c_{i,N,t} P_{i,N,t} = \left(1 - R_{i,w}\right) \left(w_{i,A,t} * \frac{L_{i,A,t}}{L_{i,t}} + w_{i,N,t} * \frac{L_{i,N,t}}{L_{i,t}} \right) + g_t. \qquad (3)$$

Households earn wages from agricultural sectors ($w_{i,A,t}$) and non-agricultural sectors ($w_{i,N,t}$), by providing labor $L_{i,A,t}$ to the agricultural production and $L_{i,N,t}$ to the non-agricultural production. In HC, household also receives *per capita* government transfer g_t. From the expenditure side, households pay income taxes at the rate of $R_{i,w}$ and spend on agricultural and non-agricultural goods, with consumer prices indexed to $P_{i,A,t}$ and $P_{i,N,t}$, respectively.

Agricultural Firms

Each country features a perfectly competitive agricultural sector. Representative agricultural firms produce homogenous agricultural goods for sale in domestic market ($Y_{i,i,A,t}$) at the sales prices of $p_{i,i,A,t}$, and for shipping to overseas market ($Y_{i,j,A,t}$), incurring trading cost $\tau_{i,j,A}$ and sold at $p_{i,j,A,t}$.

In both countries, agricultural firms utilize labor inputs from households. In HC, firm also invests in non-labor inputs and the government provides public capital to be strategically allocated, based on distinct investment goals: one to support standard agriculture development and one to finance climate change adaptation.

The two investment strategies are distinguished both conceptually within the model and in practical application. Standard development capital, by definition, contributes to agricultural production, whereas adaptation capital not only participates in production but more importantly, responds to productivity loss due to climate change. In line with the notion of additionality in adaptation finance – see the Introduction section – adaptation capital becomes essential *only* when climate change risks are expected to materialize. Without such risks, adaptation capital functions the same as standard development capital in production but at a higher cost, rendering it relatively inefficient. To capture this in the model, the aggregate public capital is a composite of standard development capital, $K_{1,t}$ and adaptation capital, $K_{2,t}$. $K_{2,t}$ is then adjusted for its relative inefficiency compared to $K_{1,t}$, through a discount factor κ (where $0 \leq \kappa < 1$), with $1-\kappa$ representing the productivity gap between adaptation and development capitals in the production function. As a result, the total public capital equates to $K_{1,t} + \kappa K_{2,t}$.

Once climate risks are anticipated, productivity of agricultural firm in HC, $B_{1,A,t}$, is expected to decline by a fraction Ω_t due to climate change. Damage due to climate change is modeled as a quadratic function of the degree of warming, denoted by H_t,[6] and a function of adaptation capital $K_{2,t}$.

$$\Omega_t = \frac{a * H_t^2}{1 + b * K_{2,t}} . \quad (4)$$

Ω_t enters the production function as the following,

$$Y_{1,1,A,t} + Y_{1,2,A,t} = (1 - \Omega_t) * B_{1,A,t} * \left(K_{1,t} + \kappa K_{2,t}\right)^{\iota} X_{1,t}^{\gamma} L_{1,A,t}^{1-\gamma}, \quad (5)$$

where $X_{i,t}$ is the intermediate inputs from non-agriculture sector (such as fertilizer, seeds, or other supplies), and γ represents the share of output allocated to private investment in those inputs.

The agricultural firm maximizes its profit $\Phi_{1,A,t}$,

$$\Phi_{1,A,t} = p_{1,1,A,t} Y_{1,1,A,t} + p_{1,2,A,t}(Y_{1,2,A,t}/\tau_{1,2,A}) - L_{1,A,t} w_{1,A,t} - X_{1,t} P_{1,N,t} , \quad (6)$$

where $P_{1,N,t}$ is the indexed consumers price of intermediate inputs, sourced from non-agricultural firms both domestically and abroad.

Similarly, the representative agricultural firm in ROW also maximizes its profit $\Phi_{2,A,t}$.

$$\Phi_{2,A,t} = p_{2,2,A,t} Y_{2,2,A,t} + p_{2,1,A,t}(Y_{2,1,A,t}/\tau_{2,1,A}) - L_{2,A,t} w_{2,A,t} - X_{2,t} P_{2,N,t}, \quad (7)$$

where the production does not involve public investments and is not subject to climate impacts explicitly:

$$Y_{2,2,A,t} + Y_{2,1,A,t} = B_{2,A,t} * X_{2,t}^{\gamma} L_{2,A,t}^{1-\gamma} . \quad (8)$$

The impacts of climate change on trade are reflected implicitly as part of the iceberg costs. The model posits that greater climate change impacts lead to higher trade costs.

Non-Agricultural Firms

Like the agricultural sector, the non-agricultural sectors in both countries are also perfectly competitive, but with a simpler production structure, only involving labor supplied by households. Similar to agricultural goods, non-agricultural goods are for sale in domestic markets $Y_{i,i,N,t}$ and in overseas markets $Y_{i,j,N,t}$, at the sales prices of $p_{i,i,N,t}$ and $p_{i,j,N,t}$, respectively.

Non-agricultural firm seeks to maximize its profits $\Phi_{i,N,t}$,

$$\Phi_{i,N,t} = p_{i,i,N,t} Y_{i,i,N,t} + p_{i,j,N,t}(Y_{i,j,N,t}/\tau_{i,j,N}) - L_{i,N,t} w_{i,N,t}, \quad (9)$$

where the production function is written as follows,

$$Y_{i,i,N,t} + Y_{i,j,N,t} = B_{i,N,t} L_{i,N,t}. \quad (10)$$

$B_{i,N,t}$ represents labor productivity in either HC or the ROW.

[6] This damage function captures the effects of warming through various channels including changes of temperature and rainfall patterns.

As discussed, non-agricultural products can be sold not only to households for consumption ($c_{i,N,t}$), but also to be invested as non-agricultural inputs ($X_{i,t}$) for agricultural firms, and as public investments[7] ($I_{1,t}$ and $I_{2,t}$ in HC, representing standard development investment and adaptation investment, respectively). In contrast, agricultural outputs are sold exclusively to households as consumption goods ($c_{i,A,t}$).

Government in HC

The model features a benevolent government in HC, seeking to maximize household's welfare by strategically determining a cost-efficient combination of investments. It taxes household's income, and the revenues are utilized to fund agricultural investments and provide transfer to household. The government's budget constraint is expressed as follows,

$$L_{1,t}g_t + I_{1,t} + I_{2,t} = R_{1,w}\left(L_{1,A,t}w_{1,A,t} + L_{1,N,t}w_{1,N,t}\right). \quad (11)$$

Standard development capital and adaptation capital both depreciate over time albeit at their own rates, δ_1 and δ_2, respectively. These rates are influenced by the nature of specific investment projects. Currently there is no well-established guidance from the literature on whether the two depreciation rates should differ significantly, nor on which rate should be consistently higher. The dynamics governing the two types of public capital are represented as follows,

$$K_{1,t+1} = I_{1,t} + (1 - \delta_1)K_{1,t}, \quad (12)$$

$$K_{2,t+1} = I_{2,t} + (1 - \delta_2)K_{2,t}. \quad (13)$$

Market-clearing Conditions and Distortion

The model reaches equilibria in both the agricultural and non-agricultural final goods markets.

Households consume agricultural goods purchased from domestic market and abroad. Consumption, $L_{i,t}c_{i,A,t}$, is represented by a CES aggregation of the products from the two markets:

$$\left(Y_{i,i,A,t}^{\frac{\sigma_A - 1}{\sigma_A}} + Y_{i,j,A,t}^{\frac{\sigma_A - 1}{\sigma_A}}\right)^{\frac{\sigma_A}{\sigma_A - 1}} = L_{i,t}c_{i,A,t}, \quad (14)$$

where σ_A represents the elasticity of substitution between products differentiated by their regions of origin.

Similarly, non-agricultural goods are purchased from both markets and consumed by households in both countries. But they are also used as intermediate inputs to agricultural production $X_{i,t}$ in both countries, and as public investments $I_{1,t}$ and $I_{2,t}$ by the government in HC.

$$\left(Y_{i,i,N,t}^{\frac{\sigma_N - 1}{\sigma_N}} + Y_{i,j,N,t}^{\frac{\sigma_N - 1}{\sigma_N}}\right)^{\frac{\sigma_N}{\sigma_N - 1}} = L_{i,t}c_{i,N,t} + X_{i,t} + I_{1,t} + I_{2,t}, \quad (15)$$

where σ_N represents the elasticity of substitution between non-agricultural products from the two markets.

The labor market clears as follows:

$$L_{i,A,t} + L_{i,N,t} = L_{i,t}. \quad (16)$$

[7] Following settings in literature that discuss growth and sectoral composition of economies, e.g., Echevarria (1997) and Kongsamut et al (2001).

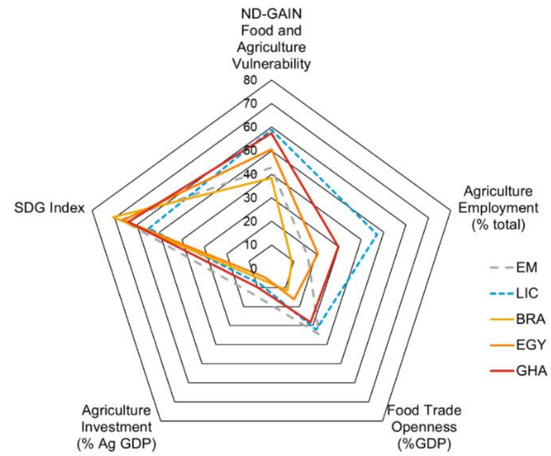
We introduce a distortion (θ_i) to reflect barriers to labor mobility broadly, which could include various government interventions through regulatory and legal measures, as well as skill mismatches.[8] The labor market friction is represented by:

$$w_{i,A,t} = \theta_i w_{i,N,t} \quad (\theta_i \leq 1). \tag{17}$$

4. Model application to country cases

4.1 Country cases

Figure 6. Elements of Balanced Adaptation Investment Strategy: Brazil, Egypt, Ghana, 2019



Source: ND-GAIN Index data, FAO, WEO, WB, Sustainable Development report

The model can be applied to a country whose agricultural sector is exposed to adverse impacts of climate change. Based on data availability, we chose three countries to apply the model: Ghana, Egypt, and Brazil. The three countries differ in terms of development levels, level of food security, and vulnerability to climate change in the agricultural sector. Despite increasing spending on agriculture over the years, all three countries are still underinvested in agriculture development, compared to the emerging market's average (Figure 6).

Ghana

In 2022, the agricultural sector in Ghana accounts for 20 percent of GDP and 40 percent of employment.[9] Agricultural production accounts for over 40 percent of export earnings;[10] the country is one of the world's largest producers and exporters of cocoa. The sector is dominated by smallholder family farms that are mostly rain-fed, therefore sensitive to climate change. Climate change is projected to lower yields in major staple crops in Ghana.[11] The rising temperatures could also intensify the prevalence of pests and diseases, leading to further crop losses. Areas suitable for cocoa production (mainly along the coast) are also contracting because of temperature increases, floods, soil salinization, and continued coastal erosion.

Egypt

Egypt's agricultural sector contributes about 10 percent of GDP, and it is an important source of subsistence and income, employing about 25 percent of the labor force.[12] Predominantly characterized by small-scale farms

[8] Agricultural subsidies and preferential tax policies, although not modelled explicitly, would produce similar distortionary labor market impacts, in addition to associated budgetary costs.

[9] Data source: World Bank Open Data.

[10] FAO "Ghana at a glance", July, 2024.

[11] For example, cassava yields are projected to fall by 30 percent by 2080 and corn yields by seven percent by 2050 (USAID Climate Change Risk Profile Ghana, 2017).

[12] Data source: World Bank Open Data.

that rely heavily on the Nile River for irrigation, the sector is highly susceptible to climate change. Increasing temperatures and changing precipitation patterns are expected to severely affect water availability, posing a significant threat to crop yields. Additionally, Egypt faces the challenge of sea level rise, particularly in the Nile Delta, a key agricultural area, exposing it to intensified risks of flooding and soil salinization. Egypt remains one of the world's largest wheat importers, relying heavily on imports to meet domestic food security requirements, a situation further complicated by the anticipated decline in local wheat yields due to climate change.

Brazil

In Brazil, traditional agriculture (farming and livestock) contributes about seven percent of GDP. However, considering agribusiness (including processing and agro-related services), its agriculture sector accounts for almost 25 percent of GDP and about 50 percent of total exports.[13] Brazil is a leading exporter of soybeans, coffee, and sugar. Rising temperatures and shifting rainfall patterns are expected to impact water availability and crop productivity.[14]

4.2 Model Calibration

The model is calibrated to the three economies separately, but a few parameters are common across all versions.

1. The long-run Cobb-Douglas weight of agricultural consumption (ω) in equation (2) is determined at 0.01, a reasonable mid-value within the range observed in literature on structural transformation (e.g. Buera and Kaboski, 2009, Herrendorf et al. 2013, Uy et al., 2013).[15]
2. Agricultural production function (5) incorporates an output elasticity (ι) of 0.122 for public capital, based on the meta-analysis conducted by Bom and Ligthart (2015).
3. The discount factor κ in the total public capital equation (5) is set to be 0.1.
4. The output share to non-agricultural intermediate inputs (γ) in equation (5) and (8) varies between 0.335 and 0.59 in literature (Uy et al., 2013; Tombe, 2015). We adopted a mid-value of 0.5 for the calibration.
5. Labor productivities of the non-agricultural firm in HC ($B_{1,N,t}$) in equation (10) are adopted from the World Bank's estimates of value-added per worker of the industry, which are country specific.
6. The labor ratios (between HC and the ROW) adopted for each country are based on the data from year 2015, which marks the beginning of the simulation period.
7. The labor market distortion (θ) in equation (17) remains constant over time and aligns with the ratio between value-added per worker of agriculture, forestry, and fishing sector and that of industry in the base year.[16]
8. Financing constraints are set to be two percent of GDP[17] for all three economies.

[13] IMF WP "Changing Climate in Brazil. Key Vulnerabilities and Opportunities" by C. Chen, K. Kirabaeva, C. Kolerus, I. Parry, and N. Vernon, forthcoming.

[14] For instance, productions of soybean, production corn, and sugar cane are projected to decrease by up to about 40, 30, and 10 percent respectively in 2050, under RCP8.5 scenario (Zilli et al, 2020).

[15] See Herrendorf et al. (2014) for a review of literature on structural transformation.

[16] Data source: World Bank Open Data.

[17] The two-percent constraint is set to be roughly equivalent to current government spending in agriculture. The real agricultural spending ratios are higher for Ghana than for Egypt and Brazil, with the spending ratio of the latter two close to two percent annually. But we have set the same constraint for all three countries for the purpose of comparability. In the later section, we will relax this constraint for Ghana to demonstrate the robustness of our results.

To capture the impacts from climate change on agricultural productivity loss, the model uses country-specific central projections from Cline (2007)[18] and calibrates damage parameter α in the agriculture production function accordingly. Cline (2007) determines that 3.3 degree of warming leads to agricultural productivity loss by 19.8 percent, 30.9 percent, and 28.7 percent in Ghana, Egypt, and Brazil without adaption, respectively.[19]

Additionally, efficiency of adaptation capital, governed by parameter b, is calibrated based on the Agrawala (2010). Adaptation investment rate of 0.01 percent reduces climate change-induced damage by 30 percent in Egypt and Ghana; investment rate of 0.005 percent reduces damage by 37 percent in Brazil.[20]

For both agriculture and non-agriculture goods, elasticities of substitution between goods from HC and the ROW in the Armington functions (14) and (15), σ_A and σ_N are set to be 4.06 and 4.63 based on the estimations from Tombe (2015), which broadly align with the elasticity estimated in other literature on international trade (e.g. Simonovska and Waugh, 2014).

The parameters that remained to be calibrated are the agricultural TFPs in both HC and the ROW, $B_{i,A,t}$, labor productivity of the non-agriculture sector in ROW, $B_{2,N,t}$, trade costs of each sector $\tau_{i,j,k}$, and the subsistence level of agricultural consumption $\bar{a}$. These parameters are calibrated jointly by matching a series of target variables to historical data: *labor share in agriculture, agricultural outputs in share of GDP, agricultural imports in shares of total, agricultural exports in share of total*, *export-to-GDP ratio*, *food expenditure in share of total, and the imported goods in shares of total consumption (agricultural and non-agricultural)*. Climate change impacts in ROW are not parameterized explicitly but incorporated in the trade cost, which could be attributed to a multitude of risk factors including strain on the global food supply chain due to climate shocks. Table 2 below lists key parameters selected for calibration.

Table 2. Key Parameters in the Model

Preference Parameters					**Production Parameters**	
α	β	ω	σ_A	σ_N	ι	γ
1.45	0.985	0.01	4.06	4.63	0.122	0.5
Nordhaus (2017)	Nordhaus (2017)	Literature	Tombe (2015)	Tombe (2015)	Bom and Ligthart (2015)	Uy et al., (2013) Tombe, (2015)

While the calibration in our study is stylized, the projections of adaptation investment needs are broadly comparable with other major country studies, such as the World Bank's Climate Change Development Reports

[18] Cline (2007) is one of the rare papers that provides forward-looking country-level estimation of agriculture productivity loss due to climate change. Users could replace the parameter α in the damage function to tailor the calibration even more accurately, if a better country-level estimate exists.

[19] According to Bilal and Kanzig (2024), country-level estimations of broad climate change impacts, based on local temperature anomalies, may be substantially lower than those based on global temperature. Therefore, the impacts quantified in these country applications may represent conservative estimates.

[20] Estimations of investment efficiency vary in literature. However, to our best knowledge, all the estimations are under 0.1 percent of GDP for the EMDEs between 2015 and 2050. The grand total of *additional* investment needs for agricultural adaptation is estimated between 0.005 percent and 0.05 percent of EMDE's total GDP in 2030 (Narain et al., 2011; Sulser et al, 2023), to not only fully offset damages on agriculture but also boost total output (for example, by as high as 38 percent). Such high efficiency is primarily driven by the productivity gain from investing in agriculture R&D as well as water efficiency. Estimations from Agrawala et al. (2010) are at lower end of investment efficiency but provides more nuanced benefit estimates.

(CCDR). For example, as shown in the following sections, our model projects that without financing constraint, Ghana's additional adaptation investment needs reach 0.24 percent of GDP by 2030. This compares with the CCDR's bottom-up estimation for Ghana, which projects investment needs of about 0.3 percent of GDP annually by 2030 (World Bank, 2022).[21] Similarly, our model suggests that Brazil's broad agricultural adaptation investment needs, if unconstrained by financing, will reach 0.31 percent of GDP by 2030. To compare, the Brazil CCDR's assessment estimates a need for 0.22 percent of GDP for additional investment in land-use measures, to align with a resilient and low-carbon development path (World Bank, 2023).[22]

4.3 Investing in Cost- Efficient Adaptation to Ensure Food Security

Adaptation and Development Investments

Finding an optimal balance between adaptation and development investments allows to minimize climate damages in a cost-efficient manner. This is particularly relevant for countries with tight financing constraints.

We apply the model to examine a cost-efficient mix of adaptation and development investments under financing constraints. We contrast the two investment strategies designed to address climate-induced damages with a counterfactual baseline, where climate change is assumed to be absent.

- *Development-only investment strategy* (policy option 1): investing only in standard development capital.
- *Balanced investment strategy* (policy option 2): investing in both development and adaptation capitals.

First, we consider a scenario without climate shocks as a counterfactual baseline. Under this "no climate change" baseline, only policy option 1 is relevant, since adaptation is unnecessary. Next, we consider a scenario with climate change damages and the two policy options described above. Figures 7-9 present optimal paths of endogenous variables (output, investment, export, and import) for the two investment strategies, in percentage deviations from the respective "no climate change" baselines.

- *Development-only investment strategy* (policy option 1): When climate change causes damage to agricultural production, countries cannot fund more development investments to counteract the damages if they are under financing constraints (dashed orange lines in Figure 7a, 8a, and 9a). As a result, agricultural outputs are lowered and declining, alongside the declining total outputs (dashed orange lines in Figures 7c and 7f, Figures 8c and 8f, Figures 9c and 9f) and the increasing agricultural net imports (Figures 7b and 7e, Figures 8b and 8e, Figures 9b and 9e).
- *Balance investment strategy* (policy option 2): Under climate change, when countries decide to invest in adaptation, they will have to reallocate part of finance from investing in standard development if financing constraints are binding (blue solid lines in Figure 7a, 8a, and 9a). However, such finance reallocation allows the pathways of key variables, including agricultural and non-agricultural outputs, to return closer to the no-climate change baselines (solid blue lines in Figure 7-9). Therefore, even though total investments remain unchanged due to the constraints, investing in adaptation improves macroeconomic outcomes, by raising overall cost-efficiency of public investments.[23] The model costs adaptation investments at around

[21] Ghana CCDR estimates that between 2022 and 2030, USD 2.7 billion are needed to invest in climate-smart agriculture and expansion of irrigation, equivalent to about 0.3 percent of GDP in the same period.

[22] Brazil CCDR suggests that R$124.8 billion are needed in total between 2022 and 2030 to meet capital investment needs in pasture recovery, plantation, forestry, and natural forest restoration as measures to strengthen resilience of agriculture. This is equivalent to about 0.2 percent of GDP in the same period.

[23] This result is robust with respect to the productivity gap parameter κ. A higher κ increases the optimal level of investment in adaptation, reduces the development investment needs, and improves the overall cost-efficiency of the total investment spending compared to the "development-only" strategy.

0.15 percent of GDP in 2030 for all three countries under two percent of total constraint for agriculture. The optimality of these investments suggests that excessive adaptation investment would be wasteful from the cost-efficiency perspective, as it diverts resources needed for development.

Figure 7. Model results for Ghana

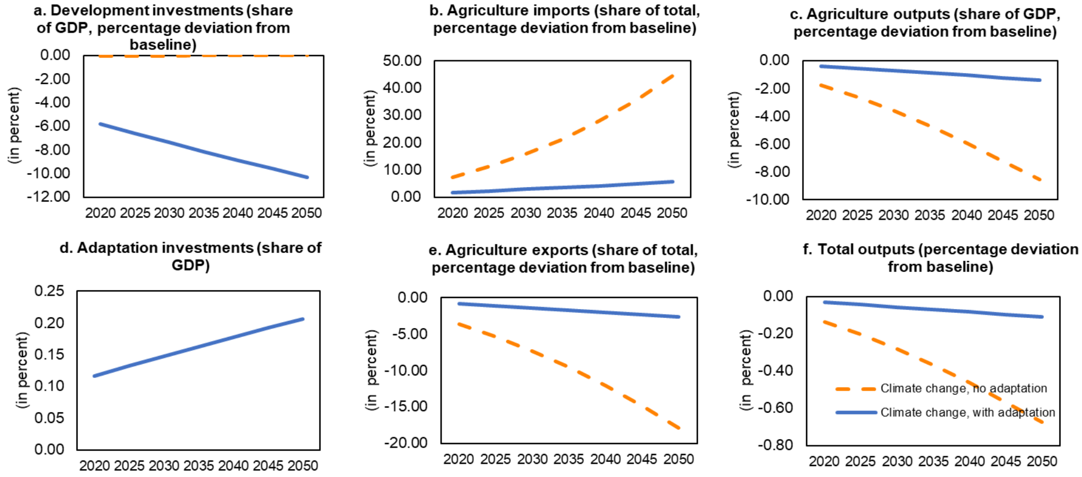


Figure 8. Model results for Egypt

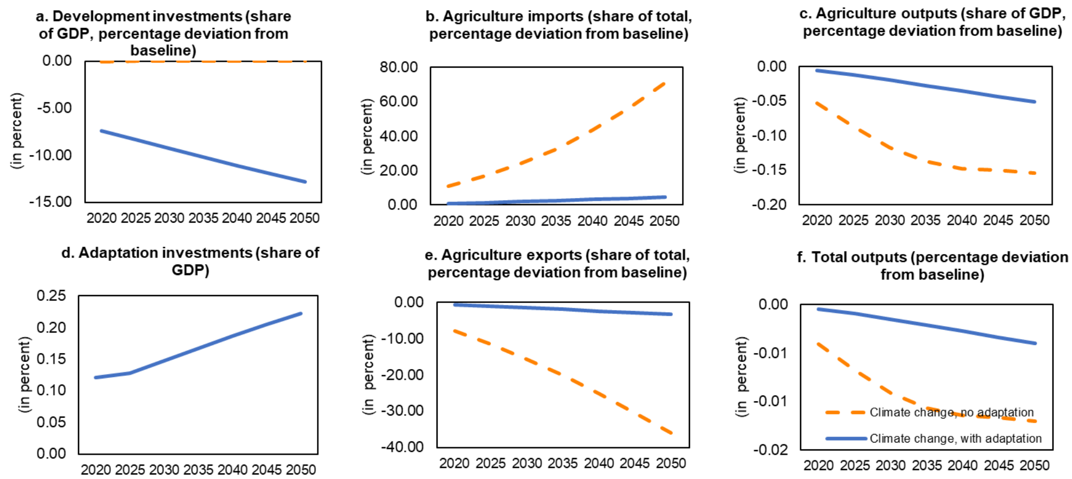
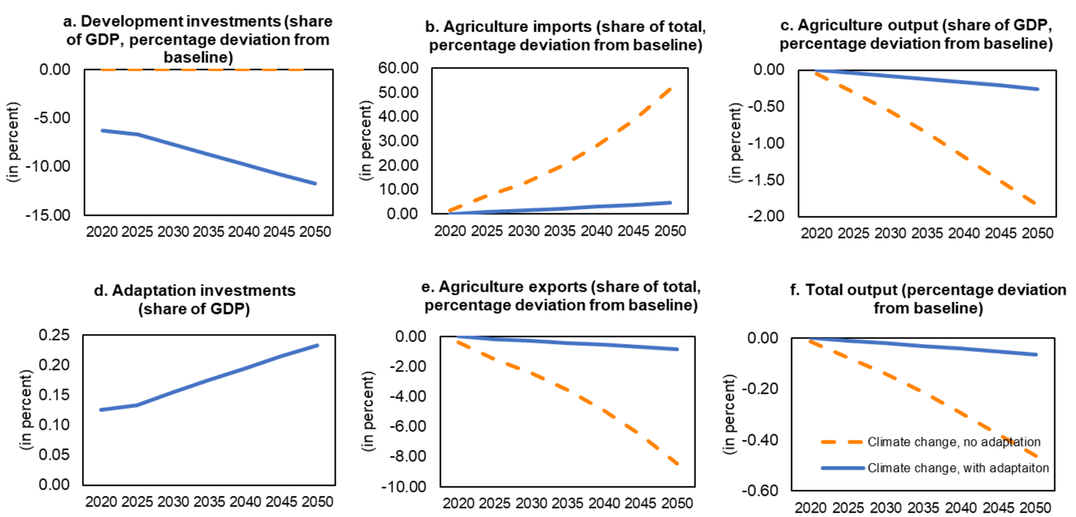
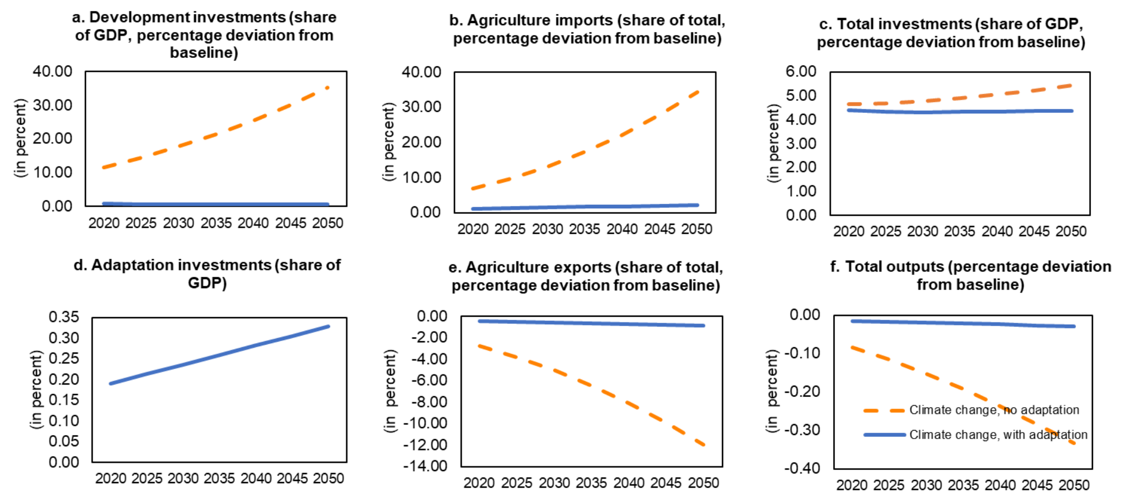


Figure 9. Model results for Brazil



In the event that a country's financing constraint is relaxed, these findings still hold. Taking Ghana as an example: should it secure extra concessional finance (for instance, through donor support) and ease its financing constraint, it could potentially amplify investments in both development and adaptation. However, channeling funds into adaptation remains a more cost-efficient strategy compared to investing in development alone. By investing in adaptation, the total investment to GDP ratio could reduce by up to one percentage point, compared to a development-only strategy (Figure 10c). To put the percentage in context, one percent of GDP would be fourfold the annual optimal adaptation investment in 2030 without financing constraint, and sevenfold if constraint is present.

Figure 10. Model results for Ghana with no financing constraint



Adaptation Investment and Trade

Trade openness helps lower required adaptation investment, by enabling a diversification of strategies to cope with domestic climate shocks.

In addition to general efficiency gains, trade also helps alleviate production shocks caused by climate change, through food imports and exports. In this sub-section, we consider two scenarios with low and high trade costs to illustrate the impacts of trade constraints on efficient adaptation and development investments. Under more constrained trade (with higher trade costs), a country that relies more on food imports would require a larger domestic agricultural production. However, that comes at the expense of non-agricultural output as well as consumptions of both food and non-food. More adaptation investments would be needed to offset production losses and meet residual food consumption needs.

Figure 11. Model results for Egypt with financing constraint: under low and high trade costs

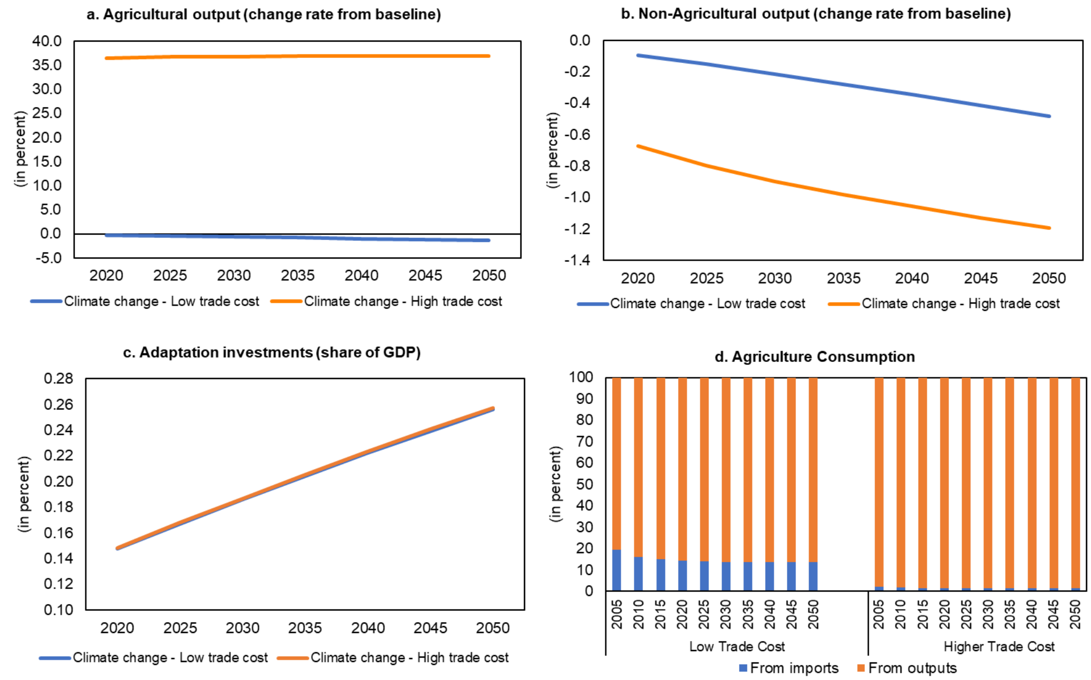
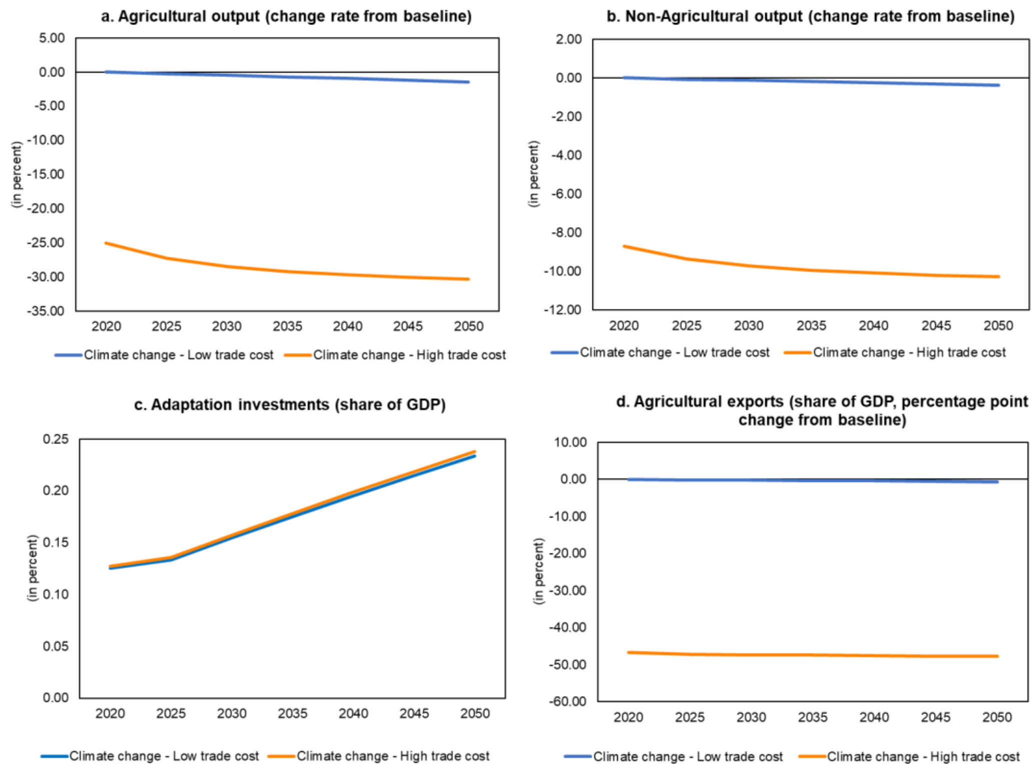


Figure 11 shows model simulations for Egypt. Once the trade costs are adjusted upwards by 1.5 times (the orange lines in Figure 11), the resulted lower imports are compensated by expanding agriculture outputs, at the expense of non-agriculture production (Figure11a and 11b). Higher trade cost even prompts the country to investment slightly more to adaptation, even under the binding financing constraint (Figure 11c). Finally, the contribution from imports to food consumption is significantly smaller when the trade cost is higher (Figure 11d).

If a country is mainly a food exporter (like Brazil in Figure 12), higher trade costs would discourage exports (Figure 12d), leading to output decline in both agricultural and non-agricultural sectors (Figure 12a and 12b). Since Brazil also purchases agricultural products from abroad, higher trade costs also discourage imports, diminishing the buffering role of trade when climate change compromises its agricultural productivity. Similar to food importers, adaptation investment needs slightly increases despite the binding financing constraint (Figure 12c).

From the food security perspective, higher trade costs have adverse effect not as much on a food-exporting country itself but more on the global food supply, hence, increasing risks of food insecurity globally. It would result in higher adaptation investment needs in countries that are more dependent on food imports.

Figure 12. Model results for Brazil with financing constraint: under low and high trade costs



In the scenarios above, we assumed that climate shocks are specific to the country of interest, and the impacts of climate change on the rest of the world do not directly affect agricultural productions but are only implicitly incorporated into trade costs. Under these assumptions, a country can offset some of the damages to food consumption through trade. However, if the climate change impacts are global, affecting agricultural productions domestically and internationally, trade could be limited as others prioritize meeting their own food consumption needs. This would weaken the adaptive role of trade in ensuring food security and necessitate larger adaptation investments across countries. Such investments would be especially critical for countries facing high risks of agricultural production loss, where consumption could drop below subsistence level, since relying on food imports becomes less feasible.[24]

Next, we run a series of comparative static exercises around our baseline parameters, for the case of Egypt, to better understand whether, and if so to what extent the average optimal investment rates[25] are sensitive to our key parameters. Importantly, the optimal policy pathways always make sure that the households' minimal food consumption needs are met in the most cost-efficient manner.

Climate Shocks and Trade

More constrained trade (with higher trade costs) has stronger negative impacts when climate shocks are more damaging.

[24] For example, see Gaupp, Hall, Hochrainer-Stigler, and Dadson, S. (2020).

[25] Investment rates are the average investment shares in GDP, optimized under no financing constraint.

We run comparative statics to demonstrate how trade costs affect adaptation investment needs. In this exercise, we assume no financing constraints, to allow investment to adjust freely. This way, the results could more clearly reflect the magnitude of the effects we intend to highlight.

As anticipated, when facing higher expected climate damages, higher investment is required to offset a larger loss. However, the increasing investment demand concentrates in adaptation because it directly targets reducing damages (Figure 13), while development investment stays broadly at the same level (blue dotted line).

If trade is less constrained (lower trade costs), a country does not require large investment in adaptation, even when higher damage is expected. Lower costs allow trade to play a more effective role in offsetting food consumption loss due to climate change, complementing adaptation investment (Figure 14).

Figure 13. Climate Damage, Development and Adaptation Investment (%GDP)

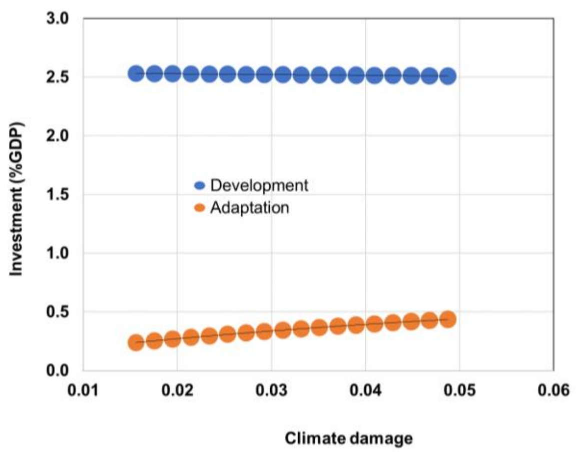
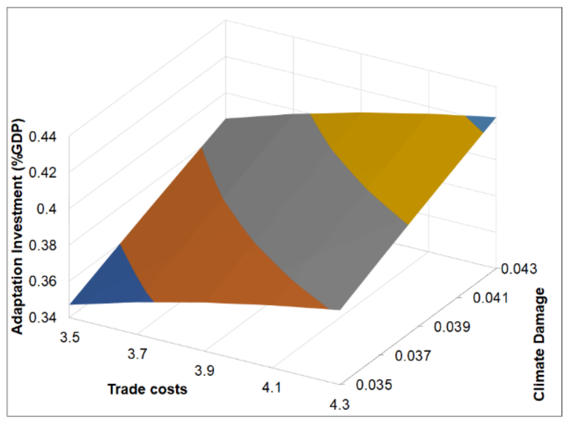


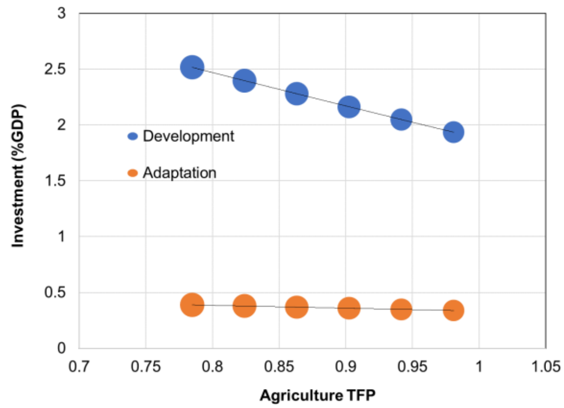
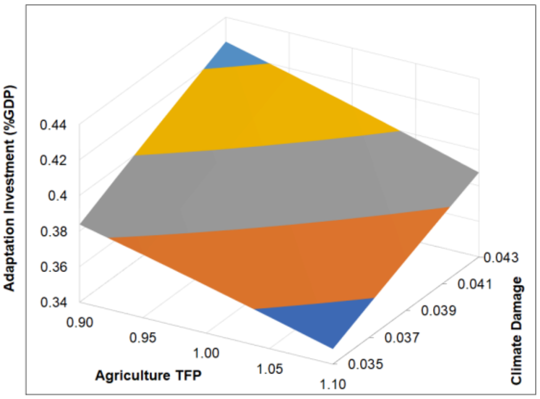
Figure 14. Climate Damage, Trade Costs, Adaptation Investment (%GDP)



Agriculture Productivity

Improving agriculture productivity reduces adaptation and development investment needs.

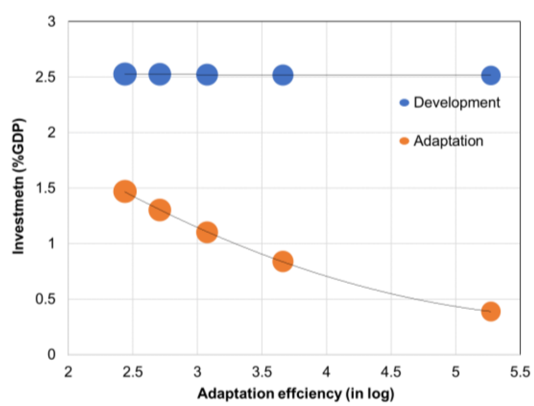
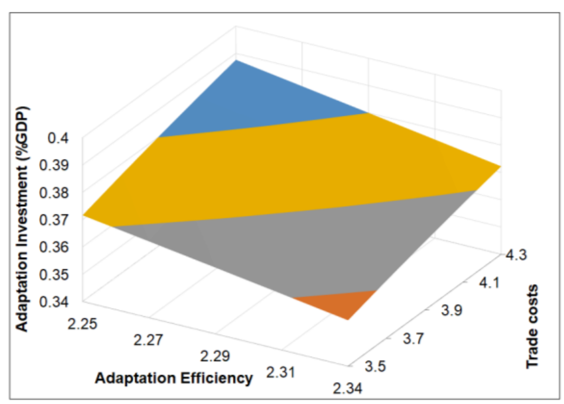
A country with a more productive agricultural sector can maintain a required level of production to ensure food security with smaller capital. Therefore, higher agricultural TFP is associated with lower investment rates. The effect on investment rate mainly concerns development capital (Figure 15), as the damage directly impacts TFP, which adaptation helps to restore. When expecting higher climate change damages, required adaptation investment is proportionally higher; but as agricultural productivity increases, the production may withstand higher damage without requiring higher adaptation investment (Figure 16).

Figure 15. Agriculture TFP, Adaptation and Development Investment (%GDP)	Figure 16. Climate Damage, Agriculture TFP, and Adaptation Investment (%GDP)
	

Adaptation Efficiency

Improving adaptation efficiency enhances adaptation investment benefits and food security.

As anticipated, higher adaptation efficiency lowers the needs for adaptation investment to offset climate change impact (Figure 17). Meanwhile, optimal development investment level (blue dotted line) is slightly elevated, given that adaptation capital protects productivity from declining. The benefits of more efficient adaptation increase proportionally as trade becomes more constrained (Figure 18).

Figure 17. Adaptation Efficiency, Adaptation and Development Investment (%GDP)	Figure 18. Trade Costs, Adaptation Efficiency, and Adaptation Investment (%GDP)
	

Labor Market Distortions

Reducing labor market distortions, for example, by reducing regulatory barriers and upskilling, would reduce adaptation investment needs and benefit more from trade openness.

Labor market distortion in the model captures obstacles for labor to freely migrate from agricultural to non-agricultural sectors, including a lack of skills as well as direct government support for agriculture, which helps ensure a certain level of agricultural production. The government may choose to support agriculture through fiscal measures such as subsidies or transfers, resulting in similar distortions on top of budgetary costs. Such market distortions lead to capital and labor misallocation and hence, lower overall consumption level in general.

Larger support for agricultural sectors reflected in labor market distortions increases adaptation investment needs and offsets benefits of trade (especially for food importers). Direct agricultural support would result in higher adaptation investment requirement to protect agricultural output against climate shocks (Figure 19). Similar to the results of other comparative static exercises, the impact of distortions on adaptation investment is larger when trade costs are higher (Figure 20).

Figure 19. Labor market distortions, Adaptation and Development Investment (%GDP)

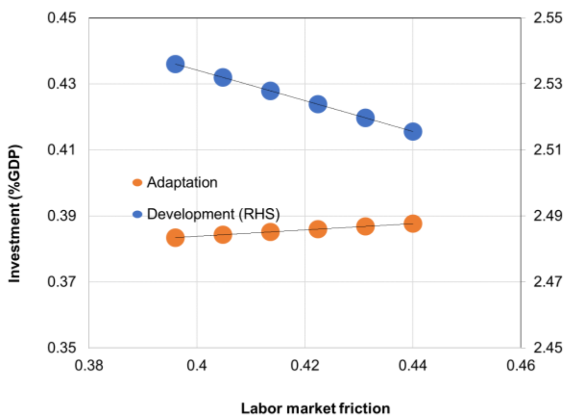
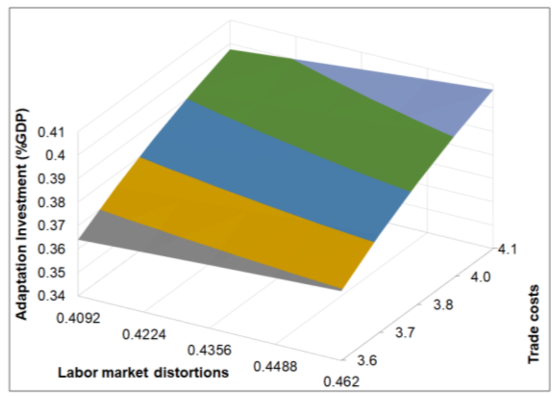


Figure 20. Trade Costs, Labor Market distortions, and Adaptation Investment (%GDP)



5. Conclusion and Policy Implications

The model developed in the paper provides a framework for cost-benefit analysis on agricultural adaptation investment. Such analysis helps identify a balanced strategy to manage negative impacts of climate change shocks on food supply losses, identifying adaptation and broad development investment needs, taking into account financing and international trade constraints.

Targeted adaptation investments are essential to directly protect production from climate shocks. However, they should be balanced against broader development investment needs, especially in countries under financing constraints. Inadequate adaptation investment would have to be compensated by much higher level of standard development investment, while excessive adaptation investment diverts funds from standard investment, which is particularly relevant when financing is limited.

Our results also demonstrate benefits of international trade for adaptation and food security. While adaptation benefits tend to be local, international trade of agricultural goods allows to share these benefits, making them more global. Therefore, in a more economically integrated world, investing in adaptation in food exporting countries can benefit food security globally, by protecting production and promoting exports. In the case of food importing countries, international trade serves as a buffer to cushion food supply against domestic climate shocks, complementing adaptation investments. It allows countries to more effectively manage adverse impacts of climate shocks on domestic agricultural production, and as a result, reduces their adaptation investment needs. The adaptive role of trade has to be weighed against potential trade-offs, such as support for domestic agriculture and exposure to global shocks.

Improving agriculture productivity and adaptation efficiency enhances the benefits of adaptation investment and food security. Countries with higher agricultural productivity and adaptation efficiency require less investments in adaptation. Reducing labor market distortions, for example, through regulatory reforms and upskilling, would also reduce adaptation investment needs.

Relevant structural reforms also help to improve overall economic efficiency under climate change. Reforms that would not require additional spending include strengthening institutional framework and improving government effectiveness. For example, green public financial management (PFM) adapts existing PFM practices, especially the budget process, to make them environment and climate sensitive. Strengthening climate public investment management would increase spending efficiency. More efficient regulation such as better land use planning could improve adaptation investment efficiency. These reforms are especially relevant for countries that are more impacted by climate change, facing increased trade barriers, and more financially constrained.

At global level, promoting trade openness and mobilizing concessional finance for climate change adaptation would help to address climate-related challenges and ensure food security. Global efforts to strengthen international trade system and to mobilize finance for adaptation in vulnerable and less developed countries would support growth and resilience, especially when these countries face high debt levels.

Adaptation investment could have co-benefits for climate change mitigation. We focused on adaptation in the agricultural sector, which is particularly relevant to lower-income countries that are not among the large global emitters. However, it should be noted that agriculture tends to be a significant source of domestic emissions in those country groups. Some adaptation investments, such as water management, land protection, resilient crops, could help restore and expand carbon sinks, improve production efficiency, and lower losses, thereby contributing to mitigation targets too.

We conclude with several proposals for future research. First, while there is a strong link between food security and income inequality, our current model does not distinguish between different income groups within a country. As a result, it is not capable of capturing the distributional impacts of climate damage, development investments, and adaptation measures (including through trade). Further research in this area is needed. Second, our model features a highly stylized fiscal sector. Enhancing this aspect could lead to a more thorough analysis of fiscal responses to climate shocks and investments in adaptation. Third, our model categorizes trade partners into HC and the ROW, which has helped structure the model in a simple yet comprehensive manner. However, it poses calibration challenges due to the lack of detailed ROW data. Climate and trade research often recommends subdividing the ROW into specific regions or countries to avail more data and gain a finer understanding of the interplay between international trade and domestic adaptation measures. Lastly, the model could be expanded into a full-fledged integrated assessment model. This would allow for an investigation of the co-benefits of agriculture adaptation, in terms of emission reduction in the agricultural sector.

References

1. Agrawala, Shardul, Francesco Bosello, Carlo Carraro, Kelly de Bruin, Enrica De Cian, Rob Dellink, and Elisa Lanzi. "Plan or react? Analysis of adaptation costs and benefits using integrated assessment models." OECD Environment Working Papers, No. 23, OECD Publishing, Paris, France. 2010.
2. Aggarwal, Rimjhim, Piergiorgio Carapella, Tewodaj Mogues, and Julieth Pico-Mejía “Accounting for Climate Risks in Costing the SDGs”, IMF Working Paper WP/24/49. International Monetary Fund, Washington, DC. 2024.
3. Aligishiev, Zamid, Emanuele Massetti, and Matthieu Bellon. “Macro-fiscal implications of adaptation to climate change.” IMF Staff Climate Note 2022/002, International Monetary Fund, Washington, DC. 2022.
4. Bilal, Adrien and Kanzig. Diego R.. “The Macroeconomic Impact of Climate Change: Global vs. Local Temperature”. NBER Working Paper 32450. Cambridge, MA. 2024.
5. Bom, Pedro RD, and Jenny E. Ligthart. "What have we learned from three decades of research on the productivity of public capital?." Journal of Economic Surveys 28, no. 5 (2014): 889-916.
6. Buera, Francisco J. and Joseph P. Kaboski. “Can Traditional Theories of Structural Change Fit the Data?” Journal of the European Economic Association, Volume 7, Issue 2-3, (2009): 469–477.
7. Cline, William R. “Global warming and agriculture: Impact estimates by country”. Peterson Institute, 2007.
8. Costinot, Arnaud, Dave Donaldson, and Cory Smith. "Evolving comparative advantage and the impact of climate change in agricultural markets: Evidence from 1.7 million fields around the world." Journal of Political Economy 124, no. 1 (2016): 205-248.
9. Chen, Chen, Ian Noble, Jessica Hellmann, Joyce Coffee, Martin Murillo, and Nitesh Chawla. “University of Notre Dame global adaptation index: Technical Report”. University of Notre Dame. Notre Dame, Indiana. 2015.
10. Echevarria, Cristina. “Changes in Sectoral Composition Associated with Economic Growth”. International Economic Review. Vol.38 (2) (1997): 431-452
11. Gouel, Christophe, and David Laborde. “The crucial role of international trade in adaptation to climate change”. No. w25221. National Bureau of Economic Research. 2018.
12. Gaupp, Franziska, Jim Hall, Stefan Hochrainer-Stigler, and Simon Dadson. "Changing risks of simultaneous global breadbasket failure." Nature Climate Change 10, no. 1 (2020): 54-57.
13. Goyal, Aparajita, and John Nash. “Reaping richer returns: Public spending priorities for African agriculture productivity growth.” World Bank Publications. 2017.
14. Gouel, Christophe, and David Laborde. “The Crucial Role of Domestic and International Market-Mediated Adaptation to Climate Change.” Journal of Environmental Economics and Management 106 (2021): 102408
15. Herrendorf, Berthold, Richard Rogerson, and Akos Valentinyi. "Growth and structural transformation." Handbook of Economic Growth 2 (2014): 855-941.
16. Herrendorf, Berthold, Richard Rogerson, and Akos Valentinyi. "Two perspectives on preferences and structural transformation." American Economic Review 103, no. 7 (2013): 2752-2789.

17. IMF Blog “Global Debt Is Returning to its Rising Trend” 2023 https://www.imf.org/en/Blogs/Articles/2023/09/13/global-debt-is-returning-to-its-rising-trend

18. Kongsamut, Piyabha, Sergio Rebelo, and Danyang Xie. “Beyond Balanced Growth”. The Review of Economic Studies. Vol. 68, No. 4 (2001): 869-882

19. Marto, Ricardo, Chris Papageorgiou, and Vladimir Klyuev. "Building resilience to natural disasters: An application to small developing states." Journal of Development Economics 135 (2018): 574-586.

20. Millner, Antony, and Simon Dietz. "Adaptation to climate change and economic growth in developing countries." Environment and Development Economics 20, no. 3 (2015): 380-406.

21. Narain, Urvashi, Sergio Margulis, and Timothy Essam "Estimating costs of adaptation to climate change." Climate Policy 11(3) (2011): 1001-1019.

22. Nath, Ishan. "Climate Change, the Food Problem, and the Challenge of Adaptation through Sectoral Reallocation." Conference papers 333404, Purdue University, Center for Global Trade Analysis, Global Trade Analysis Project. 2022.

23. Nelson, Gerald C., Mark W. Rosegrant, Jawoo Koo, Richard Robertson, Timothy Sulser, Tingju Zhu, Claudia Ringler et al. “Climate change: Impact on agriculture and costs of adaptation.” Vol. 21. International Food Policy Res Institute. 2009.

24. Ortiz-Bobea, Ariel, Toby R. Ault, Carlos M. Carrillo, Robert G. Chambers and David B. Lobell “Anthropogenic climate change has slowed global agricultural productivity growth.” Nature Climate Change. Vol 11 (2021): 306-312.

25. Sibhatu, Kibrom T. and Matin Qaim. "Rural food security, subsistence agriculture, and seasonality." PloS one 12.10 (2017): e0186406.

26. Simonovska, Ina, and Michael E. Waugh. "The elasticity of trade: Estimates and evidence." Journal of international Economics 92, no. 1 (2014): 34-50.

27. Sulser, Timothy B., Keith Wiebe, Shahnila Dunston, Nicola Cenacchi, Alejandro Nin-Pratt, Daniel Mason-D’croz, Richard Robertson, Dirk Willenbockel, And Mark W. Rosegrant. “Climate Change and Hunger: Estimating Costs of Adaptation in the Agrifood System.” International Food Policy Research Institute, Food Policy Report (2021)

28. The Economist Group “Global Food Security Index 2019” https://impact.economist.com/sustainability/project/food-security-index

29. The Sustainable Development Report, 2022 https://www.sustainabledevelopment.report/reports/sustainable-development-report-2022/

30. Tombe, Trevor. "The missing food problem: Trade, agriculture, and international productivity differences." American Economic Journal: Macroeconomics 7, no. 3 (2015): 226-258.

31. United Nations Environment Programme “Adaptation Gap Report 2023: Underfinanced. Underprepared. Inadequate investment and planning on climate adaptation leaves world exposed”. Nairobi, Kenya, 2023.

32. USAID Climate Change Risk Profile: Ghana, 2017 https://www.climatelinks.org/sites/default/files/asset/document/2017_USAID_Climate%20Change%20Risk%20Profile%20-%20Ghana.pdf

33. World Bank Group Country Climate and Development Report for Ghana, 2022 https://openknowledge.worldbank.org/server/api/core/bitstreams/9c9764c1-076d-5dcc-8339-6e4f0de2b610/content

34. World Bank Group Country Climate and Development Report for Brazil, 2023 https://openknowledge.worldbank.org/server/api/core/bitstreams/fd36997e-3890-456b-b6f0-d0cee5fc191e/content

35. Uy, Timothy, Kei-Mu Yi, and Jing Zhang. "Structural change in an open economy." Journal of Monetary Economics 60, no. 6 (2013): 667-682.

36. Zilli, Marcia, Marluce Scarabello, Aline C. Soterroni, Hugo Valin, Aline Mosnier, David Leclere, Petr Havlik, Florian Kraxner, Mauricio Antonio Lopes, and Fernando M. Ramos. "The Impact of Climate Change on Brazil's Agriculture." *Science of the Total Environment* 740 (2020): 139384.

PUBLICATIONS

Investing in Climate Adaptation under Trade and Financing Constraints:

Balanced Strategies for Food Security

Working Paper No. WP/2024/184