Essays on the nexus of climate change, agricultural productivity, and the environment.

by

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B.S., University of Ibadan, 2001
M.S., University of Birmingham, 2008
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AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Agricultural Economics
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Abstract

Agriculture is highly dependent on and sensitive to weather. Warming effects result from greenhouse gas emissions and aerosols from a small number of countries but its impact will be felt on a global scale. So far, agricultural productivity growth has sustained the continuous global supply of food, but will this continue into the foreseeable future with the incidence of climate change? The effects of climate change on crop yields have been the focus of several studies. However, the sensitivity of agricultural productivity (measured as Total Factor Productivity-TFP) to climate change is not well understood.

The first essay examines how historical changes in temperature and precipitation have affected the evolution of agricultural total factor productivity (TFP) while accounting for the short- and long-term impact. A fixed effect regression model for 128 countries for a period of 1961 to 2014 was employed to exploit yearly changes in temperature and precipitation as the identification strategy. Results show that precipitation has a significant effect on TFP growth in Sub-Saharan Africa, tropical and low-income countries. Global short term temperature effect is offset in the long run showing that farmers adapt to reduce the effects of temperature in their behavioral decisions.

Irrespective of the impact of climate change, there have been calls for an increase in agricultural productivity due to uncertainty and a global decline in Research and Development (R&D) expenditures. Previous literature accounts for the effect of global TFP growth on global food security and the environment. My second essay estimates the impact of TFP growth in different regions on global food security and the environment using a partial equilibrium model. To construct comparable TFP shocks across regions, I consider three TFP shock scenarios: (i) a uniform 100 percent increase in TFP growth in each region, (ii) TFP growth in each region

that gives the same decrease in global commodity price, and (iii) TFP growth in each region resulting from the same increase in R&D expenditure. Results show that a 100% increase in TFP in the US & Canada increases agricultural carbon emission within the US & Canada by 16.9% but with a net global decrease in agricultural carbon emissions by 4.27%. In addition, a 100% increase in TFP in the US & Canada decreases global food security (malnutrition) by 13.09%. These results provide justification to support increasing R&D expenditures in developed regions. Overall, TFP growth is most effective in Sub-Saharan Africa as it gives the largest reductions in malnutrition and carbon emissions.

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Dedication

Dedicated to my parents – Engr. Adekunle Odugbesan and Mrs. Anike Odugbesan, and hubby, my major motivators throughout these years of school. We did it!!!!!!!!!!!!

Also, to my babies – the FGGF sisters, mummy is done and will have unconditional time for you all. Thank you for your understanding. Time to start another life adventure.

Chapter 1

Introduction

Agricultural productivity is a key outcome in the process of economic development in the society. Besides providing food security, increase in agricultural productivity provides income generation, source of employment that directly reduce poverty and important for international trade. However, global trends such as population growth expected to increase to 10 billion by 2050 and income growth with countries transitioning from low to middle-income class economies (FAO, 2017) puts enormous stress on economic sustainability. In addition, climate change such as increased warming and increase in greenhouse emission from human and agricultural activities poses a threat to food availability and security.

As these issues becomes prevalent, agriculture-driven growth, poverty reduction, and food security are at risk with the main concern centered on whether global agricultural productivity growth will continue into the foreseeable future (FAO, 2017). A global collective effort is needed to combat and mitigate the effect of climate change and encourage environmental sustainability. Furthermore, as uncertainty abounds, global calls for an increase are based on the current decline in agricultural research and development (R&D) investment. With an increase in productivity comes the concern on the environment (will it be land saving or not) in the form of deforestation, land degradation, increased carbon emission, etc. For the world to continue feeding itself, the future growth of agricultural productivity growth will be dependent on investments in food and agricultural R&D.

The first essay examines how historical changes in temperature and precipitation have affected the evolution of agricultural total factor productivity (TFP) in the short and long run. I use agricultural productivity measured as total factor productivity as the outcome variable instead of a partial productivity measure like crop yields used in most previous literature. I focused on answering the following research questions. First, what is be the effect of weather changes on agricultural productivity? Second, do these effects vary from one region to another in the short or long run? Third, are farmers able to adapt or mitigate the effect of climate change in their production decisions? To answer these questions, I begin by estimating how historical global agricultural productivity (TFP) responds to climate change using a fixed-effects regression model. The identification strategy employs year-to-year changes in temperature and precipitation to estimate their effect on agricultural productivity at a regional and national level. Primary results show a nonlinear TFP response to changes in both temperature and precipitation exist. An increase in monthly precipitation has a positive and significant effect on TFP but temperature effect is insignificant. As precipitation increases over a threshold (600mm for tropical countries and 500mm for low-income countries), TFP declines rapidly. Adaptation practices that reduce the effects of extreme temperature by farmers are evident in the long term.

The second essay seeks to estimate the impact of TFP growth on food security and the environment. To do this, I address three specific questions. First, what is the impact of TFP growth in specific regions on global food security and the environment? Second, how do TFP shocks in specific regions affect food security and the environment in other regions (i.e., measuring where spillover effects occur)? Third, where is TFP growth most effective at reducing malnutrition and carbon emissions? I address these questions using a partial equilibrium model to simulate the impact of TFP growth on the malnutrition index and carbon emissions in each region of the world. To do this, I focus on TFP shocks in four major production regions: US & Canada, Sub Saharan Africa, South America, and China & Mongolia. However, I faced a challenge in comparison of TFP impacts since the regions vary in size and factor endowment; thus, the need for deriving comparable TFP shocks for each region. To estimate the comparable TFP shocks, three different scenarios of comparable TFP growth shocks in each region were evaluated. These scenarios are 1) a uniform 100% increase in TFP in each region, 2) TFP growth in each region that would lead to a 17.21 percent decrease in global price and 3) TFP growth resulting from an increase in R&D expenditures by $6.15 billion in each region.

Results show that TFP growth contributes a significant impact in reducing global food security and carbon emission. TFP growth in the US & Canada is beneficial in reducing global malnutrition and carbon emission. Other regions like Middle East and South East Asia for malnutrition reduction, Australia & New Zealand and South Africa for carbon emission were affected positively by TFP growth in Canada & US. Also, TFP growth in SSA had the greatest impact on global malnutrition making the region the most effective at improving food security and sustainable environment. In contrast, TFP growth in South America results in an increase in its own region's carbon emission in all three scenarios, although the net global effect is a reduction in carbon emissions. From a policy point of view, this result is critical for policymakers in the US, who are making decisions about R&D funding and for making decisions on where to target R&D efforts regionally to effectively reduce global malnutrition and carbon emission.

Chapter 2

Climate change impacts on agriculture: evidence from global agricultural productivity

2.1 Introduction

Agriculture is highly dependent on and sensitive to the weather. Climate change is evident through observed increases in temperature (air and ocean), rising sea levels, and melting glaciers in the Arctic and Antarctic ecosystems (IPCC, 2007). These changes are signs of warming that could affect agriculture (crop production and international trade), human and animal health (spread and outbreak of infectious disease), and human activities such as access to water, physical and natural resources (IPCC, 2007). Most of these warming effects are the result of increasing greenhouse gas emissions and aerosols from a small number of countries like the Russian Federation, the United States of America, the European Union, China, and India (IEA, 2019), but the impact will be felt on a global scale. Projected greenhouse gas (GHG) emissions are expected to continually grow by 50 percent by 2050, driven by a 70 percent growth in carbon emission from energy use unless new policies are implemented (OECD, 2012). On the other hand, the possibility of feeding the world with a growing population and changing dietary preferences has been a subject of interest and concern.

To reflect the wide range of agricultural activities, the measure of agricultural productivity used in this essay is total factor productivity (TFP), defined as "a broad measure encompassing the average productivity of all inputs with market value (land, labor, capital, and materials) employed in the production of all crops and livestock commodities" (Fuglie et al., 2012). Agricultural productivity plays an important role in food availability and stabilizing food prices such that sustained growth will be critical for global food security and poverty reduction. However, as the impact of climate change becomes more evident, agriculture-driven growth, poverty reduction and food security are at risk with the main concern centered on whether global agricultural productivity growth will continue into the foreseeable future (FAO, 2017).

The objective of this study is to examine how historical changes in temperature and precipitation have affected the evolution of agricultural TFP while accounting for its impact in the short and long run. What is the effect of weather changes on agricultural productivity? Did these effects vary from one region to another in the short to long run? Did farmers adapt or mitigate the effect of climate change in their production decisions in the long run? I address these questions using a fixed effect regression model employing yearly changes in temperature and precipitation.

The effects of climate change on crop yields have been the focus of several studies in the literature as some focus on a single crop (Tack et al., 2012; Lobell and Field, 2007; Jones and Thornton, 2003; Matthews et al., 1995) or on multiple crops (Lobell et al., 2011; Tebaldi and Lobell, 2008; Lizumi and Ramankutty, 2016; Adhikari et al., 2015.). Other studies focus on various econometric models that use panel data estimation of weather variables on economic variable like Gross Domestic Product (GDP) with a linear (Dell et al., 2012) or nonlinear specification for temperature (Hsiang, 2010; Deryugina and Hsiang, 2014; Dell et al., 2014; Schlenker et al., 2009). In addition, other studies focus on cross-sectional data estimation of the impacts of climate change (Mendelsohn et al., 1994; Gallup et al., 1999; Masters and McMillan, 2001; Sachs, 2003; Nordhaus, 2006; Hendricks, 2018; and Ortiz-Bobea, 2020). Furthermore, other outcome variables such as civil conflict (Burke et al., 2009), violence (Theisen, 2012), automobile production (Cachon et al., 2012), time allocation (Graff and Neidell, 2014), mortality rate, and migration (Deschênes and Moretti, 2009), household electricity (Auffhammer and Aroonruengsawat, 2011) and food consumption (Bhattacharya et al., 2003) on weather variables were also used to estimate the impacts of climate change. Finally, adaptation and mitigation are other important areas in climate change studies. With studies on adaption studying the adoption of agro-ecological strategies (Altieri and Nicholls, 2017), transitions in livestock systems (Weindl et al., 2015), inefficient institutions (Anderson and Hill, 2004), evolving patterns of international trade (Baldos and Hertel, 2015), and adaptation to climate change in US agriculture (Burke and Emerick, 2016; Deschênes et al., 2011). While research on mitigation is based on reducing greenhouse gas emission (Murray et al., 2005) and land-based mitigation policy (Hussein et al., 2013).

The sensitivity of TFP to climate change is not well understood. The few studies available examine the impact of climate change on TFP in the United States (Liang et al., 2017; Ortiz –Bobea et al., 2018) and global TFP (Henseler and Schumacher, 2019; Letta and Tol, 2019; and Ortiz–Bobea et al., 2020). This essay makes two contributions to the literature. First, by contributing to the growing literature on climate impacts, especially on climate change and TFP. Second, by quantifying on a macro basis (regional) the relationship between climate change and TFP on a short to long-term basis. The essay is organized as follows. The next section reviews the methodology that highlights the theoretical and empirical framework and includes the model specification for assessing the impact of climate change on agricultural productivity.

Section 3 discusses the data while section 4 presents results, and section 5 discusses limitation of the study. Section 6 concludes on the impact of climate change on TFP.

2.2 Methodology

Here I discuss the theoretical and empirical framework as well as the model specifications.

2.2.1 Theoretical Framework

To understand the impact of climate change on agricultural productivity the functional relationship proposed by Dell et al. (2014) is used:

$$y = f(C, X) \qquad (1)$$

where y refers to the outcome variable, C refers to weather variables such as temperature and precipitation and X refers to any other characteristics that may affect the outcome variable. This relationship can be estimated using cross-sectional or panel data. Each method examines the impacts of climate variables on any economic outcome. A disadvantage of the cross-sectional analysis is that it is susceptible to suffer from omitted variable bias.

I use panel data estimation that accounts for unobservable differences, thus reducing omitted variable bias (Hsiang, 2016). Panel data estimators shed light on the impact of year-to-year fluctuations in weather. Using annual data does not account for the possibility of medium to long-term impact such as technology improvement, research, and development, labor productivity, etc. (Chen and Gong, 2021). To estimate longer term impact of climate change, I make use of long time period (5-year and 10-year averages) to exploit variations in longer term changes and compare results between these two time periods to show the effect of farmers' adjustments to short- and long-term weather effects.

2.2.2 Empirical model

Fixed-effect regression analysis leverages spatial and temporal variations in TFP, temperature, and precipitation for 128 countries, ranging from 1961 to 2014 to estimate the effects of temperature and precipitation impacts. The preferred model specification is:

$$log(TFP)_{it} = \alpha_i + \beta_1 Temp_{it} + \beta_2 Temp_{it}^2 + \beta_3 Pre_{it} + \beta_4 Pre_{it}^2 + h_i t + \theta_i t^2 + \epsilon_{it} \qquad (2)$$

where log (TFP) represents the log of total factor productivity for each country i, α_i are country fixed effects that capture time-invariant heterogeneity between countries, $h_i t$ and $\theta_i t^2$ are country-specific linear and quadratic trends that allow for weather variables and TFP growth to evolve flexibly at the country level, $Temp$ refers to temperature measured in degrees Celsius and Pre refers to precipitation measured in millimeters.

2.3 Data

2.3.1 Total Factor Productivity (TFP)

TFP can be referred to as the "efficiency with which agricultural inputs are combined to produce output by using improved technology and practices" (Fuglie et.al., 2020). TFP is defined as:

$$\text{TFP} = \frac{Total\ output}{Total\ inputs}. \qquad (3)$$

The total output consists of data on production of crops and livestock aggregated into a production index while total inputs consist of data on agricultural cropland (for annual and perennial crops further subdivided into rain-fed and irrigated cropland), farm labor (active population of male and female workers in agriculture), animal stock, inorganic fertilizer usage, and farm machinery (number of riding tractors in use). TFP is denoted as an index with the base year of 2005, such that the value of TFP for each country is set to 100 in 2005 (percent change in TFP is relative to 2005), if TFP is above (below) 100 it will be interpreted as increasing (decreasing) productivity (Fuglie, 2018). The explanation above is specific to the ERS dataset, as there are other ways of measuring TFP not discussed here. There was little growth during the Green revolution (1960's to 1980s) an era that witnessed large investment in research and development coupled with policy support (Figure 2.1). However, the benefit of this investment did not manifest until the 1990's when TFP witnessed a steady increase afterwards. Presently, developed countries are experiencing a flat growth in TFP while most of the growth arises from developing countries. Data can be accessed on the USDA – ERS website for International Agricultural Productivity (USDA, 2020).

2.3.2 Weather Variables

Historical temperature and precipitation data are from the Climatic Research Unit (CRU) monthly time-series Version 3.23 (Mitchell and Jones, 2005; Harris et al., 2014). CRU produces a global gridded weather dataset providing monthly weather measures on a 0.5 X 0.5 latitude / longitudinal degree scale. Minimum and maximum temperature are measured in Celsius while precipitation is measured in millimeters. Agricultural seasons vary widely across countries; therefore, weather variables are average monthly temperature and precipitation recorded over the growing season for corn determined by using the global gridded crop calendars in Sacks et al. (2010). One of the major problems encountered when using weather datasets is issues of missing station data or measurement error; however, gridded datasets such as CRU, PRISM or terrestrial air temperature helps to adjust for these bias (Dell et al., 2014).

To show the variations in temperature, mean temperature for each region was obtained and subtracted from the monthly growing season temperature as shown in Figure 2.2 to show the temperature deviation from the long-run average. For all the regions, the series is trending upward and becoming increasingly volatile. This is in line with the observation that countries are becoming warmer with earlier predictions by Hansen et al. (2006) that temperature increased 0.2 °C every decade with warming more prevalent in the eastern equatorial Pacific than the eastern equatorial Pacific. Although not in our dataset, the last six years (2014 - 2020) have been the warmest so far (Morice et al., 2021). Global mean precipitation shows an upward volatile trend with swings i.e. periods of heavy rain and lows - dry periods characterized by droughts (Figure A.3 in Appendix). However, Figure 2.3 represents the regional mean precipitation with mild fluctuations (East Asia & Pacific) and little fluctuations for developed regions like Europe & Central Asia).

2.3.3 Descriptive Statistics

Regional decomposition gives a clearer picture for weather fluctuations (Table 2.1). On average, precipitation is highest in Latin America and the Caribbean region (184.6 mm) with the lowest experienced in the Middle East and North Africa region (13.5). The average precipitation by country is 123.07 millimeters with a minimum of 0 millimeters in Jordan (2012) and a maximum of 710.97 millimeters in Jamaica (2008). Temperature in the temperate regions like Europe & Central Asia and North America with 17.2°C, respectively recorded the lowest temperature on average while Sub-Saharan Africa recorded the highest temperature of 24.3°C. There is an increase in temperature as we move from Kyrgyzstan in Central Asia with a minimum temperature of 10.77 °C in 1992 to Iraq in the Middle East & North Africa region with a maximum temperature of 34.91 in 2010. Histograms were also created to show the frequency (temperature and precipitation data) and give more insight for estimating predictive log of total factor productivity (Figure 2.4 & 2.5). TFP will be interpreted in terms of growth rate; developed regions like North America and European Union region had an average growth rate of 1.2 percent (1960's to 1989) to 1.8 percent (1990's to 2014) and 1 percent (1960's to 1989) to 1.2 percent (1990's to 2014) respectively. While developing regions like Sub- Saharan Africa grew at a slow rate from 0.3 percent to 0.8 percent and Latin America & Caribbean with an average growth rate of 1 percent to 1.7 percent from the 1960's-1989 and 1991-2014 respectively. Agricultural output and productivity growth have plateaued in developed regions which has been offset by increasing growth in other regions netting a positive net global growth (Fuglie, 2018).

2.4 Results and Discussion

My primary analysis focuses on the effect of changes in climate on agricultural productivity (TFP) and, results are divided into three sections. In the first section, I discuss the estimates for TFP response to weather effects for global and regional estimates. The data are divided into seven regions; however, only four regions (Sub-Saharan Africa, South Asia, East Africa & Pacific and Latin America & Caribbean) will be reported as these regions represent the most populous and producers of over 50 percent of the world's crop production (UN, 2019; FAO, 2020). Furthermore, data shows that TFP in SSA is increasing but at a very slow pace, TFP in Latin America & Caribbean and South Asia regions are increasing rapidly and are two of the regions contributing to the global increase in TFP growth and East Asia & Pacific region experienced rapid TFP growth but presently slowing down. Results in this essay will give us an insight into how climate change could affect TFP. In the second section, I showcase the effects of adaptations by farmers by examining their adjustments on a long-run basis using 5-year and 10-year averages. Finally, I report and discuss results for other alternative specifications: including geographical and income decomposition.

2.4.1 Precipitation effects on TFP is significant while temperature effect is insignificant.

The results from our main specifications for TFP are given in Table 2.2 and shown graphically in Figure 2.6 & 2.7. Changes in temperature have an insignificant effect on TFP (Column 1-5 of Table 2.2) but the monthly precipitation effect is significant for the global analysis (Column 1 of Table 2.2). On further investigation, the data was divided into regional decomposition to determine region(s) driving the significant precipitation result. In column 2, Sub Saharan Africa region is significant for precipitation but insignificant for other regions. The coefficients indicate that a nonlinear TFP responses to changes in both monthly temperature and precipitation exists; exposure to temperature up to a threshold increases agricultural TFP, but above a certain threshold leads to a decline in TFP.

Predicted values of the Log of TFP are calculated along the temperature gradient as shown in Figure 2.6, holding precipitation at a constant mean level. This helps predict the value of Log of TFP for each observation as well as indicating the threshold at which temperature increase begin to harm agricultural TFP. Predictive margins give evidence that TFP growth is negatively impacted by higher temperature levels (above the threshold), resulting in a reduction of TFP from its maximum level. The graph shows how a 1°C increase in temperature affects TFP, and how these effects differ by the initial temperature. When temperature is 15°C, a 1°C increase causes TFP to increase by 1.61 percent for the global analysis, 5.4 percent for Sub-Saharan Africa (SSA), and 2.5 percent for Latin America & Caribbean (LAC). When temperature is 24 °C for global and SSA and 23 °C for LAC, then a 1-degree increases causes roughly no change in TFP for global, SSA and LAC. However, additional increase beyond 23°C causes a large decrease in TFP in these regions.

Finally, holding temperature at a constant mean level, predicted values of Log of TFP are calculated along the precipitation gradient as shown in Figure 2.7. When monthly precipitation is at 50mm, an increase in precipitation causes TFP to increase; however, as changes in precipitation increases until it gets to 400mm (global and LAC) and 300mm (SSA), a gradual decline in TFP takes place. Fluctuations in precipitation in SSA can have a negative economic implication as agriculture generates 23 percent of the continent's Gross Domestic Product (GDP). Thus, showing the importance of this result, that rainfall plays a vital role in SSA regions where 97 percent of the staple crop production relies on rain fed agriculture.

2.4.2 Temperature increase has a varying effect on TFP for 5 and 10- year average.

A focus on climate impacts in the short term cannot showcase the effect of adaptation by farmers thus, I examined adjustments in the long run using 5-year and 10-year average analogous to the long difference methodology. The results for these are given in Table 2.3 and Table 2.4 and shown graphically in Figure 2.8. The global 5-year result (Column 1 of Table 2.3) shows that an increase in monthly temperature or precipitation has an insignificant effect on TFP. The opposite is the case for global 10- year where temperature has a concave and significant effect on TFP; log TFP is expected to increase up to a temperature threshold and then decrease above that threshold.

Furthermore, Figure 2.8 helps to explain the effect of adaptation, at 15°C, additional increases in temperature increases TFP until it reaches 24°C where TFP starts to decrease. However, as the effect of temperature increases above the threshold, TFP decrease become less severe with 5-year average and 10-year average data. This shows that the short-term temperature effect is offset in the long run as evidenced by the flat function for the 10-year average graph as compared to annual. Several adaptation techniques adopted by farmers can be planting improved seeds/varieties, optimizing the growing season (early or late planting), crop diversification, soil conversation practices (tillage method), and irrigation efficiency.

2.4.3 Alternative Panel Estimation and Explanations

The analysis up to this point is focused on global and regional analysis, this subsection will compute alternative panel fixed effects estimation based on the following alternative classifications: 1) climate classification divided into tropical and temperate and 2) income decomposition based on World Bank classification divided into high income, middle upper income, middle lower income, and low income. The classification is based on the Gross National Income (GNI) per capita in U.S dollars converted from the country's local currency (World Bank, 2021). According to World Bank, a country's income classification can be reassigned if its income falls below the threshold, however in my models the income classification of countries remains the same over time.

The results for the alternative specification are specified in Table 2.5 and Table 2.6 and shown graphically in Figure 2.9, 2.10, 2.11, and 2.12 (shows results that are statistically significant). The result for the climate and income classification are in line with the main specification where an increase in temperature has an insignificant effect on TFP (column

1and 2 of Table 2.5 and column 1-4 of Table 2.6) but precipitation effect is significant for tropical climate, high income, and low income. An additional increase in monthly precipitation (temperature) for tropical climate increases TFP until it reaches precipitation (temperature) thresholds of 350mm (24°C), further increases above these thresholds result in sharp declines in TFP (Figure 2.9 and 2.10). High- and Low-income economies are highly sensitive to increased fluctuation in precipitation. An additional precipitation above 300mm will decrease TFP gradually (Figure 2.11). While the opposite is the case for high income countries; TFP decreases as it reaches 150mm of precipitation after which an additional increase in precipitation increases TFP significantly (Figure 2.12). In summary, high income and low-income groups are more sensitive to extreme monthly precipitation as compared to middle upper income and middle lower income groups. Interestingly, some countries in the tropical climate, also classified as a low-income nation are sensitive to precipitation (Table 2.5, Column 1; Table 2.6, Column 4) such as if exposed to either extreme flooding or drought.

2.5 Robustness and limitations

This section reports various robustness checks and controls for model specifications as well as limitations in this study.

2.5.1 Warming impacts are robust to the inclusion of more controls in the panel specification.

To test the robustness of the TFP results, I show in this subsection that our results are relatively insensitive to the choice of controls (Table 2.7). The reported results include country fixed effects and country-specific linear and quadratic trends and specifications with additional controls (see Appendix). The result shows further evidence that irrespective of the inclusion of additional controls, results are insensitive. In addition, the regression estimates are consistent across the range of alternative panel specifications and in line with climate impacts literature with similar signs and magnitude to the original model.

2.5.2 Limitations

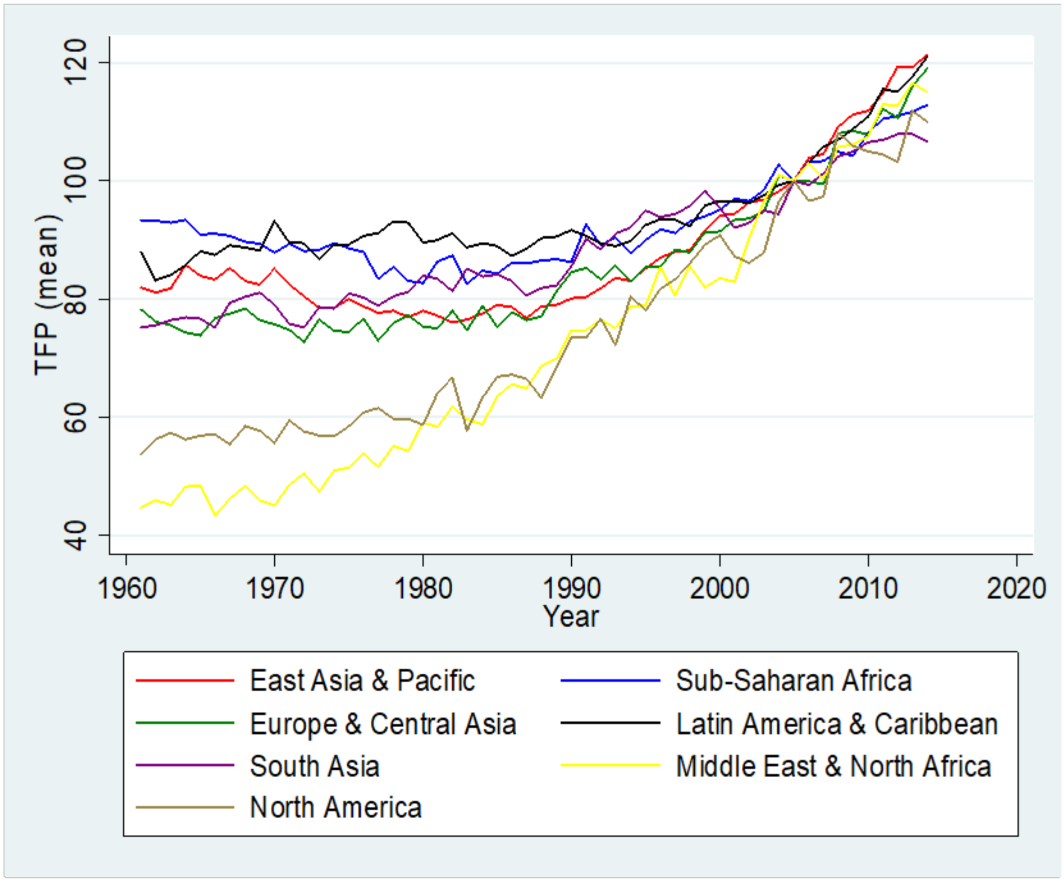
Not surprisingly, there are limitations in this paper. Firstly, weather variables such as precipitation could suffer from possible measurement errors due to substantially fewer weather stations or incomplete coverage for middle-income and developing countries (Dell et al., 2014). Secondly, the potential issue of aggregation bias (which relates to overstating or understating parameter estimates caused by presence of country level heterogeneity) might arise due to the data aggregation. Thirdly, omitted variable bias due to the omission of additional time-varying variables such as CO_2 fertilization, humidity, or solar duration. However, this limitation ought not to dampen the result of our analysis due to the robustness check of results to various alternatives model specification.

2.6 Summary and Conclusion

The purpose of this essay was to explore how agricultural productivity (TFP) is responsive to climate change from regional decomposition to the world while accounting for its impact in the short and long run. By answering these three questions: 1) What is the effect of weather changes on agricultural productivity? 2) Will these effects vary from one region to another in the long or short run? and 3) Did farmers adapt or mitigate the effect of climate change in their production decisions on the long run? To answer these questions, I begin by estimating how historical global agricultural TFP responds to climate change using a fixed-effects regression model. The identification strategy employs yearly changes in temperature and precipitation to estimate their effect on agricultural productivity at a regional level.

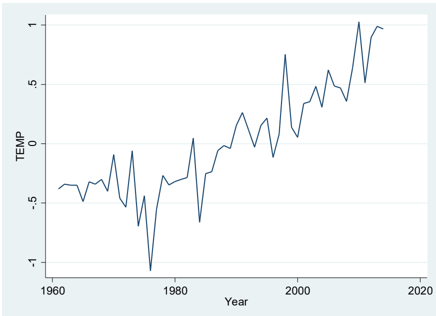
Primary results show that an increase in precipitation has a significant effect on TFP, but the temperature effect is insignificant. As monthly precipitation exceeds 400mm for global and LAC and above 300mm for SSA, the marginal impact of precipitation decreases such that TFP decreases. In addition, the short-term temperature effect is offset in the long run showing that farmers adapt to reduce the effects of temperature in their behavioral decisions. Furthermore, tropical countries are more sensitive to extreme precipitation than temperate countries. Low-income groups are also sensitive to fluctuation in precipitation as compared to other income group. In summary, precipitation effects are more prominent than temperature effects and prevalent in tropical and low-income countries that rely mainly on rain fed agriculture. Thus, technology advances, adaptation to climate change, and investment in Research and Development should be accelerated to overcome future TFP losses.

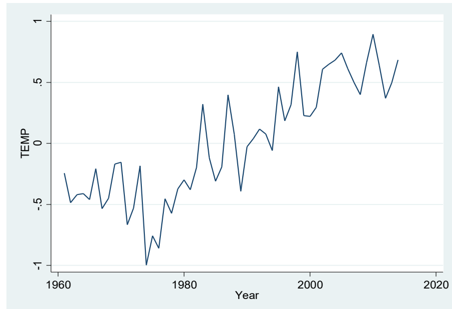
Figure 2.1: Regional average TFP from 1961 to 2014

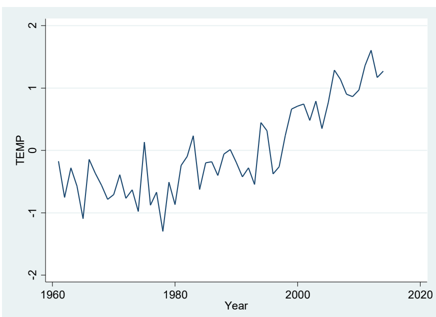


Source: USDA ERS

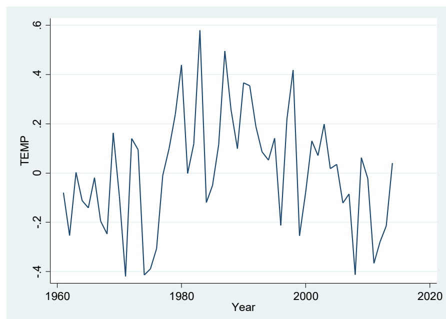
Figure 2.2: Volatility of regional temperature from 1961 to 2014



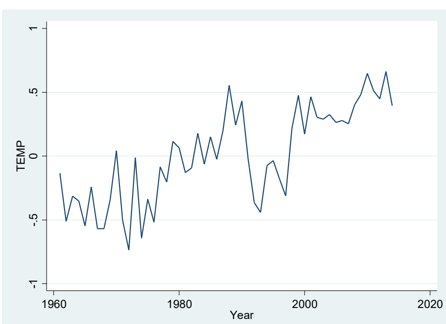




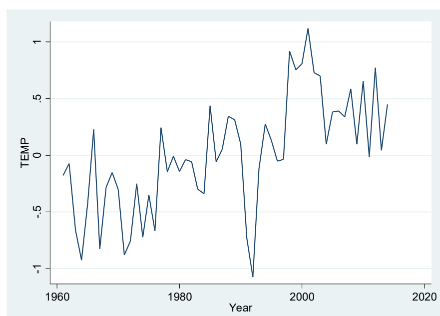
South Asia

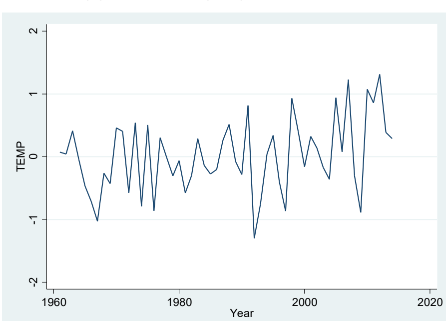


Middle East & North Africa



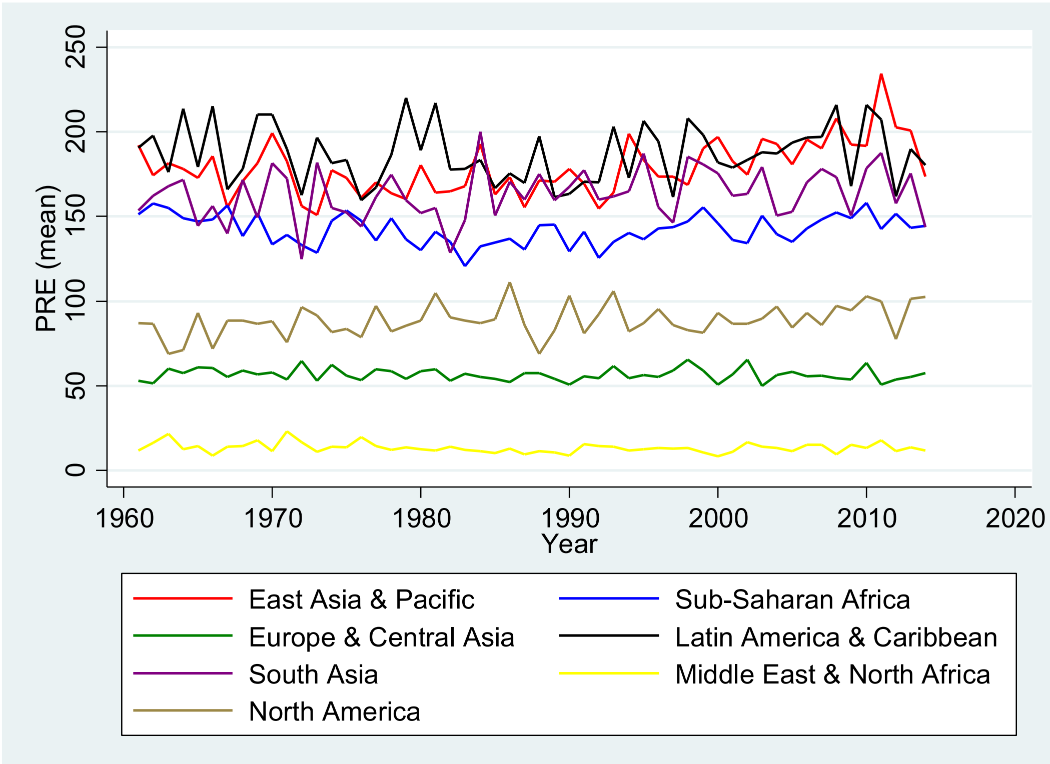
North America





Source: Author's calculation

Figure 2.3: Regional mean monthly precipitation from 1961 to 2014



Source: USDA ERS

Table 2.1: Summary statistics of regression variables from 1961 to 2014

Variable (mean)	All	East Asia & Pacific	Sub-Saharan Africa	Europe & Central Asia	Latin America & Caribbean	South Asia	Middle East & North Africa	North America
Precipitation (mm)	123.07	184.1	143.6	55.1	184.6	166.2	13.5	88.6
Temperature (^oC)	22.15	23.9	24.3	17.2	23.1	23.7	23.2	17.2
TFP (Index)	85.57	82.5	90.5	83.5	89.7	85.7	70.6	74.2

Source: USDA ERS

Figure 2.4: Histogram for Global Temperature Data

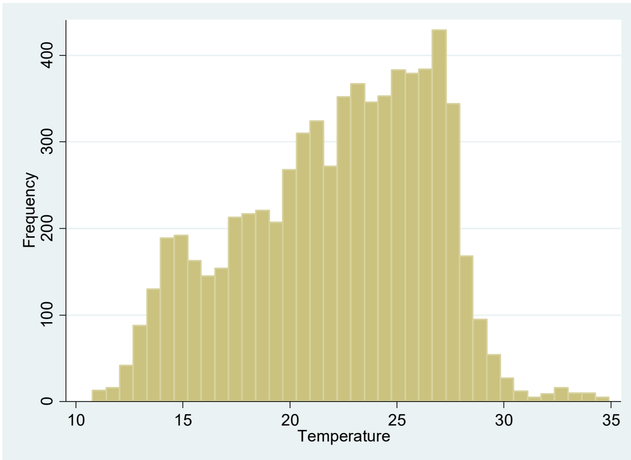


Figure 2.5: Histogram for Global Precipitation Data

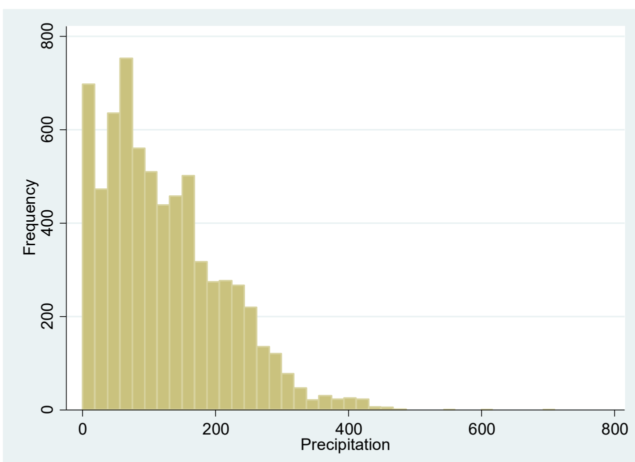


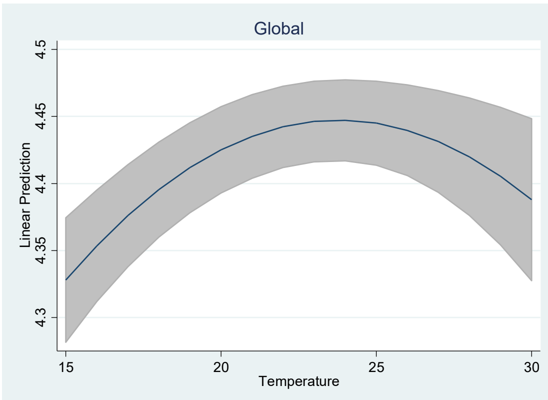
Table 2.2: Global and Regional Results of Weather Effects on Log of TFP

	Global (annual) (1)	Sub-Sahara Africa (2)	East Asia & Pacific (3)	Latin America & Caribbean (4)	South Asia (5)
	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.0161	0.0540	0.0554	0.0256	-0.102
	(1.34)	(1.10)	(1.10)	(0.69)	(-1.73)
Temperature^2	-0.000612	-0.00114	-0.00146	-0.00117	0.00204
	(-1.94)	(-1.10)	(-1.47)	(1.33)	(1.87)
Precipitation	0.000325*	0.00129**	-0.00000127	0.000108	-0.0000242
	(2.12)	(2.96)	(-0.00)	(0.77)	(-0.04)
Precipitation^2	-0.000000432	-0.00000202	2.18e-08	-0.000000111	4.52e-08
	(-1.73)	(-1.99)	(-0.30)	(-0.57)	(0.04)
N	6912	2106	648	1350	432
FE	Country	Country	Country	Country	Country
Country Time trend	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic

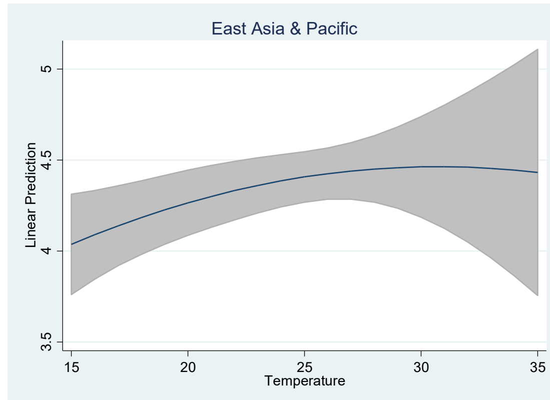
Notes: Data are for cross countries, 1961–2014. Specifications 1 are estimated with global annual data while 2-5 are regional cross-country panel data. Different fixed effects were shown at the bottom; t statistics in parentheses.
* p<0.05, ** p<0.01, *** p<0.001

Figure 2.6: Predicted Log of TFP as a function of temperature

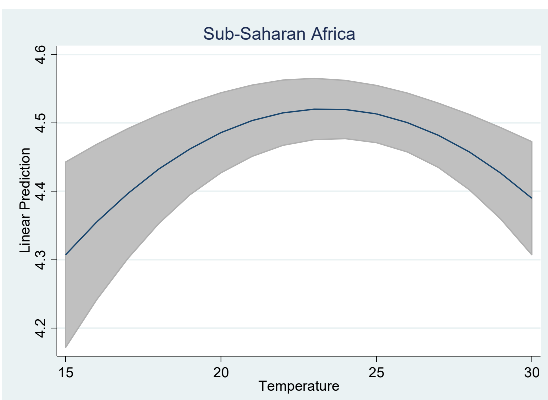
Global



East Asia & Pacific



Sub-Saharan Africa



Latin America & Caribbean

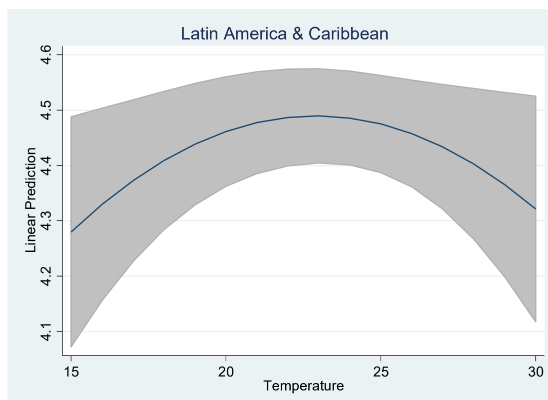
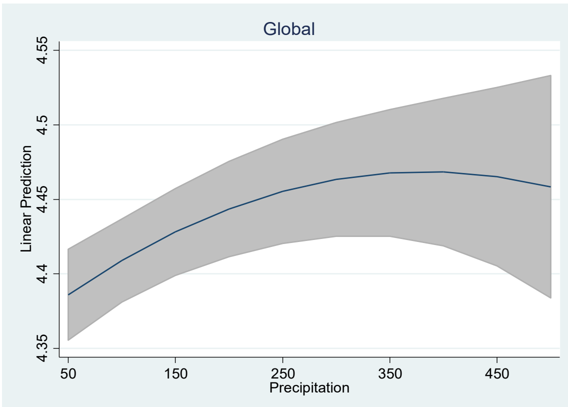
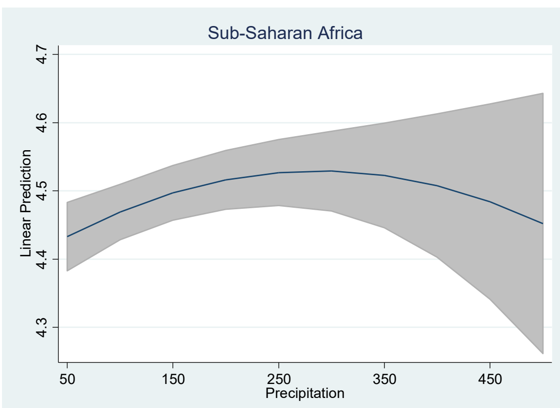


Figure 2.7: Predicted Log of TFP as a function of precipitation

Global



Sub-Saharan Africa



Latin America & Caribbean

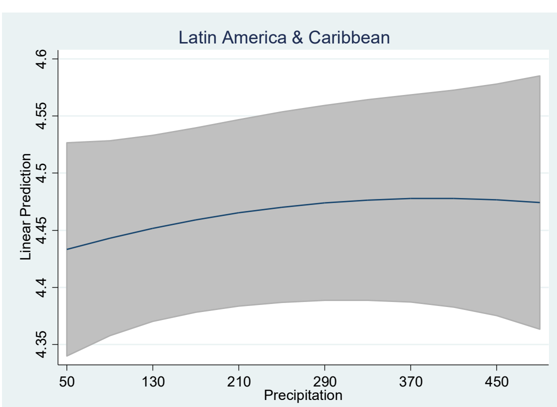


Table 2.3: Global and Regional Results of Climate Impacts for 5-year average.

	5-year average (cross country)			
	Global	**Sub- Saharan Africa**	**East Asia & Pacific**	**Latin America & Caribbean**
	(1)	**(2)**	**(3)**	**(4)**
	logTFP	logTFP	logTFP	logTFP
Temperature	0.0541	0.0930	0.100*	0.115
	(1.50)	(0.82)	(1.55)	(0.83)
Temperature^2	-0.00161	-0.00210*	-0.00285*	0.00371
	(-1.76)	(-0.93)	(-2.27)	(-1.17)
Precipitation	0.000340	0.00169	0.000542	0.000234
	(0.43)	(1.36)	(0.36)	(0.23)
Precipitation^2	-0.000000118	-0.00000341	-0.0000015	-0.00000299
	(-1.17)	(-1.17)	(-0.57)	(-0.15)
N	1280	390	120	250
FE	Country	Country	Country	Country
Country Time trend	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic

Different fixed effects were shown at the bottom; t statistics in parentheses.
* p<0.05, ** p<0.01, *** p<0.001

Table 2.4: Global and Regional Results of Climate Impacts for 10-year average.

	10-year average (cross country)			
	Global	**Sub- Saharan Africa**	**East Asia & Pacific**	**Latin America & Caribbean**
	(1)	**(2)**	**(3)**	**(4)**
	logTFP	logTFP	logTFP	logTFP
Temperature	0.164*	0.0198	0.00868	0.284
	(2.26)	(0.10)	(0.03)	(0.89)
Temperature^2	-0.00400*	-0.000895	-0.000794	-0.00734
	(-2.47)	(-0.24)	(-0.15)	(-1.1)
Precipitation	0.000814	0.00464	-0.00738	0.00291
	(0.41)	(1.89)	(-0.97)	(0.23)
Precipitation^2	-0.00000238	-0.00000915	-0.0000158	-0.00000731
	(-0.50)	(-2.02)	(0.86)	(1.00)
N	640	195	80	120
FE	Country	Country	Country	Country
Country Time trend	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic

Different fixed effects are shown at the bottom; t statistics in parentheses.
* p<0.05, ** p<0.01, *** p<0.001

Figure 2.8: Predicted Log of TFP as a function of temperature for 5 and 10-year average.

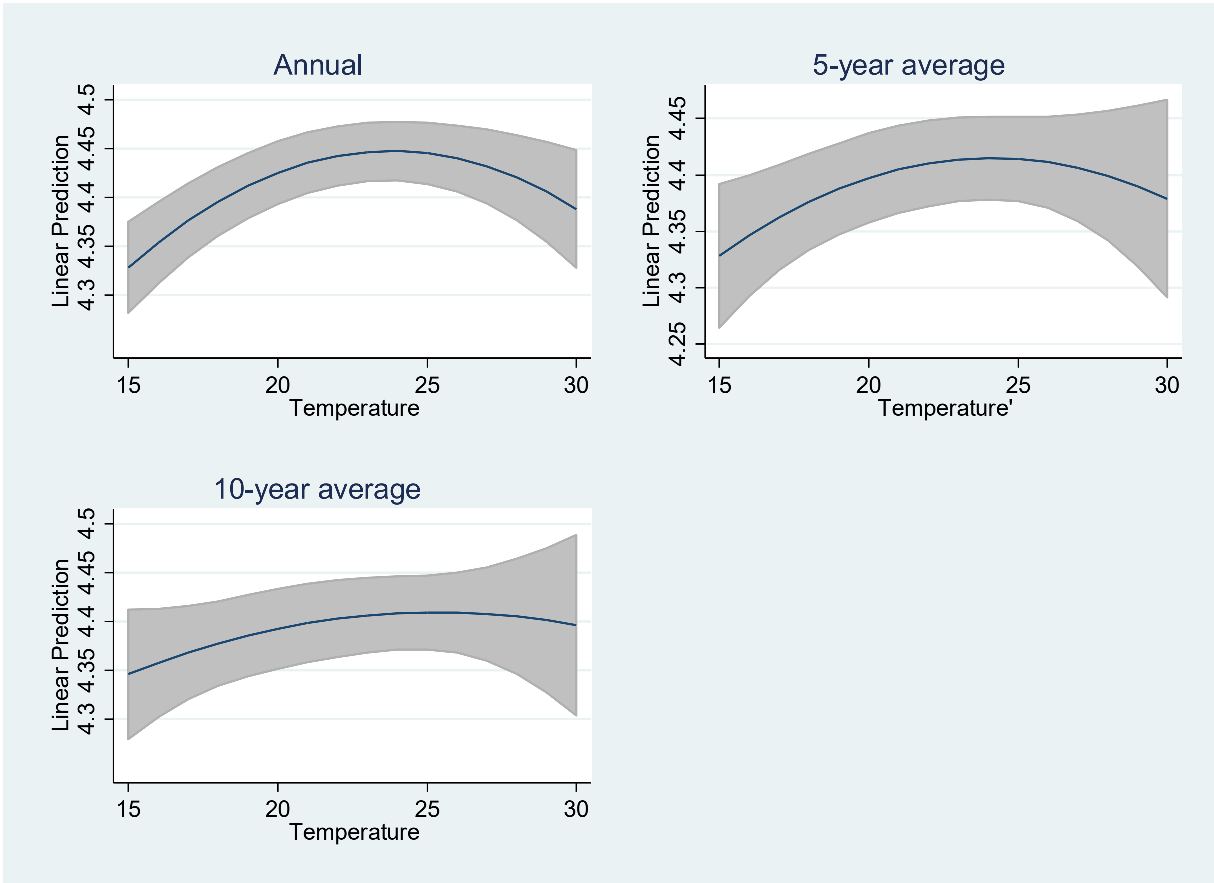


Table 2.5: Regression Result for Tropical and Temperate countries.

	Tropical countries	**Temperate countries**
	logTFP	logTFP
Temperature	0.00816	-0.00244
	(0.25)	(-0.20)
Temperature^2	-0.000541	-0.000095
	(-0.76)	(-0.26)
Precipitation	0.000516**	0.000277
	(2.99)	(-0.76)
Precipitation^2	-0.0000007	-0.0000005
	(-2.50)	(-0.70)
N	3996	2916
FE	Country	Country
Country Time trend	Linear, Quadratic	Linear, Quadratic

Notes: Data are for cross countries, 1961–2014. Different fixed effects are shown at the bottom; t statistics in parentheses.
* p<0.05, ** p<0.01, *** p<0.001

Figure 2.9: Predicted Log of TFP as a function of temperature for tropical climate Tropical climate

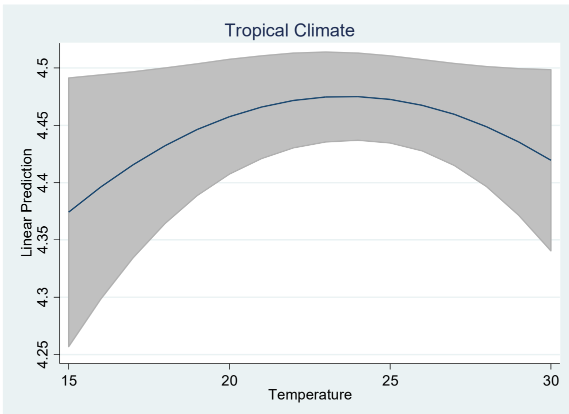


Figure 2.10: Predicted Log of TFP as a function of precipitation for tropical climate Tropical climate

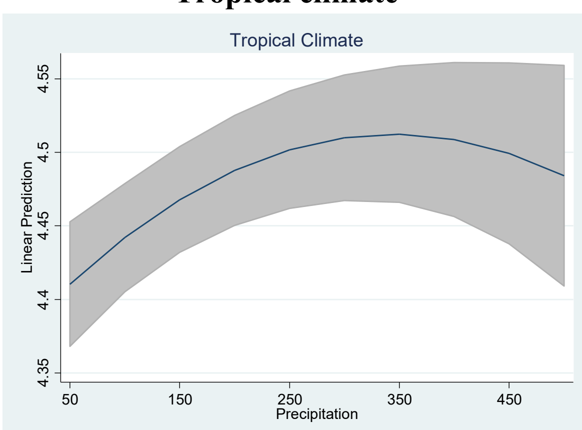


Table 2.6: Result for Income Decomposition of Weather Effects on Log of TFP.

	High Income	**Middle Upper Income**	**Middle lower Income**	**Low Income**
	logTFP	logTFP	logTFP	logTFP
Temperature	0.0371	-0.0323	-0.0181	0.0980
	(1.62)	(-1.43)	(-0.97)	(1.08)
Temperature^2	-0.00119	0.000499	0.000222	-0.00247
	(-1.68)	(1.01)	(0.46)	(-1.17)
Precipitation	-0.000550*	0.000123	0.0000449	0.00154***
	(0.41)	(0.57)	(0.13)	(3.89)
Precipitation^2	-0.00000146	0.00000015	2.19e-08	-0.00000264**
	(1.92)	(-0.48)	(0.04)	(-3.38)
N	1350	1944	2214	1404
FE	Country	Country	Country	Country
Country Time trend	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic

Notes: Data are for cross countries, 1961–2014. Different fixed effects are shown at the bottom; t statistics in parentheses.
* p<0.05, ** p<0.01, *** p<0.001

Figure 2.11: Predicted Log of TFP as a function of precipitation for low-income countries

Low Income

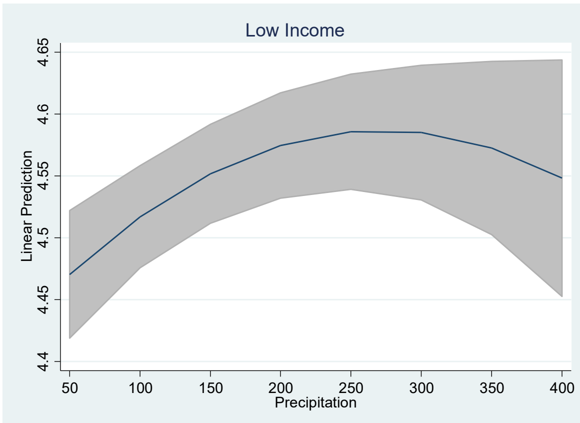


Figure 2.12: Predicted Log of TFP as a function of precipitation for high income countries

High Income

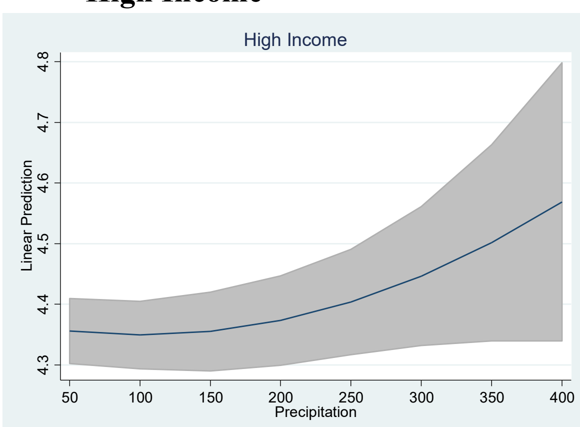


Table 2.7: Additional controls for robustness checks

	Fixed Effects (FE)		Country Specific Time Trend		Time Trends	
Models	Country	Year	Linear	Quadratic	Linear	Quadratic
A	Yes				Yes	Yes
Original	Yes		Yes	Yes		
B	Yes	Yes				
C	Yes	Yes	Yes			
D	Yes	Yes	Yes	Yes		

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Chapter 3

Economic modeling of the long-run impact of agricultural productivity (TFP) growth on food security and the environment

3.1 Introduction

Agricultural productivity plays an important role in providing food security and food availability for the present population of 7.9 billion people in the world (UN, 2021). Its role remains significant as 821 million people as of 2017 are affected by global undernourishment largely due to conflict and climate change (Fuglie et al., 2020). Furthermore, climate change is expected to have a devastating effect on the agricultural sector with estimated warming of 1.5°C above pre-industrial levels (IPCC, 2018). Therefore, implementing policies to stimulate productivity growth across regions is key to maintaining the global supply of food. Especially at a time where global population is expected to increase by 2 billion between 2019 – 2050 (UN, 2019), of which 1.05 billion in Sub -Saharan Africa region. The global middle class is expected to increase by 3.1 billion people from 2009 – 2030 with the bulk of the growth from Asia (OECD, 2012).

The overall objective of this study is to understand the impact of Total Factor Productivity (TFP) growth on food security and the environment. To do this, I address three specific questions. First, what is the impact of TFP growth in specific regions on global food security and the environment? For example, estimating how TFP growth in U.S. & Canada impacts global food security and the environment on those regions. Second, how do TFP shocks in specific regions affect food security and the environment in other regions (i.e., measuring where spillover effects occur)? Third, where is TFP growth most effective at reducing malnutrition and carbon emissions? I address these questions using a partial equilibrium model to simulate the impact of TFP growth on the malnutrition index and carbon emissions in each region of the world. I simulate various scenarios of TFP growth to ascertain desirable regions for TFP growth and the spillover effects of such growth on other regions.

The effect of global agricultural productivity growth on global food security has been extensively studied (Baldos and Hertel, 2014; Alston, Martin, and Pardey, 2014; Rada et al., 2013; Janvry and Sadoulet, 2010; Timmer, 2002). There are also case studies highlighting the effects of agricultural productivity growth on food security in specific nations like China (Anderson and Strutt, 2014), Brazil (Costa et al., 2013), and Nepal (Morioka and Kondo, 2017). However, few studies focus on regional impacts of TFP growth on food security. And exception is Muzari (2016) on the Sub-Saharan Africa region. Aside from this study, few studies have estimated how TFP growth in North America impacts malnutrition or how TFP growth in different regions impacts global malnutrition. This information is critical for policymakers in the United States, who are making decisions about Research and Development (R&D) funding and for making decisions on where to target R&D efforts regionally to effectively reduce global malnutrition.

The effect of TFP growth on cropland areas is ambiguous because TFP growth gives an incentive for land expansion and land saving. First, holding prices constant, TFP growth makes the land more productive and could incentivize cropland expansion (and thus increase carbon emissions). For example, several studies found that introducing improved varieties increases profitability which incentivizes agricultural land use expansion (Schmitz et al., 2014; Phelps et al., 2013; Angelsen et al., 2001; Gibbs et al., 2010). Others proposed that in order to increase food production to satisfy the global demand, land conversion is inevitable through land clearing and intensification and forest encroachment (Tilman et al., 2011; Godfray et al., 2010) Secondly, TFP growth decreases global prices which creates an incentive to decrease cropland area. This is consistent with several other studies that suggest agricultural productivity growth has significantly reduced negative environmental externalities, in line with Borlaug's hypothesis that says increased yield through technology adoption leads to a reduction in global cropland area (Borlaug, 2007; Stevenson et al., 2013; Byerlee et al., 2014; Villoria et al., 2014; Burney et al., 2010).

Considering the existing literature, my paper makes two contributions. First, it extends the work done by Hertel and Baldos (2014) by providing insights on the impact of regional agricultural productivity growth on global malnutrition and carbon emission using comparable TFP growth shocks in different regions. Secondly, it examines how TFP growth in a specific region affects the malnutrition and carbon emission in another region (i.e., the spillover impact of TFP growth in the region (A) on food security and the environment in the region B). From a policy point of view, these contributions will help determine the region in which TFP growth will be most effective at improving food security and reducing carbon emission.

This essay is organized as follows. The next section reviews the methodology (conceptual framework and empirical model) that includes a description of the data and model equations. Section 3 describes the scenario simulation to estimate regional TFP growth. Section 4 will present the global and region-specific results and Section 5 and 6 will continue by discussing the results and the limitations of the study and conclusions, respectively.

3.2 Methodology

The model simulation has two basic steps. First, I define three scenarios of regional TFP growth by 2050. Second, I use the TFP growth scenarios as exogenous shocks in the partial equilibrium model to quantify the long-run impact on food security and the environment. The partial equilibrium model used in this study is SIMPLE (Simplified International Model of Agricultural Prices, Land Use, and the Environment); an agricultural trade model that specializes in one sector incorporating connections between crop production and environmental variables (Baldos and Hertel, 2013). The remaining discussion in this section is divided into two sections – conceptual and empirical framework. The conceptual framework illustrates the intuition driving the results of the economic modeling of the long-run impact on food security and the environment while the empirical framework discusses the data, parameters, and equations that are used for the model simulations.

3.2.1 Conceptual Framework

The conceptual framework focuses on a single global economy while the numerical simulation is expanded into a multi-region model. The model revolves around six key determinants of long-run supply and demand for agricultural land. These are three exogenous drivers of change in the global system whilst being moderated by three elasticities referred to as margins of response to scarcity. The first exogenous driver is the percentage growth in demand (D) for agricultural output (A) denoted by Δ_A^D indicating the increasing global demand for food consumption driven by changes in population, income, energy prices, and biofuel use policy (Baldos et al, 2014). Second, percentage growth in productivity of land (L) that affects demand (D) for land (does not affect demand for agricultural output) denoted by Δ_L^D. Finally, the percentage change in the supply (S) of land to agricultural activities denoted by Δ_L^S, affected by the availability of land for farming, conversion to urban lands, or for use in other productive services.

To predict changes in global land use, three margins of economic response to scarcity are also incorporated into the model. These are the price elasticity of demand for agricultural output (A) denoted by η_A^D. When prices are high, consumer demand falls leading to lower food purchases with implications for food security. Secondly, the intensive margin of supply response (yield response to higher commodity prices) is referred to as the price elasticity of supply with respect to commodity prices denoted by $\eta_A^{S.I}$. Showing that when the prices of crop A is high, farmers will intensify production in that crop to benefit from the high price. Finally, the extensive margin of crop supply denoted by $\eta_A^{S.E}$ (area response to commodity prices) relating to the expansion of crop production which directly increases land area cultivated.

Next, I describe the analytical framework for the six factors from Hertel and Baldos (2016, p.165 -168). Aggregate demand for agricultural output (q_A^D) is governed by the aggregate price elasticity of demand ($\eta_A^D > 0$) that captures the responsiveness of demand to changes to commodity price (p_A). Subject to changes due to exogenous growth in population, per capita income, and other factors Δ_A^D, thus the percentage change long-run demand is given by:

$$q_A^D = -\eta_A^D \, p_A + \Delta_A^D . \qquad (1)$$

Next, assume a global production function that combines land and variable inputs (labor, capital, etc.) under constant returns to scale/ zero profits, the percentage change in agricultural price (p_A) is expressed as:

$$p_A = \sum (\theta_j \, p_j + \theta_L P_L). \qquad (2)$$

where P_j refers to the percentage change in the price of variable input j, θ_j is the cost share of input j in the total cost of agricultural production, P_L refers to the percentage change in the price of land input L and θ_L is the cost share of land input L in the total cost of agricultural production.

The sum of the cost shares of the land and variable inputs equals one, such that if the price of an input (land) changes by more than the cost share-weighted change of the input bundle, there is substitution away from that input (land). (I am not sure why this is here)

The long-run percentage change in global derived demand for land (q_L^D) is:

$$q_L^D = q_A^S - \sigma(p_L - p_A) - \Delta_L^D. \qquad (3)$$

where P_L refers to land rent, q_A^S the supply of agricultural output and σ is the elasticity of substitution in production.

Land rents can also be written as:

$$P_L = \theta_L^{-1} \, p_A . \qquad (4)$$

Finally describing the long-run supply of land to agriculture (q_L^S) is:

$$q_L^S = v_L^S \, p_L + \Delta_L^S. \qquad (5)$$

where v_L^S captures elasticity of land supply and Δ_L^S representing a shift in land supply to other uses. Plugging equation 4 into land supply (equation 5) to obtain land supply in terms of commodity price thus:

$$q_L^S = v_L^S \theta_L^{-1} p_A - \Delta_L^S = \eta_A^{S.E} p_A - \Delta_L^S. \quad (6)$$

where $v_L^S \theta_L^{-1}$ can be referred to as the extensive margin of supply response ($\eta_A^{S.E}$).

Rewriting Equation 3 so that commodity supply is on the left, the agricultural commodity supply equation becomes:

$$q_A^S = q_L^D + \sigma(p_L - p_A) + \Delta_L^D, \quad (7)$$

Substituting equation 4 and equation 6 into equation 7 yields:

$$q_A^S = v_L^S \theta_L^{-1} p_A - \Delta_L^S + \sigma(\theta_L^{-1} p_A - p_A) + \Delta_L^D, \quad (8)$$

Rearranged as:

$$q_A^S = [v_L^S \theta_L^{-1} + \sigma(\theta_L^{-1} - 1)] p_A - \Delta_L^S + \Delta_L^D, \quad (9)$$

The terms in bracket [.] refers to the extensive margin $\eta_A^{S.E} = v_L^S \theta_L^{-1}$ plus the intensive margin $\eta_A^{S.I} = \sigma(\theta_L^{-1} - 1)$ supply responses.

Therefore, the total supply response of agriculture measured in terms of responsiveness of output-to-output price as:

$$\frac{q_A^S}{p_A} = \eta_A^S = \eta_A^{S.I} + \eta_A^{S.E}, \quad (10)$$

Equating commodity supply (Eqn 9) to demand (Eqn 1) gives:

$$(\eta_A^{S.I} + \eta_A^{S.E})p_A - \Delta_L^S + \Delta_L^D = -\eta_A^D p_A + \Delta_A^D, \quad (11)$$

Equation 11 is then solved for the long-run equilibrium percentage changes in price p_A^* as a function of the exogenous shocks:

$$p_A^* = \frac{(\Delta_A^D + \Delta_L^S - \Delta_L^D)}{(\eta_A^{S.I} + \eta_A^{S.E} + \eta_A^D)} = \frac{\Delta}{\eta}. \quad (12)$$

Equation 12 relates the commodity price impacts on exogenous shocks to commodity demand to yields. η refers to the aggregate economic response to scarcity, so if demand and supply are inelastic, a large price change is expected due to exogenous shocks. To solve for the long-run equilibrium percentage changes in global land use in agriculture substitute Eqn 12 into Eqn 9:

$$q_L^* = [(\Delta_A^D + \Delta_L^S - \Delta_L^D)/(1 + \eta_A^{S.I} / \eta_A^{S.E} + \eta_A^D / \eta_A^{S.E})] - \Delta_L^S. \quad (13)$$

The major objective of this essay is to model the impact of regional TFP growth on global food security and the environment. Equation 13 indicates that if $\eta_A^{S.I}$ (that captures the potential for increasing yield as price increases) and η_A^D are zero and if Δ_L^S is zero (does not depend on η), then the sign of q_L^* boils down to a footrace between consumer demand and land productivity/ trend yields ($\Delta_A^D - \Delta_L^D$). So, if $\Delta_A^D - \Delta_L^D > 0$ then $q_L^* > 0$ that is if consumer demand grows faster than trend yields land use will rise. Furthermore, changes in global land use can also be explained by the responsiveness of the producers and consumers to scarcity in the food system as captured by the aggregate economic response to scarcity (η).

Most importantly, if producers respond to higher prices by intensifying the use of variable inputs $\eta_A^{S.I} > 0$, land use will reduce. Similarly, if consumers respond to higher prices by reducing consumption, then $-\eta_A^D < 0$, land expansion is moderated. The impact of producers and consumers also depends on the relative size of extensive supply elasticity $\eta_A^{S.E} > 0$. If $\eta_A^{S.E}$ is high (high availability of land) then there is a greater chance of conversion of natural land to agricultural land use. Thus, giving us an understanding on the impact of an increase in land productivity as consumer demand shifts.

In summary, as TFP growth occurs in a region, yield also increases (i.e., more agricultural output. Does land expansion or contraction take place? The answer hinges on the relative sizes of the extensive margin of supply response ($\eta_A^{S.E}$) and intensive margin of supply response ($\eta_A^{S.I}$). In addition, the demand for crop (Δ_A^D) be price elastic for expansion. Such that as the extensive margin of supply response increases, the larger the quantity of land use (q_L^*) or land being converted for agricultural use as TFP increases.

3.2.2 Empirical Model

The SIMPLE numerical model was created by Baldos and Hertel (2012) and I use their executable code and parameters programmed in the GEMPACK program (Pearson, Hertel, and Horridge, 2000). I obtained the updated model programs that incorporate both integrated and segmented markets from personal communication with Hertel and Baldos. Using the updated version of the SIMPLE model, I run my simulations using different regional TFP growth scenarios. In this section, I provide an overview of SIMPLE to better understand what drives the model simulation results. The empirical framework will be discussed in four sections following Baldos and Hertel (2013): sets, parameters, database, and equations. The model is designed to analyze long-run drivers of supply and demand for global agricultural land use and crop price. It is a multi-commodity, multi-country, and multi-regional partial equilibrium model with a single global market clearing.

3.2.3 Sets

The key elements of SIMPLE are shown in Figure 3.1 where the economy is divided into global supply and global demand. Global supply is divided into 15 regional productions where g = 15: Eastern Europe, North Africa, Sub-Saharan Africa (SSA), South America, Australia & New Zealand, European Union (EU), South Asia, Central America & Caribbean, South Africa, South East Asia, North America, China & Mongolia, Middle

East, Japan & Korea, and Central Asia. Each regional sector combines land and non-land inputs to produce commodities i = crops, livestock, processed food, and non-processed food.

These commodities are in turn used to satisfy global demand through direct consumption, indirect consumption (feedstuff and raw materials), and feedstock use (biofuel production). Demand is divided into income regions y = Upper High, Lower High, Upper Middle, Lower Middle, and Low. Households in regions with low per capita income are assumed to be more responsive to price fluctuations.

3.2.4 Equations

The model revolves around three types of equations - consumer demand, crop supply/ agricultural production, and commodity market clearing.

a) Consumer demand

Consumer demands are a simple log-linear relationship that follows Engel's law where own price and income elasticities vary as per capita income changes:

$$\varepsilon_{p(i,y)} = \alpha_{p(i)} + \beta_{p(i)} \ln [Y_{pC(y)}]. \qquad (14)$$

$$\varepsilon_{y(i,y)} = \alpha_{Y(i)} + \beta_{Y(i)} \ln [Y_{pC(y)}]. \qquad (15)$$

where $\varepsilon_{p(i,y)}$ is the price elasticity of demand, $\varepsilon_{y(i,y)}$ is income elasticity of demand, $\alpha_{p(i)}$ *and* $\alpha_{Y(i)}$ are intercept of price and income elasticity regression with the log of per capita income respectively, $\beta_{p(i)}$ *and* $\beta_{Y(i)}$ are the slope of price and income elasticity regression with the log of per capita income respectively, and Y_{pC} is per capita income.

The consumer demand equation is

$$Q_{PC(i,y)} = \alpha_{PC(i,y)} P_{(i,y)}{}^{\varepsilon_{p(i,y)}} Y_{PC(y)}{}^{\varepsilon_{y(i,y)}} \qquad (16)$$

where $Q_{PC(i,y)}$ is per capita commodity demand, and $P_{(i,y)}$ is the price of the commodity.

b) Crop supply/ agricultural production

The crop production equation is a Constant Elasticity of Substitution (CES) function resulting from producers maximizing profit subject to technology, prices, policies, and resource constraint to produce crop output (Eqn 17).

$$X_{CROP(g)} = AOCROP_{(g)} \ [X_{LAND(g)}{}^{\frac{\sigma_{CROP(g)^{-1}}}{\sigma_{CROP(g)}}} + X_{NLAND(g)}{}^{\frac{\sigma_{CROP(g)^{-1}}}{\sigma_{CROP(g)}}}] \wedge^{\frac{\sigma_{CROP(g)}}{\sigma_{CROP(g)^{-1}}}} \quad (17)$$

where $X_{CROP(g)}$ is the quantity of crops produced, $AOCROP_{(g)}$ is input-neutral productivity change in the crop sector which can be swapped with $TFP_{CROP(g)}$, $X_{LAND(g)}$cropland area and $X_{NLAND(g)}$ is non-land input quantity.

The supply of cropland is a function of cropland availability and competing uses of land and cropland returns in each region:

$$X_{LAND(g)} = \alpha_{LAND(g)} \ P_{LAND(g)}{}^{\varepsilon_{LAND(g)}} \quad (18)$$

where $\alpha_{LAND(g)}$ is the intercept of land supply equation, $P_{LAND(g)}$ is cropland rent and $\varepsilon_{LAND(g)}$ is cropland supply response to cropland rent.

The supply of non-land inputs is price elastic and reflects the supply of inputs to the crop sector:

$$X_{NLAND(g)} = \alpha_{NLAND(g)} \ P_{NLAND(g)}{}^{\varepsilon_{NLAND(g)}} \quad (19)$$

where $\alpha_{NLAND(g)}$ is the intercept of non-land supply equation, $P_{NLAND(g)}$ is non-land price and $\varepsilon_{NLAND(g)}$ is non-land supply response to non-land prices.

Besides, there are also production equations for livestock production and processed food but not stated here, as they are not the focus of this essay.

c) Market clearing conditions

The market-clearing condition for crops at a global scale is:

$$\sum_{g=1}^{15} X_{CROP(g)} \ = \ \sum_{y=1}^{15} [Q_{("Crops",y)} + \ X_{CRPFEED(y)} \ + \ X_{CRPFOOD(y)}] + \ X_{CRPBIOF} \quad (20)$$

where $Q_{("Crops",y)}$ is the quantity of crops produced for direct consumption, $X_{CRPFEED(y)}$ is crop feed used in the livestock sector, $X_{CRPFOOD(y)}$ is crops inputs used in the processed food sector and $X_{CRPBIOF}$ is crop feedstock used in the global biofuel sector.

To complete the model, there are zero profit conditions for crops, livestock, and processed food sectors but only the equation for crops is stated below:

$$P_{CROP}X_{CROP(g)} = P_{LAND(g)}X_{LAND(g)} + P_{NLAND(g)}X_{NLAND(g)} \quad (21)$$

where P_{CROP} refers to global crop price and $X_{CROP(g)}$ is the quantity of crops produced.

3.2.5 Parameters

The model allows for the potential of increasing yield either through the intensive margin (use of more non-land inputs), governed by the elasticity of substitution between land and non-land inputs ($\sigma_{crop(g)}$), or through the extensive margin (use of more land), governed by the elasticities of supply of land with respect to land rents ($\varepsilon_{LAND(g)}$); reflecting the scarcity of cropland across regions such that regions like SSA and South America will have higher elasticity values than developed regions. As well as price elasticity of non-land inputs with respect to non-land prices ($\varepsilon_{NLAND(g)}$) that shows that land is finite in its supply whereas non- land inputs are easily available. Demand for food is a function of population growth, per capita income, and commodity price governed by income ($\varepsilon_{Y(i.y)}$) and price ($\varepsilon_{p(i.y)}$) elasticities of demand (Table 3.1).

3.2.6 Database

To implement the model, a global database for the year 2001 is constructed for 119 countries (Appendix). Data used are from external sources such as income, population, consumption expenditure, crop production, land cover, and GDP (Table 3.2). The data sources are as follows: GDP from World development indicators (2011), population data obtained from World population prospects, consumption expenditure from GTAP v.6 database (2006), cropland cover, production, the value of crop production, and crop prices from FAOSTAT (2011). The model is multi-commodity, but global crop quantities were converted into corn-equivalent quantities using weights constructed from world crop prices and the world price of corn. Also, the data above is combined with other information of industry cost and sales shares to construct the rest of the database.

3.2.7 Food Security Module

One of the objectives of this essay is to model the economic long-run impact of food security as TFP grows. To extract nutritional outcomes information, I make use of the food security model (an add-on) introduced in SIMPLE by Baldos and Hertel (2014) to estimate how future drivers of TFP affect nutritional outcomes such as malnutrition index (measure for food security in this essay). The module has three purposes: i) characterize the Distribution of Energy Consumption (DEC) regionally to calculate malnutrition index, headcount, and gap ii) relates changes in DEC to shifts in its distribution and iii) link food caloric content to per capita income capturing changes in diets. Here, our emphasis will only be on the malnutrition index defined by FAO (2012) as the fraction of the population whose daily dietary energy intake is below the minimum requirement. The distribution of caloric consumption among the population is assumed to be log-normal, given the Minimum Dietary Energy Requirement is similar to minimum caloric requirement measured as Kcal/day (MDER shown by the red line in Figure 3.2), the malnutrition index represents the proportion of the population below MDER that is illustrated as the gray shaded area. The Standard Deviation of the log-normal distribution of per capita caloric consumption (SDEV_CAL) elasticity helps to capture observed differences in caloric consumption (Table 3.3). As changes occur in average consumption regionally owing to increased income or reduced prices, it either decreases the proportion of the population below the MDER line and malnutrition index decreases. If TFP growth occurs in the SSA region, we expect that commodity prices will fall and an increase in caloric consumption. Such that the percentage of the population below the MDER line will reduce.

3.2.8 Segmented Markets

Initially, SIMPLE revolved around the integrated market assumption where the law of one price exists (prices in all regions are the same). Now the model has incorporated the segmented market model where prices differ across regions due to the introduction of demand for differentiated products – domestic and imported goods (Armington, 1969). Based on this assumption, countries that consume or produce a larger proportion domestically are less integrated with the world market so the domestic price will respond less to changes in the international prices in these regions. Therefore, changes in consumption or production in regions with a larger domestic proportion will have a smaller impact on global markets. The extent of market segmentation is determined by parameters that govern this concept which is the elasticity of substitution for consumption and elasticity of transformation for production between domestic and imported products. However, for this essay, the focus is the elasticity of substitution which describes a region's willingness to shift consumption of a domestic product to imported product when the price of domestic (imported) rises. The segmented model in SIMPLE assumes an elasticity of substitution value of 3 for all regions-meaning that a 1 percent decrease in the price of domestic relative to imported goods will lead to a 3 percent increase in the ratio of the domestic relative to the imported quantity.

Furthermore, percent shares of international goods (Table 3.4) affect market segmentation. Such that when market access is limited, such a region has little or no effect on the world price. For example, a change in world price is likely to affect prices in the US & Canada more than Sub- Saharan Africa region (SSA) insulated from the world market. Likewise, if a region has zero shares in international goods, then the prices of domestic and international prices will not interlink. Finally, the segmented market introduces new variables into SIMPLE such as local prices, world price, regional supply to the local market, supply to the global market, regional demand from the local market, and demand from the global market.

3.2.9 Carbon Emissions

I use carbon emissions from the expansion (change) of crop land use as the key indicator for the environmental impacts. Agriculture and forestry contribute roughly 24 percent of the total global greenhouse emission (EPA, 2018). SIMPLE estimates the carbon emission in each region by multiplying the quantity of land cover change by carbon emission factors per hectare (estimated using yield and carbon loss estimates from West et al. 2010).

3.3 Scenarios

The goal of this essay is to compare the impact of TFP shocks in different regions on food and environmental security. To do this, I focus on TFP shocks in four major production regions: US & Canada, Sub Saharan Africa, South America, and China & Mongolia. However, I faced a challenge in comparison of TFP impacts since the regions vary in size and factor endowment; thus, the need for deriving comparable TFP shocks for each region. To estimate the comparable TFP shocks, I create three different scenarios of comparable

TFP growth shocks in each region. To simulate the impacts of TFP growth in each region, the shock is applied separately in each region rather than simultaneously in all regions.

Scenario 1 (Uniform): A uniform 100% increase in TFP in each region.

The first set of scenarios explore the impacts of food security and carbon emission, if each region increases its TFP growth by 100 percent. A uniform growth implies that a region producing at a particular capacity will increase its production by 100 percent. This scenario does not give a fair comparison but is useful as a counterfactual scenario for uniform growth in all regions. In addition, scenario 1 does not consider that richer developed countries will on average increase production more than developing countries. Neither does it consider differences in rates of growth of factor endowment nor differences in productivity and technology. For instance, the rate of TFP growth in SSA is increasing at a slower pace due to lack of investment in R&D, weak institutions, civil unrest, so a 100 percent increase in TFP growth will be less likely increase crop production up to the level of other regions.

Scenario 2 (Price Impact): **Each region has TFP growth that would lead to a 17.21 percent decrease in global price in the integrated SIMPLE model.**

The second set of scenarios explore the impact of TFP growth in each region such that the TFP shock would have the same impact on global price if there were no trade frictions (i.e., in the integrated market model). I choose a 17.21 percent decrease in price in the integrated model because this corresponds with a 100 percent increase in TFP in the US & Canada. I then find the TFP shock in every other region that corresponds with the same decrease in global price. Intuitively, this scenario allows us to compare TFP shocks in each region that are comparable roughly in terms of creating the same increase in global production. TFP shocks in this scenario are larger in smaller production regions like SSA.

Scenario 3 (R&D Expenditure): Each region has TFP growth resulting from an increase in R&D expenditures by $6.15 billion.

The final method that I use to construct comparable TFP shocks is to assume the same increase in R&D expenditures in every region. The assumption of $6.15 billion of additional R&D expenditures reflects the predicted change in US & Canada R&D expenditures from 2010 to 2050 obtained by multiplying the percent change in R&D ($) by the R&D expenditure in 2010.

To calculate the projected TFP growth that corresponds with this increase in R&D expenditures, I calculate the R&D expenditure scenario by increasing baseline (2010) expenditure by $6.15 billion in all regions (see Table 3.5). I then calculate the percent change in R&D expenditures in other regions as follows:

$$\%\ change\ in\ R\&D\ (\$) = \frac{\text{R\&D scenario} - \text{R\&D in 2010}}{\text{R\&D in 2010}}. \quad (22)$$

Then I calculate the percent change in TFP in each region for the simulations as

$$\%\ \text{change in TFP} = \%\ change\ in\ R\&D\ (\$) \times R\&D\ elasticity \quad (23)$$

where R&D elasticity measures the percentage change in TFP given a one percent change in R&D capital stock (Baldos et al. 2020).

3.3.1. TFP growth for all scenarios.

Table 6 shows the TFP growth for each region in the three different scenarios. Scenario 1 assumes that TFP growth will increase uniformly by 100 percent. The second column in Table 6 reports the projected TFP growth for scenario 2. The results indicate that Sub-Saharan Africa (134.63) needs a higher TFP growth to achieve the predetermined commodity price decrease. China & Mongolia require the lowest TFP growth to decrease global prices by 17.21 percent (35.48). The third column in Table 3.6 reports the projected TFP growth for scenario 3. This scenario has the largest change in TFP growth in South

America and Sub-Saharan Africa (63.2) because the R&D expenditure scenario gives the largest percent increase in expenditures in these regions.

3.4 Results

In this section, I report results for the long-run effects of TFP growth on food security and the environment outcomes. Although the economy is divided into fifteen regions in SIMPLE, only results for four regions (US & Canada, Sub-Saharan Africa, South America, and China & Mongolia) will be discussed. US & Canada will be the benchmark region for comparison such that outcomes can be said to be better or worse off. Furthermore, South America and China & Mongolia regions are of interest due to their competitiveness with the US & Canada region. Finally, SSA plays a critical role as it is prevalent for chronic malnutrition.

3.4.1 Global Impacts for Scenario 1

The second column in Table 3.7 reports the simulated results for the food security outcome while the third column reports the environmental outcome. Results indicate that a uniform increase in TFP growth translates into varying levels of outcome impacts. For example, as TFP growth increases by 100 percent in the US & Canada and the Sub-Saharan Africa region, global malnutrition decreases by 13 percent and 20 percent, respectively. A 100 percent increase in TFP in US & Canada and SSA reduces global carbon emissions by 4.27 percent and 3.7 percent, respectively. Developing regions like South America known for their extensification in production (i.e., might use more land to increase output), when exposed to a TFP shock increase land use directly increasing total production, however increasing carbon emissions within their own region. Implying that a decrease in carbon emissions globally exist, but the increase in emissions in their own region means that the net effect of the global decrease in emissions is less. Similarly, SSA increases its crop production by cultivating more land translating into a positive reduction in food security, but with a little reduction in carbon emissions. Furthermore, the change in cropland use will also depend on the elasticity of the supply of land ($\varepsilon_{LAND(g)}$). The larger the response, the more the increase in land use, although China & Mongolia and US & Canada have the same elasticity (0.280), but they differ as regards their cropland availability. As China & Mongolia region have fewer permanent croplands (143,308 ha) compared to US & Canada (236,046 ha) thus, China & Mongolia region have the highest percent reduction in carbon emission with 6.47.

3.4.2 Global Impacts for Scenario 2

The second column in Table 3.8 reports the simulated results for the food security outcomes while the third column reports the environmental outcome for scenario 2. Results indicate that TFP growth in the US & Canada and SSA due to a price impact decreases global malnutrition by 13.09 percent and 22.85 percent, respectively. Likewise, a TFP increase in the US & Canada and SSA decrease global carbon emission by 4.27 percent and 4.76 percent, respectively. The result for China & Mongolia region is so much smaller in this scenario than scenario 1 due to the smaller TFP shock. I assume that this is because China is a much larger producer than the US & Canada so the 100% TFP shock in scenario 1 gives a large impact, but when it gets to the same international price impact the TFP shock in China is much smaller. Also, shares of international goods matter, for example, China is the region most insulated from international prices of agricultural products (I's assume), and TFP growth in China has such a small impact on malnutrition. Also, TFP growth in the US & Canada is more effective at reducing malnutrition than South America and China

& Mongolia region. TFP growth in SSA is much more effective at reducing malnutrition than US & Canada but similar impacts on carbon emissions.

3.4.3 Global Impacts for Scenario 3

The second column in Table 3.9 reports the simulated results for scenario 3. Six billion dollars spent on R&D expenditure in the US & Canada and SSA decreases global malnutrition by 4.31 percent and 26.73 percent, respectively. Carbon emission also decreases on average by 2 percent globally, for example, an increase in TFP growth in South America has a decrease of 15.08 percent in global malnutrition, but a much lower reduction in global carbon emission (2.31 percent) as compared to SSA; showing a tradeoff between the outcomes of interest. On further analysis, the US & Canada and China & Mongolia region have similar initial R&D expenditures with similar result for both outcomes.

In this scenario, the TFP growth in South America is much more effective than in the US & Canada. This is due to the assumptions of R&D elasticity and initial levels of R&D expenditures. South America has low levels of initial R&D and a similar R&D elasticity as the US & Canada, so this gives an assumption of a large TFP shock in the South America region, translating into a higher global impact on food security. SSA also has low levels of initial R&D expenditure, but they have a much smaller R&D elasticity, so the results are not as different between scenarios 2 and 3.

3.4.4 Region-specific impacts on malnutrition

In this section, I highlight which regions are impacted and present the results in terms of the number of people lifted out of malnutrition. To aid with interpretation, the legend in figures 3-8 relates to the region experiencing the TFP growth (regions shocked in SIMPLE with estimated TFP growth). The x-axis label refers to the regional outcome in terms of the decrease in malnutrition. For example, the first blue bar in the figures refer to the region that was shocked with its corresponding outcome in the SSA region (i.e., TFP growth in the US & Canada causes a decrease in malnutrition for the SSA region). Finally, ROW refers to the rest of the world, a combination of other regions like Eastern Europe, central Asia, Japan & Korea, European Union, and North Africa with a little significant reduction in malnutrition outcome.

Figure 3.3 displays the impact of TFP growth on regional malnutrition for scenario 1. TFP growth in SSA is most effective at reducing malnutrition in SSA (Figure 3, 4, and 5). TFP growth in the US & Canada region reduces malnutrition in SSA by 5.8 million people, by 2 million people in the Central Asia region, and by 1.7 million people in the Middle East. TFP growth in China & Mongolia reduces malnutrition in SSA, Central Asia, and the Middle East by 6.7 million, 2.4 million, and 2 million people respectively.

Figure 3.4 shows the impact of TFP growth on regional malnutrition in scenario 2. TFP growth in South America region reduces malnutrition in SSA by 5.2 million, in the Central Asia region by 1.8 million, and in the Middle East by 1.5 million people. A TFP increase in SSA reduces malnutrition in its own region, in Central Asia, and in the Middle East by 17.2 million, 1.1 million, and 1.3 million people, respectively. Results also highlight the effect of TFP growth on regions such as the Middle East hindered with insufficient access to food and its availability, lack of food utility, and stability. Often attributed to various factors such as food shortage caused by reduction in domestic production or access to imports, political turmoil, war, etc. (FAO, 2017). Finally, estimated malnutrition reduction in South America is small when TFP increase for a leading food exporter (corn, soybeans). Figure 3.5 shows the impact of TFP growth on regional malnutrition for scenario 3, TFP growth in the US & Canada region reduces malnutrition in SSA by 1.9 million, Central Asia region by 0.63 million, and South East Asia by 0.47 million people. Scenario 3 gives smaller impacts for TFP shocks in the US & Canada is because the assumed TFP shock are much smaller in scenario 3 than scenarios 1 and 2.

3.4.5 Region-specific impacts on Carbon Emission

Next, we focus on regional carbon emission reduction. Across all scenarios, an increase in TFP growth in South America increases carbon emission in their own region by from 777 metric tons of carbon - MT C (highest) to 534 MT C (lowest). US & Canada regions show an increase in carbon emissions in all the scenarios by 72 MT C (highest) and 54 MT C (lowest) in its own region (Figure 3.6, 3.7 and 3.8). Figure 3.6 shows how TFP growth impacts regional carbon emission in scenario 1. TFP growth in the US & Canada region reduces carbon emission in South America by 452 MT C, South East Asia by 346 MT C, and Central America by 233 MT C. Also, a TFP increase in China & Mongolia region reduces carbon emission in South America region by 521 MT C, SSA, and South East Asia by 409 MT C, and 402 MT C, respectively.

Figure 3.7 shows regional results for scenario 2. TFP growth in the SSA region decreases carbon emission in its own region by 412 MT C, South America region by 316 MT C and South East Asia by 237 MT C. TFP growth in South America region reduces carbon emission in SSA region by 308 MT C, South East Asia, and Central America by 311 MT C and 208 MT C, respectively. Furthermore, results also show the effect of TFP growth on regions such as Australia & New Zealand and South Africa. Showing that the impact of TFP growth has varying effects on regions. Figure 3.8 shows regional results for scenario 3 where TFP growth in the US & Canada region reduces carbon emission by 158 MT C in South America, 117 MT C in South East Asia region, and 110 MT C in SSA. Again, this is because the TFP shock is the smallest for the US & Canada in scenario 3 thereby translating into a lower reduction in carbon emission in other regions.

3.5 Discussion and Limitations

The focus of this essay is the impact of TFP growth on global food security and the environment. I find that TFP growth of 100 percent in the US & Canada decreases global malnutrition by 13 percent (scenario 1 and 2). In other words, for each 1 percent increase in TFP in the US and Canada, global malnutrition decreases by 0.13 percent and carbon emissions by 0.04 percent. In terms of R&D expenditures, I find that an increase of expenditure of six billion in the US & Canada decreases global malnutrition by 4.31 percent and carbon emissions by 1.31 percent (scenario 3). Therefore, for every $1 billion of R&D expenditure in the U.S, global malnutrition decreases by 0.71 percent and carbon emissions by 0.22 percent. There is a large literature that finds a large economic rate of return to public R&D expenditures (e.g., Pardey et al., 2018). My results highlight the additional benefits of R&D expenditures in terms of reduced malnutrition and carbon emissions.

Secondly, the essay examines the impacts of TFP growth in specific regions on food security and the environment in other regions. Our estimates suggest that technological progress in SSA and China & Mongolia would reduce malnutrition and carbon emission levels within its own region as well as in other regions. TFP growth in the US & Canada will influence other regions like the Middle East and Central Asia for a reduction in malnutrition while it affects regions like Australia & New Zealand and South Africa for carbon emission (inclusive of other regions of the world). In contrast, TFP growth in South America and US & Canada will likely increase the region's carbon emission, although the net global effect is the reduction of global carbon emission.

Thirdly, an increase in TFP growth in SSA had the most promising effect on the reduction of global malnutrition (scenario 1 (20 percent), scenario 2 (22.8 percent), and scenario 3(26.7 percent) and global reduction in carbon emission. Likewise, TFP growth in SSA had the highest reduction in malnutrition on average by 14.8 million people in its own region. This answers our last research question that SSA is the most effective region at improving global food security and reducing carbon emission. However, increasing R&D expenditures in SSA may be unlikely from a political perspective. Among the other region, South America region is more effective at improving global malnutrition than China and Mongolia region (in scenarios 2 & 3) due to the higher TFP growth shock that will translate into a higher impact. However, in its own region, an increase in TFP growth causes an increase in carbon emission for South America region.

Not surprisingly, there are significant limitations evident in this essay. The first is the simplicity of our partial equilibrium model. SIMPLE is a parsimonious model i.e. tractable but does not capture all the complexity present in the global agricultural economy; it's simple enough to captures regional disparities. The analysis is done on an aggregated composite crop, with a pre-determined number of economic variables and assumed behavioral elasticities. The model also neglects the inter-sectoral input and output linkages as well as constraints of factors of production movement across sectors. Secondly, the model incorporates a simplified form of international trade where the extent of market segmentation depends on market access and shares of international goods as a proxy for current levels of trade barriers. Many of the developing countries still have limited infrastructure and prohibitive tariffs that segregate them from the international market which is not fully accounted for in the model. Irrespective of these limitations the model was validated and calibrated to test its reliability for future projections (Baldos and Hertel, 2013). Therefore, our results offer an insight into the economic long-run impacts of TFP growth on food security and the environment; with our results in line with the economic literature thereby boosting our confidence in projections obtained.

3.6 Summary and Conclusion

The purpose of this article was to explore three questions. (i) What are the economic impacts of TFP growth on global food security and the environment? (ii) Is there any spillover effect of TFP shocks in specific regions affecting food security and the environment in other regions? (iii) Where is TFP growth most effective at improving food security and reducing carbon emission? To answer these questions, we begin by creating three TFP growth scenarios: (1) uniform growth, (2) same commodity price impact, and (3) same investment in R&D. Estimated TFP shocks were then used for modeling the long-run impacts of TFP growth on food security and the environment using a partial equilibrium model.

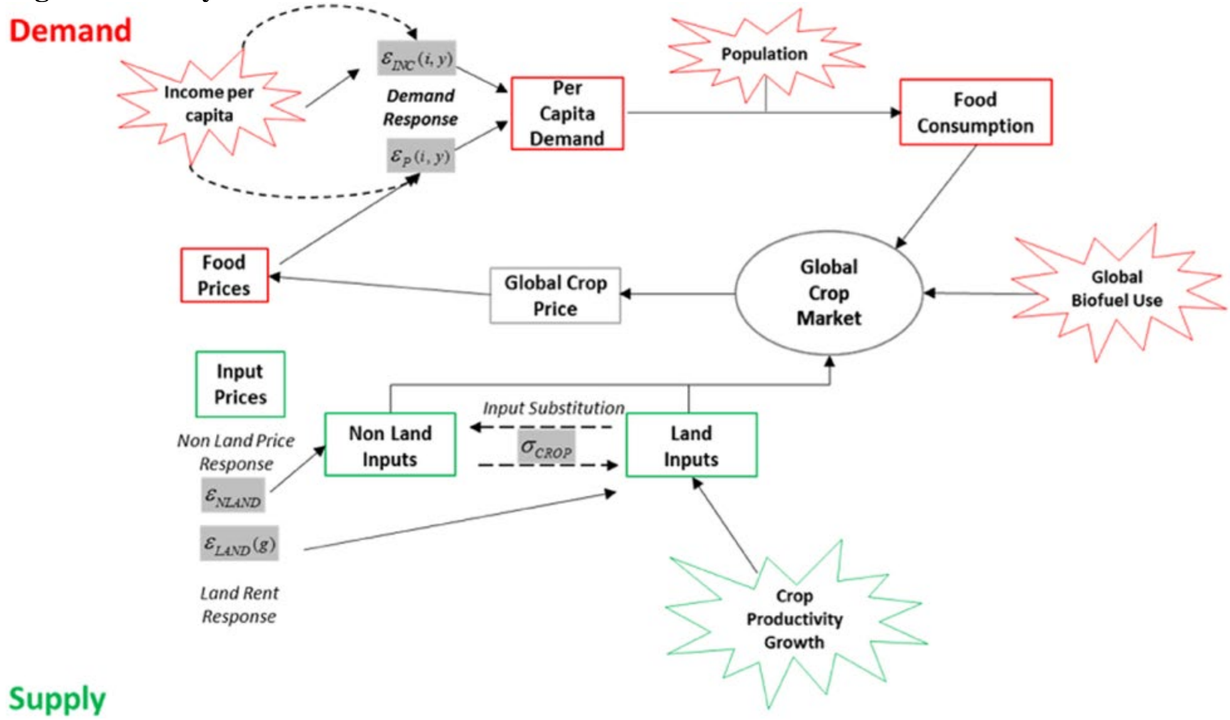
TFP growth in the US & Canada had a reduction in global malnutrition and carbon emission. So does TFP growth in the other three regions (SSA, South America, and China & Mongolia) regions of interest with varying magnitude; however, TFP growth in SSA had the greatest impact on global malnutrition followed by the South America region. In contrast, TFP growth in South America and the US & Canada results in an increase in its own region's carbon emission in all three scenarios, although the net global effect is a reduction in carbon emission. SSA is the most effective region at improving food security and the sustainable environment if TFP growth occurs in the region.

From a policy point of view, this result is critical for policymakers in the US and globally, who are making decisions about R&D funding and for making decisions on where to target R&D efforts regionally to effectively reduce global malnutrition and carbon emission. It also suggests that intentional investment in agricultural productivity in Sub-Saharan Africa will have positive payoffs, for improvement in food security, and for ensuring a sustainable environmental (Villoria 2019). In addition, other options could be considered such as importing technologies and importing food; with food importation evaluated as being the best option due to the constraints facing the region (Hertel et al., 2020).

The issue of malnutrition or undernutrition caused by food insecurity, lack of food access or availability, and population growth remains one of the focal points of this essay and the paper by Hertel et al. (2020). The latter paper focuses mainly on the SSA region considering various channels of alleviating food insecurity through an increase in R&D investment (TFP route), technology importation, and virtual technology trade (food importation) while this essay focuses on the long-term regional impact of TFP growth and its effect on food security and the environment. The results are similar in the sense that either TFP growth (through a decrease in commodity price due to international trade or R&D investment) or technology import or food importation approach, all options are expected to have positive impact on food security and the environment in SSA as well as other regions of the world. Although one can attribute more success to one option over the others due to the unique constraints facing the SSA region.

Finally, a tradeoff exists between reduction in malnutrition index and carbon emission on a regional level, as some of my results show that a decrease in malnutrition index can be accompanied by a corresponding increase in carbon emission and vice versa. But this is not the same on a global scale. When considering TFP growth in the United States, a consideration of not only the impacts on carbon emissions within the United States is needed but also the global impacts. When looking at a global perspective, TFP growth in the United States decreases malnutrition and carbon emissions; providing another reason to support increasing United States R&D expenditures

Figure 3.1: Key elements of SIMPLE



Source: Baldos and Hertel, 2013

Table 3.1: Regional values of parameters in SIMPLE

Regions	Elasticities				
	$\varepsilon_{LAND(g)}$	$\varepsilon_{NLAND(g)}$	$\sigma_{CROP(g)}$	$\varepsilon_{p(i,y)}$	$\varepsilon_{Y(i,y)}$
US & Canada	0.280	1.34	3.0	-0.670	0.782
Sub Saharan	0.560	1.34	3.0	-0.670	0.782
Africa	0.560	1.34	3.0	-0.670	0.782
South America	0.280	1.34	3.0	-0.670	0.782
China & Mongolia					

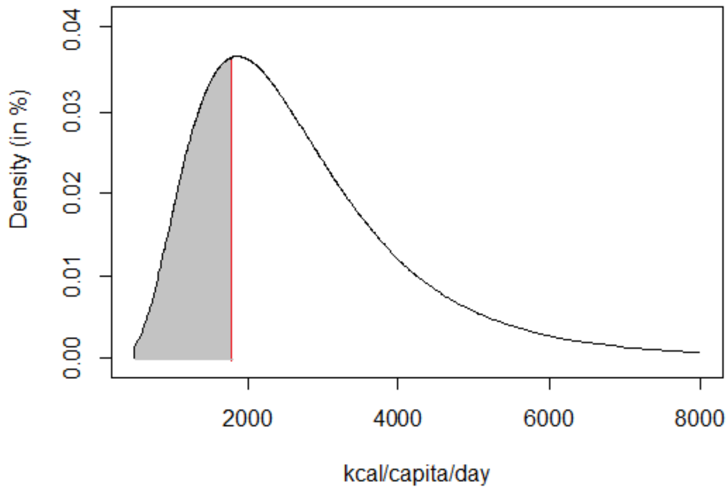
Source: SIMPLE

Table 3.2: Global values of selected variables in SIMPLE for the base year 2001

Crop Production Variable	
Crop output (in M Mt)	20,289
as biofuel feedstock	77
as livestock feed	2,279
as processed food	8,267
Consumption expenditure (M USD)	180,067,584
Value of commodity consumed (M USD)	175,772,745
Crop land (1000 Ha)	1,547,465
Value of crop production (M USD)	2,244,413
Per capita income (USD)	362,549
Population (M)	8,928

Source: SIMPLE

Figure 3.2: Minimum Daily Energy Requirement



Source: Hertel and Baldos Hertel and Baldos (2016).

Table 3.3: Regional values of selected variables in Food Security

Regions	MIN_CAL	SDEV_CAL	MAL_INDEX
US & Canada	1977	0.232	0.400
Sub-Saharan Africa	1746	0.227	1.15
South America	1843	0.294	0.751
China & Mongolia	1910	0.306	0.689

Source: SIMPLE

Table 3.4: Percent Shares of international goods in the regional demand and supply of crops in 2006

Regions	Shares (%)
Crop Demand	
US & Canada	21
Sub-Saharan Africa	7
South America	7
China & Mongolia	6
Crop Supply	
US & Canada	30
Sub-Saharan Africa	5
South America	28
China & Mongolia	2

Source: Hertel and Baldos (2016)

Table 3.5: R&D expenditures for 2010 and 2050

Region	R&D Expenditure 2010 Billion ($)[a]	R&D Expenditure 2050 Scenario Billion ($)	Average R&D Elasticity[b]
US & Canada	5.086	11.2328	0.30
South America	2.236	8.3828	0.23
China & Mongolia	5.273	11.4198	0.21
Sub-Saharan Africa	1.306	7.4328	0.13

*Projected R&D expenditure in Canada/US region in 2050 - $6.1468 billion

[a,b] Source of R&D expenditure 2010 and average R&D elasticity estimates is Fuglie (2018).

Table 3.6: Projected TFP growth (%) for all Scenarios

Region	Scenario 1	Scenario 2	Scenario 3
Canada & USA	100	100	36.26
South America	100	86.68	63.2
China & Mongolia	100	35.48	24.4
Sub-Saharan Africa	100	134.63	63.2

Source: Author's calculations

Table 3.7: Global Food Security and Environment outcomes under Segmented Markets (Scenario 1)

Region with TFP shock	% Change in global Malnutrition	% Change in global Ag Carbon Emission	TFP growth shocks (%)
US & Canada	-13.09	-4.27	100
South America	-14.81	-1.29	100
China & Mongolia	-18.96	-6.47	100
Sub-Saharan Africa	-20.04	-3.7	100

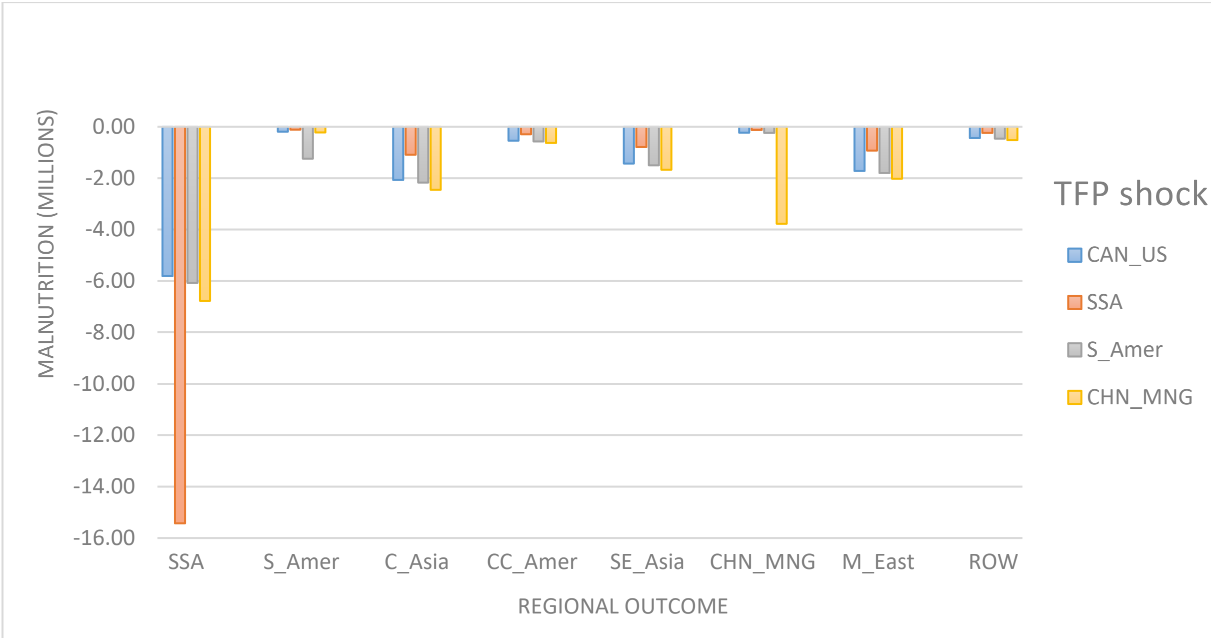
Table 3.8: Global Food Security and Environment outcomes under Segmented Markets (Scenario 2)

Region with TFP shock	% Change in global Malnutrition	% Change in global Ag Carbon Emission	TFP growth shocks (%)
US & Canada	-13.09	-4.27	100
South America	-12.73	-0.96	86.68
China & Mongolia	-6.57	-2.05	35.48
Sub-Saharan Africa	-22.85	-4.76	134.63

Table 3.9: Global Food Security and Environment outcomes under Segmented Markets (Scenario 3)

Region with TFP shock	% Change in global Malnutrition	% Change in global Ag Carbon Emission	TFP growth shocks (%)
US & Canada	-4.31	-1.33	36.26
South America	-15.08	-2.31	63.2
China & Mongolia	-4.31	-1.33	24.4
Sub-Saharan Africa	-26.73	-2.26	63.2

Figure 3.3: Regional changes in malnutrition (millions) for Scenario 1



where SSA = Sub Saharan Africa, S_Amer = South America, C_Asia = Central Asia, CC_Amer = Central America, SE_Asia = South East Asia, CHN_MNG = China & Mongolia, M_East= Middle East, CAN_US= Canada & US, ROW= Rest of the world.

Figure 3.4: Regional changes in malnutrition (millions) for Scenario 2

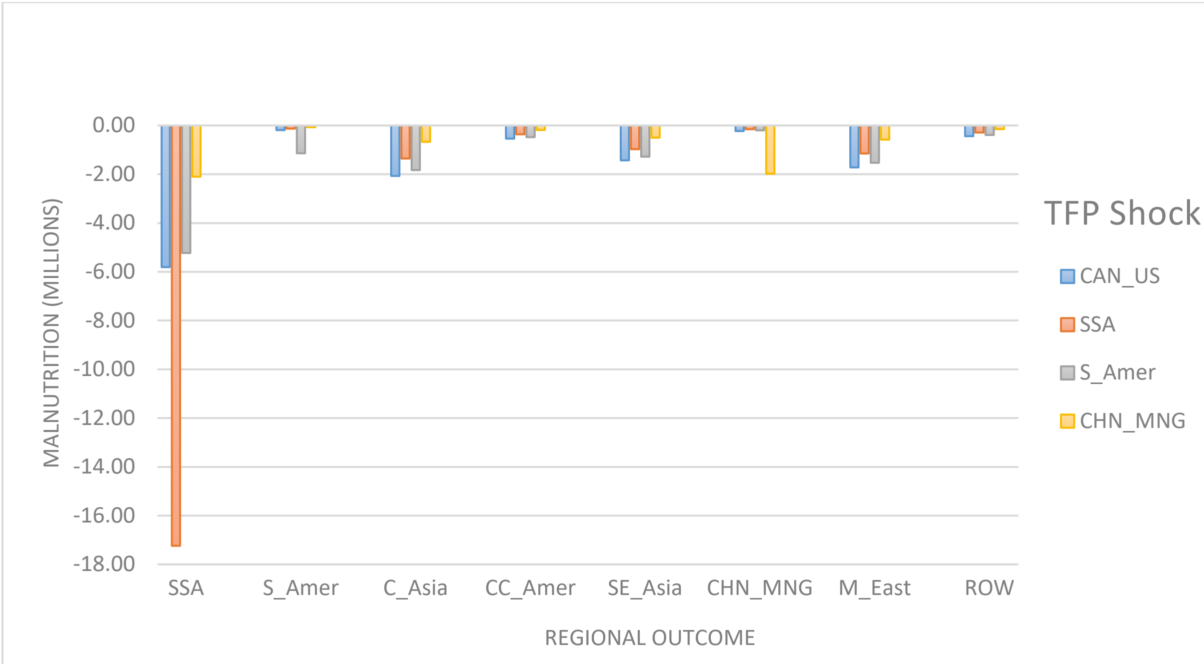
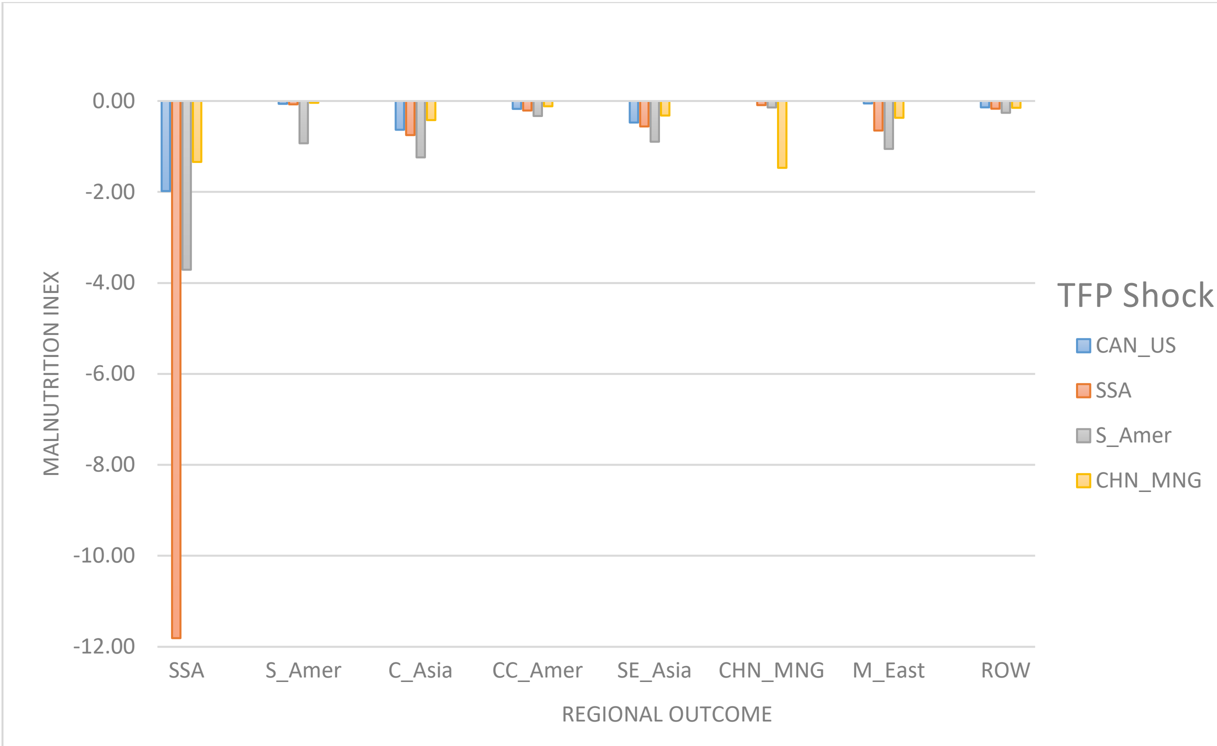


Figure 3.5: Regional changes in malnutrition (millions) for Scenario 3



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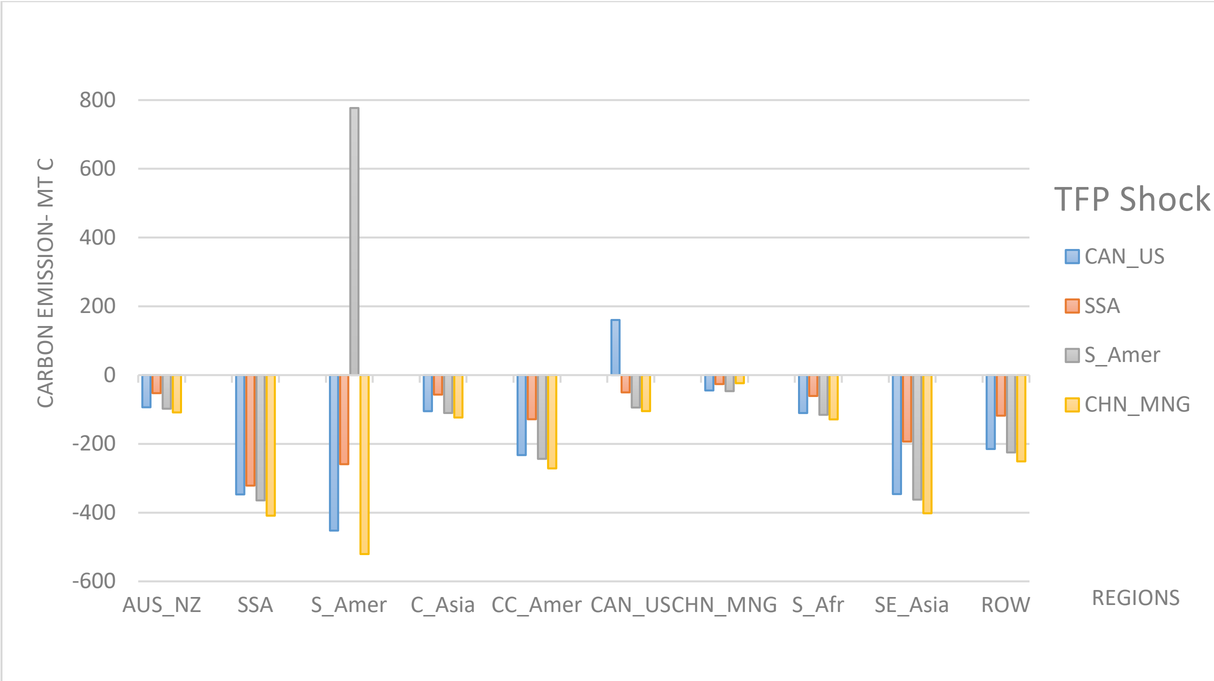
where SSA = Sub Saharan Africa, S_Amer = South America, C_Asia = Central Asia, CC_Amer = Central America, SE_Asia = South East Asia, CHN_MNG = China & Mongolia, M_East= Middle East, CAN_US= Canada & US, ROW= Rest of the world.

Figure 3.6: Regional changes in Carbon Emission (MT C) for Scenario 1



where SSA = Sub Saharan Africa, S_Amer = South America, C_Asia = Central Asia, CC_Amer = Central America, SE_Asia = South East Asia, CHN_MNG = China & Mongolia, S_Afr= South Africa, CAN_US= Canada & US, ROW= Rest of the world, AUS_NZ = Australia & New Zealand

Figure 3.7: Regional changes in Carbon Emission (MT C) for Scenario 2

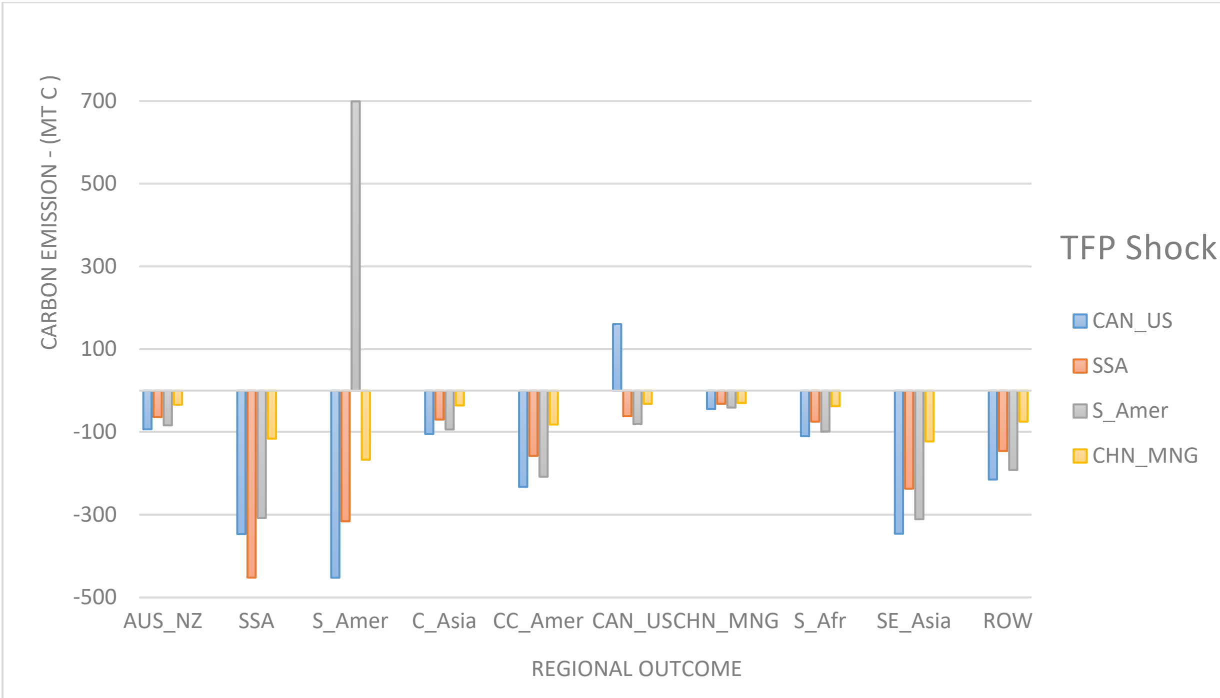
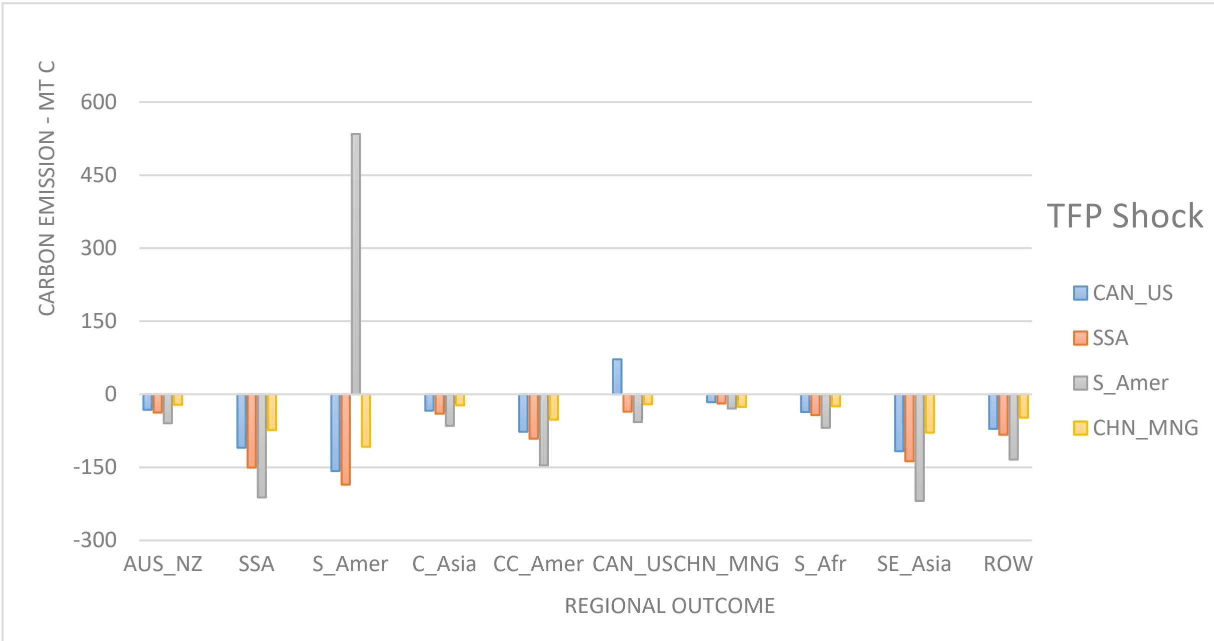


Figure 3.8: Regional changes in Carbon Emission (MT C) for Scenario 3 by 2050



where SSA = Sub Saharan Africa, S_Amer = South America, C_Asia = Central Asia, CC_Amer = Central America, SE_Asia = South East Asia, CHN_MNG = China & Mongolia, S_Afr= South Africa, CAN_US= Canada & US, ROW= Rest of the world, AUS_NZ = Australia & New Zealand

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Chapter 4

Summary and Conclusions

A relationship exists between climate change, agricultural productivity, and the environment. Attempts to increase agricultural productivity will either have a negative or positive effect on the environment, with a positive impact on food availability and security. But climate change is a phenomenon which its effects cannot be stopped but can be mitigated to increase agricultural productivity. The general objective of this dissertation is to examine the historical impacts of climate change on TFP in the short and long term and model the impact of TFP growth on food security and the environment in the future.

In the first essay, I show that weather variations had an effect on agricultural productivity. The results show that fluctuation in the precipitation effect is predominant especially in Sub-Saharan Africa and among the low-income countries. As precipitation increases, TFP also increases. Additional increase in monthly precipitation above 300mm for SSA and low-income countries makes TFP decrease rapidly. Adaptation practices that reduce the effects of extreme temperature by farmers are evident in the long term. Future research will examine the impact of future weather variations on agricultural TFP.

In the second essay, I estimate the long run impact of TFP growth on food security and the environment. My results show that a 1 percent increase in TFP in the US and Canada, decreases global malnutrition by 0.13 percent and carbon emissions by 0.04 percent. Results obtained for TFP growth induced by R&D expenditure shows that for every $1 billion of R&D expenditure in the U.S, global malnutrition decreases by 0.71 percent and carbon emissions by 0.22 percent. Finally, an increase in TFP growth in SSA is the most effective region at improving global food security and reducing malnutrition by 14.8 million people in its own region. In summary, this result has important policy implications for policymakers and policy analyst with interest in SSA region to be mindful of the effect that precipitation has on the economic development of this region. Also, investment in agricultural R&D is another crucial factor that is essential to improve agricultural productivity. As shown in this research, SSA is susceptible to climate change impacts through fluctuations. However, an increase in agricultural productivity will help mitigate climate change impacts as well as alleviate malnutrition and ensure food security both within the region and the world at large. Finally, policymakers in US and Canada also have an opportunity to allocate more funding to agricultural R&D to reduce the incidence of global malnutrition in the world.

Appendix

Figure A.1: Global mean TFP from 1961 to 2014

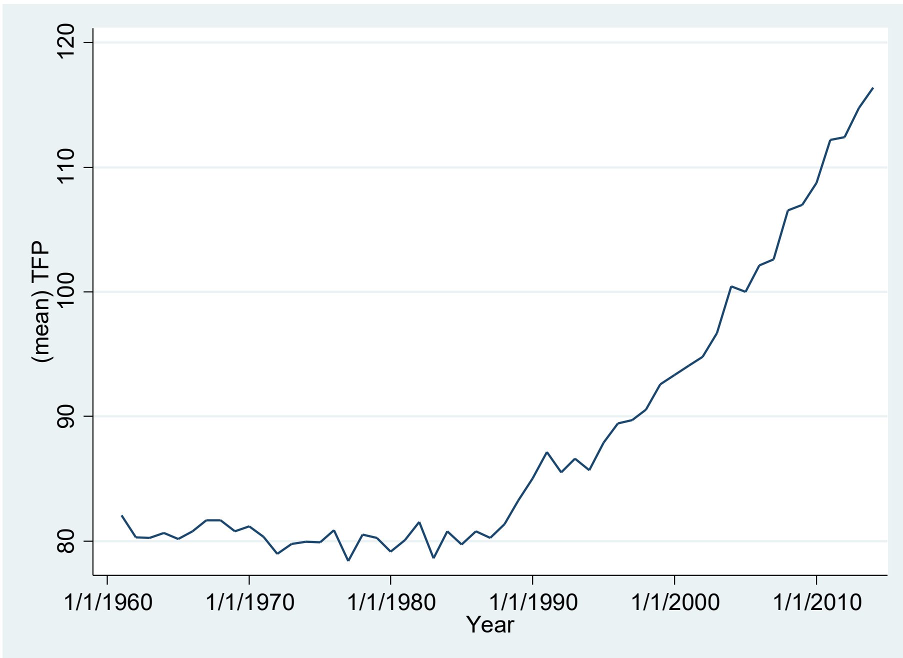


Figure A.2: Global mean Temperature from 1961 to 2014

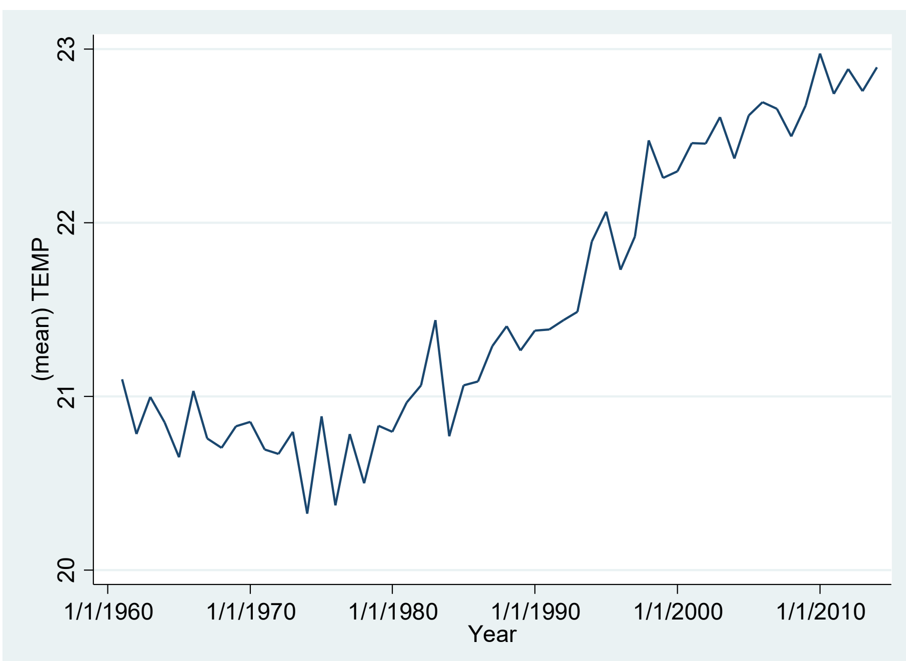


Figure A.3: Global mean Precipitation from 1961 to 2014

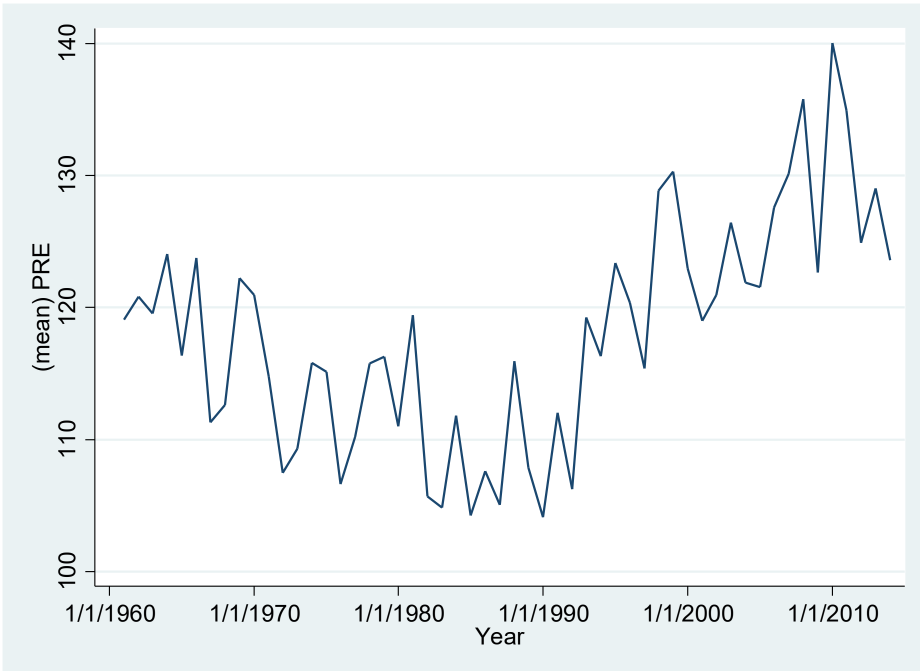
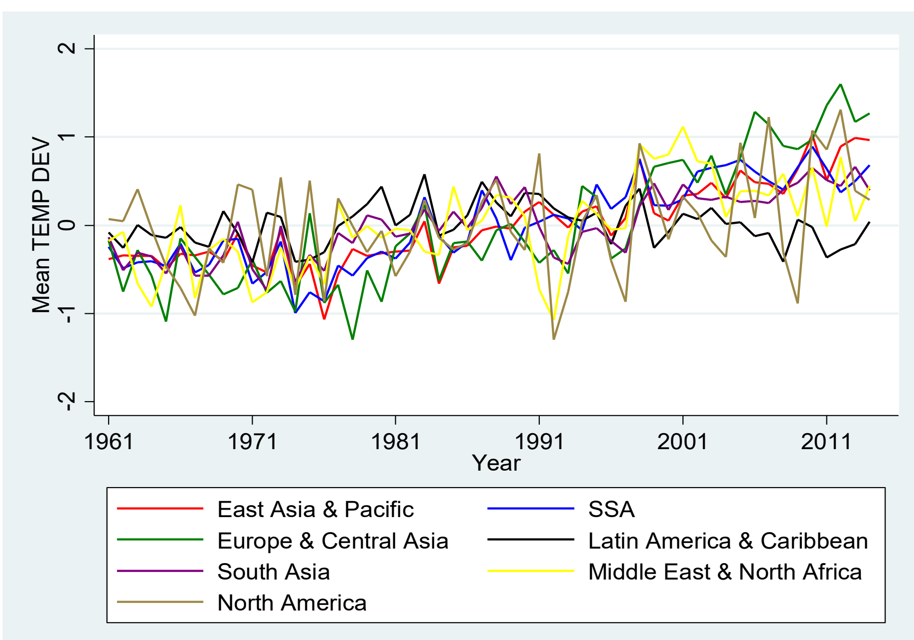


Figure A.4: Regional Temperature from 1961 to 2014



A.1: Summary statistics of regression variables

Variable	Observation	Mean	Standard deviation	Minimum	Maximum
Precipitation (mm)	6,912	123.07	89.37	0	710.97
Temperature (^oC)	6,912	22.15	4.47	10.77	34.91
TFP (Index)	6,912	85.57	22.19	17.13	191.32

A.2: Alternative global regression model specification for robustness check

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.0924	0.0161	0.0933	0.0220	0.0128
	(1.80)	(1.34)	(1.79)	(1.47)	(1.06)
Temperature^2	-0.00199	-0.000612	-0.00193	-0.000726	-0.000498
	(-1.57)	(-1.94)	(-1.48)	(-1.86)	(-1.54)
Precipitation	0.000461*	0.000325*	0.000493*	0.000334	0.00326*
	(2.06)	(2.12)	(2.16)	(1.82)	(2.13)
Precipitation^2	-0.000000501	-0.000000432	-0.000000573	-0.000000511	-0.000000478
	(-1.46)	(-1.73)	(-1.67)	(-1.63)	(-1.93)
N	6912	6912	6912	6912	6912
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.3: Alternative 5- year average model specification for robustness check

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.192*	0.0541	0.198*	0.0596	0.0539
	(2.11)	(1.50)	(2.18)	(1.51)	(1.47)
Temperature^2	-0.00343	-0.00161	-0.00343	-0.00169	-0.00158
	(-1.50)	(-1.76)	(-1.50)	(-1.75)	(-1.72)
Precipitation	0.00151	0.000340	0.00149	0.000753	0.000349
	(1.37)	(0.43)	(1.35)	(0.93)	(0.43)
Precipitation^2	-0.00000175	-0.000000118	-0.00000173	-0.000000937	-0.000000232
	(-0.80)	(-0.07)	(-0.79)	(-0.56)	(-0.13)
N	1280	1280	1280	1280	1280
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.4: Alternative 10- year average model specification for robustness check

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.234*	0.164*	0.245*	0.0883	0.173*
	(2.23)	(2.26)	(2.35)	(1.31)	(2.22)
Temperature^2	-0.00391	-0.00400*	-0.00393	-0.00269	-0.00394*
	(-1.48)	(-2.47)	(-1.50)	(-1.74)	(-2.35)
Precipitation	0.00285	0.000814	0.00268	0.000950	0.000762
	(1.44)	(0.41)	(1.36)	(0.58)	(0.38)
Precipitation^2	-0.00000418	-0.00000238	-0.00000382	-0.00000198	-0.00000259
	(-1.13)	(-0.50)	(-1.05)	(-0.63)	(-0.55)
N	640	640	640	640	640
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.5: Alternative region decomposition model specification for robustness check
East Asia & Pacific

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.187	0.0554	0.180	-0.0147	0.0488
	(0.84)	(1.10)	(0.69)	(-0.23)	(0.96)
Temperature^2	-0.00335	-0.00146	-0.00289	0.000509	-0.00127
	(-0.69)	(-1.47)	(-0.49)	(0.32)	(-1.25)
Precipitation	-0.00156	-0.00000127	-0.00157	-0.000107	0.0000461
	(-0.78)	(-0.00)	(-0.70)	(-0.16)	(-0.13)
Precipitation^2	0.00000361	2.18e-08	0.00000353	-6.51e-08	-0.000000233
	(0.90)	(-0.30)	(-0.79)	(-0.05)	(-0.39)
N	648	648	648	648	648
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.6: Alternative region decomposition model specification for robustness check
Sub-Sahara Africa

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.163	0.0540	0.160	0.00679	0.0440
	(1.16)	(1.10)	(1.04)	(0.10)	(0.83)
Temperature^2	-0.00349	-0.00114	-0.00350	-0.000276	-0.000948
	(-1.19)	(-1.10)	(-1.10)	(0.20)	(-0.84)
Precipitation	0.00110*	0.00129**	0.00102	0.00119*	0.00125**
	(2.10)	(2.96)	(1.95)	(2.62)	(3.19)
Precipitation^2	-0.00000183	-0.00000202	-0.00000186	-0.00000187	-0.00000215*
	(-1.57)	(-1.99)	(-1.63)	(-1.66)	(-2.28)
N	2106	2106	2106	2106	2106
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.7: Alternative region decomposition model specification for robustness check

Europe & Central Asia

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.124*	-0.00955	0.126*	-0.0464*	-0.0272
	(2.73)	(-0.42)	(2.54)	(-2.06)	(1.59)
Temperature^2	-0.00366**	0.0000790	-0.00357*	0.00110	0.000618
	(-2.89)	(0.11)	(-2.62)	(1.57)	(1.13)
Precipitation	0.000524	0.00100	0.000634	0.000459	0.00106
	(0.58)	(1.24)	(0.73)	(0.53)	(1.43)
Precipitation^2	-0.00000776	-0.0000103	-0.00000722	-0.00000733	-0.00000955
	(-1.17)	(-1.77)	(-1.14)	(-1.22)	(-1.75)
N	1620	1620	1620	1620	1620
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.8: Alternative region decomposition model specification for robustness check

Latin America & Caribbean

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.178	0.0256	0.189	0.0112	0.0176
	(0.67)	(0.69)	(0.69)	(0.16)	(0.37)
Temperature^2	-0.00420	-0.00117	-0.00409	-0.000913	-0.000653
	(-0.70)	(1.33)	(-0.65)	(-0.55)	(-0.60)
Precipitation	0.000313	0.000108	0.000368	0.0000781	0.000102
	(1.06)	(0.77)	(1.12)	(0.41)	(0.77)
Precipitation^2	-0.000000370	-0.000000111	-0.000000459	-8.32e-08	-0.000000127
	(-0.92)	(-0.57)	(-1.02)	(-0.30)	(-0.70)
N	1350	1350	1350	1350	1350
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.9: Alternative region decomposition model specification for robustness check

South Asia

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	-0.0568	-0.102	-0.0656	-0.150	-0.128*
	(-0.28)	(-1.73)	(0.31)	(1.58)	(2.70)
Temperature^2	0.000215	0.00204	0.0000394	0.00274	0.00255
	(0.05)	(1.87)	(0.01)	(1.31)	(2.32)
Precipitation	-0.0000724	-0.0000242	-0.000437	-0.000208	-0.000281
	(-0.08)	(-0.04)	(-0.50)	(-0.51)	(-0.50)
Precipitation^2	-3.23e-08	4.52e-08	0.000000240	-0.000000165	0.000000301
	(-0.02)	(0.04)	(0.15)	(-0.20)	(0.28)
N	432	432	432	432	432
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.10: Alternative region decomposition model specification for robustness check

Middle East & North Africa

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.103	0.0285	0.0838	-0.00838	0.00497
	(1.37)	(0.59)	(0.94)	(-0.17)	(0.08)
Temperature^2	-0.00254	-0.000585	-0.00236	-0.000165	-0.0000666
	(-1.60)	(-0.60)	(-1.32)	(-0.17)	(-0.06)
Precipitation	-0.00306	0.00144	-0.00409	-0.000373	0.00105
	(-0.69)	(0.55)	(-0.82)	(-0.09)	(0.38)
Precipitation^2	0.000103	0.00000454	0.000124	0.0000370	0.0000130
	(1.25)	(0.10)	(1.36)	(0.60)	(0.27)
N	648	648	648	648	648
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.11: Alternative 5-year average region decomposition model specification for robustness check

	logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.100 (1.55)	0.0554 (1.10)	0.000675 (0.01)	0.115 (0.83)	-0.800 (-2.05)	0.2206338 (1.06)
Temperature^2	-0.00285* (-2.27)	-0.00146 (-1.47)	0.000120 (0.06)	-0.00371 (-1.17)	0.0156 (2.12)	-0.0041372 (-0.93)
Precipitation	0.000542 (-0.36)	-0.00000127 (-0.00)	0.00432 (1.39)	0.000234 (0.23)	-0.00334 (-1.77)	-.0074582 (-0.56)
Precipitation^2	-0.00000150 (-0.57)	2.18e-08 (-0.30)	-0.0000339 (-1.43)	0.000000299 (0.15)	0.00000747 (1.67)	.0001816 (0.61)
N	120	390	300	250	80	120
FE	Country	Country	Country	Country	Country	Country
Country Time trend	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic
Region	East Asia & Pacific	SSA	Europe & central Asia	Latin America & Caribbean	South Asia	Middle East & North Africa

A.12: Alternative 10-year average region decomposition model specification for robustness check

	logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.00868 (0.03)	0.0198 (0.10)	0.0390 (0.42)	0.284 (0.89)	-1.335* (-2.49)	0.672 (1.05)
Temperature^2	-0.000794 (-0.15)	-0.000895 (-0.24)	0.000719 (0.24)	-0.00734 (-1.12)	0.0270* (2.79)	-0.0151 (-1.04)
Precipitation	-0.00738 (-0.97)	0.00464 (1.89)	0.00843 (0.88)	0.00291 (0.98)	-0.00545 (-1.16)	-0.0199 (-0.68)
Precipitation^2	0.0000158 (0.86)	-0.00000915 (-2.02)	-0.0000745 (-0.97)	-0.00000738 (-1.00)	0.0000135 (1.30)	0.000373 (0.46)
N	60	195	150	125	40	60
FE	Country	Country	Country	Country	Country	Country
Country Time trend	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic	Linear, Quadratic
Region	East Asia & Pacific	SSA	Europe & central Asia	Latin America & Caribbean	South Asia	Middle East & North Africa

A.13: Alternative Income decomposition regression model specification for robustness check.

High Income Countries

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	-0.0283	0.0371	-0.0377	0.0451	0.0185
	(-0.17)	(1.62)	(-0.20)	(1.21)	(0.61)
Temperature^2	0.00120	-0.00119	0.00152	-0.00147	-0.000704
	(0.24)	(-1.68)	(0.28)	(-1.26)	(-0.75)
Precipitation	-0.00102	-0.000550*	-0.000993	-0.000477	-0.000523*
	(-1.99)	(-2.36)	(-1.79)	(-1.38)	(-2.34)
Precipitation^2	0.00000360	0.00000146	0.00000367	0.000000798	0.00000142
	(1.63)	(1.92)	(1.54)	(0.88)	(1.85)
N	1350	1350	1350	1350	1350
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.14: Alternative Income decomposition regression model specification for robustness check

Middle Upper Income Countries

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	-0.0496	-0.0323	-0.0423	0.0238	-0.0281
	(-0.58)	(-1.43)	(-0.47)	(0.78)	(-1.17)
Temperature^2	0.00145	0.000499	0.00145	-0.000546	0.000490
	(0.74)	(1.01)	(0.69)	(-0.83)	(0.72)
Precipitation	0.00000737	0.000123	0.00000757	0.000156	0.0000768
	(0.02)	(0.57)	(0.02)	(0.51)	(0.35)
Precipitation^2	8.95e-08	-0.000000152	6.62e-08	-0.000000219	-0.000000119
	(0.19)	(-0.48)	(0.13)	(-0.48)	(-0.43)
N	1944	1944	1944	1944	1944
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.15: Alternative Income decomposition regression model specification for robustness check

Middle lower Income Countries

logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.0483	-0.0181	0.0460	-0.0127	-0.0256
	(0.69)	(-0.97)	(0.63)	(-0.39)	(-1.30)
Temperature^2	-0.00115	0.000222	-0.00103	0.000171	0.000481
	(-0.75)	(0.46)	(-0.63)	(0.21)	(0.93)
Precipitation	-0.00000798	0.0000449	-0.000131	0.00000233	-0.0000875
	(-0.01)	(0.13)	(-0.23)	(0.01)	(-0.27)
Precipitation^2	2.01e-09	2.19e-08	0.000000173	-5.35e-08	0.000000210
	(0.00)	(0.04)	(0.18)	(-0.08)	(0.04)
N	2214	2214	2214	2214	2214
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

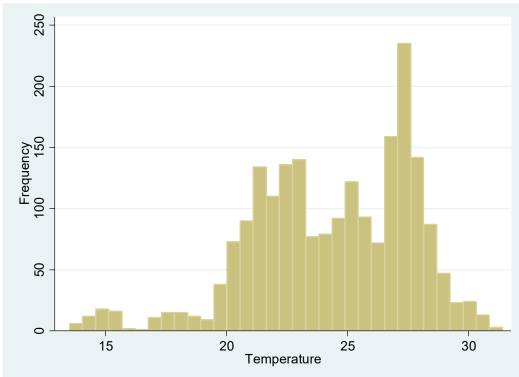
A.16: Alternative Income decomposition regression model specification for robustness check

Low Income Countries

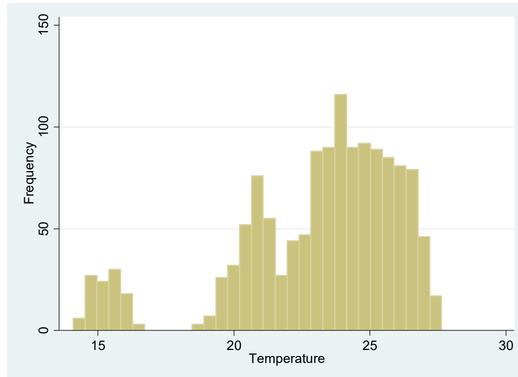
logTFP	logTFP	logTFP	logTFP	logTFP	logTFP
Temperature	0.0444	0.0980	0.0534	0.0535	0.101
	(0.23)	(1.08)	(0.26)	(0.53)	(1.06)
Temperature^2	-0.00174	-0.00247	-0.00224	-0.00179	-0.00273
	(-0.43)	(-1.31)	(-0.50)	(-0.85)	(-1.36)
Precipitation	0.00126*	0.00154***	0.00120*	0.00164***	0.00153***
	(2.58)	(3.89)	(2.61)	(4.45)	(4.47)
Precipitation^2	-0.00000229*	-0.00000264**	-0.00000232*	-0.0000028**	-.00000277***
	(-2.21)	(-3.38)	(-2.32)	(-3.15)	(-3.83)
N	1404	1404	1404	1404	1404
FE	Country	Country	Country Year	Country Year	Country Year
Time trend	Linear Quadratic				
Country Time trend		Linear, Quadratic		Linear	Linear Quadratic

A.5: Histograms for Temperature dataset

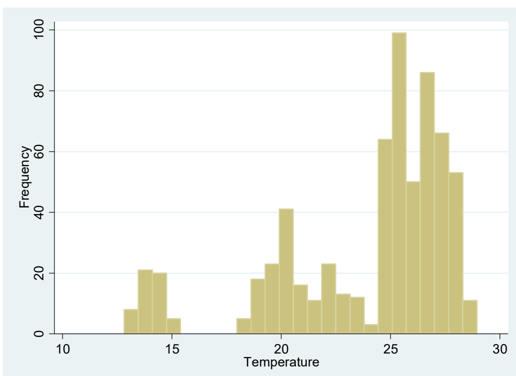
Sub-Saharan Africa



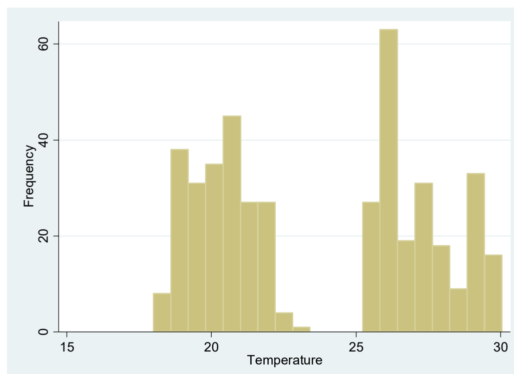
Latin America & Caribbean



East Asia & Pacific

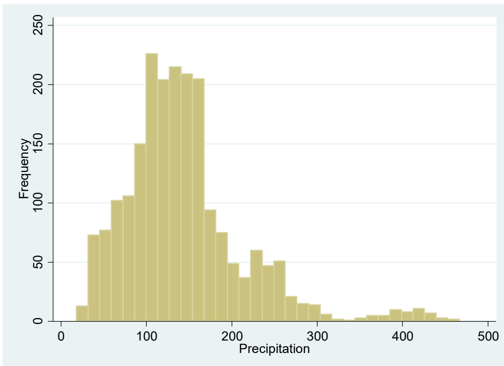


South Asia

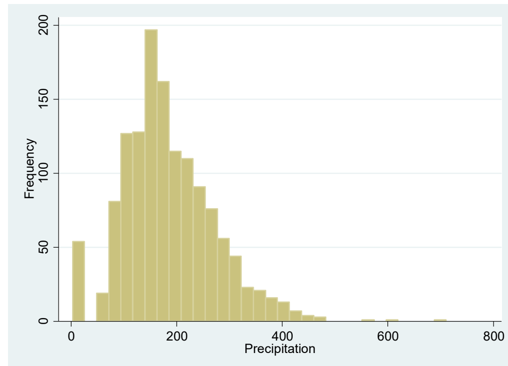


A.6: Histograms for Precipitation dataset

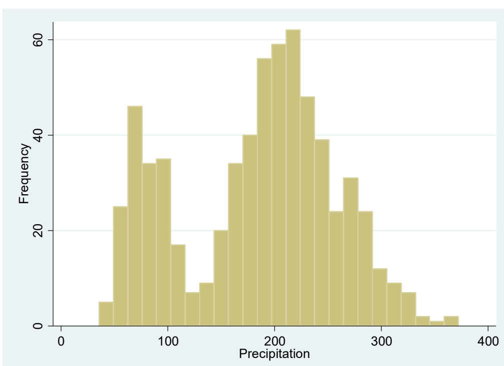
Sub-Saharan Africa



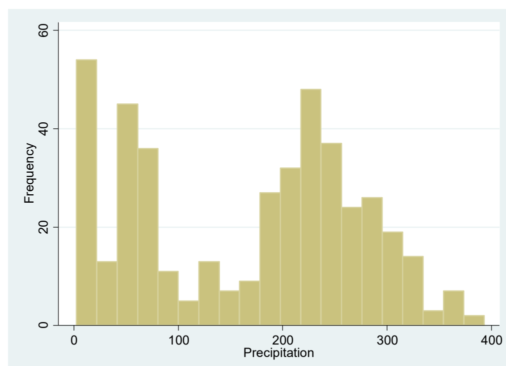
Latin America & Caribbean



East Asia & Pacific



South Asia



A.17: List of countries

Country	Region	Climatic region	Income
Afghanistan	South Asia	Tropical	Low
Albania	Europe & Central Asia	Temperate	Middle-Upper
Algeria	Middle East & North Africa	Temperate	Middle-Upper
Angola	Sub-Saharan Africa	Tropical	Middle-Low
Argentina	Latin America & Caribbean	Tropical	Middle-Upper
Armenia	Europe & Central Asia	Temperate	Middle-Low
Australia	East Asia & Pacific	Tropical	High
Austria	Europe & Central Asia	Temperate	High
Azerbaijan	Europe & Central Asia	Temperate	Middle-Upper
Bangladesh	South Asia	Tropical	Middle-Low
Belarus	Europe & Central Asia	Temperate	Middle-Upper
Belgium	Europe & Central Asia	Temperate	High
Belize	Latin America & Caribbean	Tropical	Middle-Upper
Benin	Sub-Saharan Africa	Tropical	Low
Bhutan	South Asia	Tropical	Middle-Low
Bolivia	Latin America & Caribbean	Tropical	Middle-Low
Botswana	Sub-Saharan Africa	Tropical	Middle-Upper
Brazil	Latin America & Caribbean	Tropical	Middle-Upper
Bulgaria	Europe & Central Asia	Temperate	Middle-Upper
Burkina Faso	Sub-Saharan Africa	Tropical	Low
Burundi	Sub-Saharan Africa	Tropical	Low
Cambodia	East Asia & Pacific	Temperate	Middle-Low
Cameroon	Sub-Saharan Africa	Tropical	Middle-Low
Canada	North America	Temperate	High
Central African Republic	Sub-Saharan Africa	Tropical	Low
Chad	Sub-Saharan Africa	Tropical	Low
Chile	Latin America & Caribbean	Temperate	High
China	East Asia & Pacific	Temperate	Middle-Upper
Colombia	Latin America & Caribbean	Tropical	Middle-Upper
Congo, DR	Sub-Saharan Africa	Tropical	Low
Congo, Republic	Sub-Saharan Africa	Tropical	Middle-Low
Costa Rica	Latin America & Caribbean	Tropical	Middle-Upper
Côte d'Ivoire	Sub-Saharan Africa	Tropical	Middle-Low
	Latin America &	Tropical	Middle-Upper
Cuba	Caribbean	Tropical	Middle-Upper

Country	Region	Climatic region	Income
Dominican Republic	Latin America & Caribbean	Tropical	Middle-Upper
Ecuador	Latin America & Caribbean	Tropical	Middle-Upper
Egypt	Middle East & North Africa	Temperate	Middle-Low
El Salvador	Latin America & Caribbean	Tropical	Middle-Low
Ethiopia, former	Sub-Saharan Africa	Tropical	Low
France	Europe & Central Asia	Temperate	High
Gabon	Sub-Saharan Africa	Tropical	Middle-Upper
Gambia	Sub-Saharan Africa	Tropical	Low
Georgia	Europe & Central Asia	Temperate	Middle-Low
Germany	Europe & Central Asia	Temperate	High
Ghana	Sub-Saharan Africa	Tropical	Middle-Low
Greece	Europe & Central Asia	Temperate	High
Guatemala	Latin America & Caribbean	Tropical	Middle-Low
Guinea	Sub-Saharan Africa	Tropical	Low
Guinea-Bissau	Sub-Saharan Africa	Tropical	Low
Guyana	Latin America & Caribbean	Tropical	Middle-Upper
Haiti	Latin America & Caribbean	Tropical	Low
Honduras	Latin America & Caribbean	Tropical	Middle-Low
Hungary	Europe & Central Asia	Temperate	High
India	South Asia	Tropical	Middle-Low
Indonesia	East Asia & Pacific	Temperate	Middle-Low
Iran	Middle East & North Africa	Temperate	Middle-Upper
Iraq	Middle East & North Africa	Temperate	Middle-Upper
Israel	Middle East & North Africa	Temperate	High
Italy	Europe & Central Asia	Temperate	High
Jamaica	Latin America & Caribbean	Tropical	Middle-Upper
Jordan	Middle East & North Africa	Temperate	Middle-Low
Kazakhstan	Europe & Central Asia	Temperate	Middle-Upper
Kenya	Sub-Saharan Africa	Tropical	Middle-Low
Korea, Republic	East Asia & Pacific	Temperate	High
Kyrgyzstan	Europe & Central Asia	Temperate	Middle-Low
Laos	East Asia & Pacific	Temperate	Middle-Low

Country	Region	Climatic region	Income
Lesotho	Sub-Saharan Africa	Tropical	Middle-Low
Libya	Middle East & North Africa	Temperate	Middle-Upper
Lithuania	Europe & Central Asia	Temperate	High
Madagascar	Sub-Saharan Africa	Tropical	Low
Malawi	Sub-Saharan Africa	Tropical	Low
Malaysia	East Asia & Pacific	Temperate	Middle-Upper
Mali	Sub-Saharan Africa	Tropical	Low
Mauritania	Sub-Saharan Africa	Tropical	Middle-Low
Mexico	Latin America & Caribbean	Tropical	Middle-Upper
Moldova	Europe & Central Asia	Temperate	Middle-Low
Morocco	Middle East & North Africa	Temperate	Middle-Low
Mozambique	Sub-Saharan Africa	Tropical	Low
Myanmar	South Asia	Tropical	Middle-Low
Namibia	Sub-Saharan Africa	Tropical	Middle-Upper
Nepal	South Asia	Tropical	Low
Netherlands	Europe & Central Asia	Temperate	High
New Zealand	East Asia & Pacific	Temperate	High
Nicaragua	Latin America & Caribbean	Tropical	Middle-Low
Niger	Sub-Saharan Africa	Tropical	Low
Nigeria	Sub-Saharan Africa	Tropical	Middle-Low
Pakistan	South Asia	Tropical	Middle-Low
Panama	Latin America & Caribbean	Tropical	Middle-Upper
Paraguay	Latin America & Caribbean	Tropical	Middle-Upper
Peru	Latin America & Caribbean	Tropical	Middle-Upper
Philippines	East Asia & Pacific	Temperate	Middle-Low
Poland	Europe & Central Asia	Temperate	High
Portugal	Europe & Central Asia	Temperate	High
Puerto Rico (USA)	Latin America & Caribbean	Tropical	High
Romania	Europe & Central Asia	Temperate	Middle-Upper
Russian Federation	Europe & Central Asia	Temperate	Middle-Upper
Rwanda	Sub-Saharan Africa	Tropical	Low
Saudi Arabia	Middle East & North Africa	Tropical	High
Senegal	Sub-Saharan Africa	Tropical	Low
Sierra Leone	Sub-Saharan Africa	Tropical	Low
Somalia	Sub-Saharan Africa	Tropical	Low
South Africa	Sub-Saharan Africa	Tropical	Middle-Upper

Country	Region	Climatic region	Income
Sri Lanka	South Asia	Tropical	Middle-Low
Sudan, former	Sub-Saharan Africa	Tropical	Middle-Low
Swaziland	Sub-Saharan Africa	Tropical	Middle-Low
Switzerland	Europe & Central Asia	Temperate	High
Syria	Middle East & North Africa	Tropical	Middle-Low
Tajikistan	Europe & Central Asia	Temperate	Middle-Low
Tanzania	Sub-Saharan Africa	Tropical	Low
Thailand	East Asia & Pacific	Temperate	Middle-Upper
Timor-Leste	East Asia & Pacific	Temperate	Middle-Low
Togo	Sub-Saharan Africa	Tropical	Low
Trinidad and Tobago	Latin America & Caribbean	Tropical	High
Turkey	Europe & Central Asia	Temperate	Middle-Upper
Turkmenistan	Europe & Central Asia	Temperate	Middle-Upper
Uganda	Sub-Saharan Africa	Tropical	Low
Ukraine	Europe & Central Asia	Temperate	Middle-Low
United States	North America	Temperate	High
Uruguay	Latin America & Caribbean	Temperate	High
Uzbekistan	Europe & Central Asia	Temperate	Middle-Low
Venezuela	Latin America & Caribbean	Tropical	Middle-Upper
Viet Nam	East Asia & Pacific	Temperate	Middle-Low
Yemen	Middle East & North Africa	Tropical	Middle-Low
Zambia	Sub-Saharan Africa	Tropical	Middle-Low
Zimbabwe	Sub-Saharan Africa	Tropical	Low

A.18: List of countries in SIMPLE

Country Name	Income Reg.	Geographic Region	Country Name	Income Reg.	Geographic Region
Albania	Low Middle	Europe & Central Asia	Kenya	Low	Sub-Saharan Africa
Algeria	Low Middle	Middle East & North Africa	Kyrgyzstan	Low	Europe & Central Asia
Argentina	Up Middle	Latin America & Caribbean	Lao People's Democratic Rep.	Low	East Asia & Pacific
Armenia	Low	Europe & Central Asia	Latvia	Up Middle	Europe & Central Asia
Australia	Up Higher	East Asia & Pacific	Lebanon	Up Middle	Middle East & North Africa
Austria	Up Higher	Europe & Central Asia	Lithuania	Up Middle	Europe & Central Asia
Azerbaijan	Low	Europe & Central Asia	Luxembourg	Up Higher	Europe & Central Asia
Bangladesh	Low	South Asia	Madagascar	Low	Sub-Saharan Africa
Barbados	Up Middle	Latin America & Caribbean	Malawi	Low	Sub-Saharan Africa
Belarus	Low Middle	Europe & Central Asia	Malaysia	Up Middle	East Asia & Pacific
Belgium	Up Higher	Europe & Central Asia	Maldives	Low Middle	South Asia
Belize	Low Middle	Latin America & Caribbean	Mali	Low	Sub-Saharan Africa
Bolivia	Low Middle	Latin America & Caribbean	Malta	Up Middle	Middle East & North Africa
Bosnia & Herzegovina	Low Middle	Europe & Central Asia	Mauritius	Up Middle	Sub-Saharan Africa
Brazil	Up Middle	Latin America & Caribbean	Mexico	Up Middle	Latin America & Caribbean
Bulgaria	Low Middle	Europe & Central Asia	Mongolia	Low	East Asia & Pacific
Burkina Faso	Low	Sub-Saharan Africa	Morocco	Low Middle	Middle East & North Africa
Burundi	Low	Sub-Saharan Africa	Mozambique	Low	Sub-Saharan Africa
Cambodia	Low	East Asia & Pacific	Namibia	Low Middle	Sub-Saharan Africa
Cameroon	Low	Sub-Saharan Africa	Nepal	Low	South Asia
Canada	Up Higher	North America	Netherlands	Up Higher	Europe & Central Asia
Cape Verde	Low Middle	Sub-Saharan Africa	New Zealand	Up Higher	East Asia & Pacific
Chile	Up Middle	Latin America & Caribbean	Nicaragua	Low	Latin America & Caribbean
China	Low Middle	East Asia & Pacific	Niger	Low	Sub-Saharan Africa
Colombia	Low Middle	Latin America & Caribbean	Nigeria	Low	Sub-Saharan Africa
Congo	Low	Sub-Saharan Africa	Norway	Up Higher	Europe & Central Asia
Costa Rica	Up Middle	Latin America & Caribbean	Pakistan	Low	South Asia
Côte d'Ivoire	Low	Sub-Saharan Africa	Panama	Up Middle	Latin America & Caribbean
Croatia	Up Middle	Europe & Central Asia	Paraguay	Low Middle	Latin America & Caribbean
Cyprus	Low Higher	Europe & Central Asia	Peru	Low Middle	Latin America & Caribbean
Czech Republic	Up Middle	Europe & Central Asia	Philippines	Low Middle	East Asia & Pacific
Denmark	Up Higher	Europe & Central Asia	Poland	Up Middle	Europe & Central Asia
Dominican Republic	Low Middle	Latin America & Caribbean	Portugal	Up Higher	Europe & Central Asia
Ecuador	Low Middle	Latin America & Caribbean	Romania	Low Middle	Europe & Central Asia
Egypt	Low Middle	Middle East & North Africa	Russian Federation	Low Middle	Europe & Central Asia
El Salvador	Low Middle	Latin America & Caribbean	Rwanda	Low	Sub-Saharan Africa
Estonia	Up Middle	Europe & Central Asia	Saudi Arabia	Up Middle	Middle East & North Africa
Ethiopia	Low	Sub-Saharan Africa	Slovakia	Up Middle	Europe & Central Asia
Fiji	Low Middle	East Asia & Pacific	Slovenia	Low Higher	Europe & Central Asia
Finland	Up Higher	Europe & Central Asia	South Africa	Low Middle	Sub-Saharan Africa
France	Up Higher	Europe & Central Asia	Spain	Up Higher	Europe & Central Asia
Gambia	Low	Sub-Saharan Africa	Sri Lanka	Low Middle	South Asia
Georgia	Low	Europe & Central Asia	Sudan	Low	Sub-Saharan Africa
Germany	Up Higher	Europe & Central Asia	Suriname	Low Middle	Latin America & Caribbean
Ghana	Low	Sub-Saharan Africa	Sweden	Up Higher	Europe & Central Asia
Greece	Up Higher	Europe & Central Asia	Switzerland	Up Higher	Europe & Central Asia
Guinea	Low	Sub-Saharan Africa	Tajikistan	Low	Europe & Central Asia
Guinea-Bissau	Low	Sub-Saharan Africa	Togo	Low	Sub-Saharan Africa
Honduras	Low Middle	Latin America & Caribbean	Trinidad and Tobago	Up Middle	Latin America & Caribbean
Hungary	Up Middle	Europe & Central Asia	Tunisia	Low	Middle East & North Africa
India	Low	South Asia	Turkey	Low Middle	Europe & Central Asia
Indonesia	Low	East Asia & Pacific	Turkmenistan	Low Middle	Europe & Central Asia
Iran (Islamic Republic of)	Low Middle	Middle East & North Africa	Ukraine	Low	Europe & Central Asia
Ireland	Up Higher	Europe & Central Asia	United Kingdom	Up Higher	Europe & Central Asia
Israel	Low Higher	Middle East & North Africa	United States of America	Up Higher	North America
Italy	Up Higher	Europe & Central Asia	Uruguay	Up Middle	Latin America & Caribbean
Jamaica	Low Middle	Latin America & Caribbean	Venezuela	Up Middle	Latin America & Caribbean
Japan	Up Higher	East Asia & Pacific	Yemen	Low	Middle East & North Africa
Jordan	Low Middle	Middle East & North Africa	Macedonia	Up Middle	Europe & Central Asia
Kazakhstan	Low Middle	Europe & Central Asia			