Food Security and Environmental Implications of Carbon Pricing in High-Income Regions

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A thesis submitted to the
University of Colorado Boulder
In partial fulfillment
Of the requirements to receive
Honors designation in
Environmental Studies

Defense date: **April 4, 2022**

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Preface

I chose to explore the food security implications of emissions pricing because of my commitment to environmental justice. I hope to make an impact on environmental justice concerns and the general inequitable effects of climate change felt by marginalized communities. Sudan is my homeland; I want it to be 'allowed' to thrive sustainability. The relative proportions of pollutants emitted throughout history is wildly inequitable, and so should the mitigation efforts. In my opinion, the mitigation level should be proportional to the damage added. Wealthier nations industrialized and added most of the pollution throughout history; however, less-developed nations have not enjoyed most of the rewards of said 'progress' yet are subject to the same mitigation standards at times. I have used my thesis as an opportunity to explore a potential fairly equitable climate change mitigation strategy for one of life's essentials- food.

Abstract

Food and agriculture contribute approximately one-third of global GHG emissions, but also provide a basic human necessity: food. A recent study projected that global food systems alone could prevent the world from achieving the United Nations' target of limiting warming to 1.5C by 2100, and thus illustrates the need to mitigate GHG emissions in global food systems. Carbon taxes are an approach proposed by economists to incentivize emissions reductions, but they can also cause prices to increase, which would be a concern in food systems. However, the food insecurity concern is greatest in poorer countries, while the emissions from food systems are greatest in richer countries. This raises the question: what if a carbon tax was imposed only on rich countries? Could this both meaningfully reduce emissions and lower global food prices, thereby reducing food insecurity in poor countries? To model the effects of a carbon tax placed upon food in rich countries, I used both a simple analytical model of supply, demand, and trade in two hypothetical countries, and a computer-based simulation model calibrated to real-world data: the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE). I found that carbon taxes on food in rich countries have the desired effects on GHG emissions and food security when they target consumers (demand), but, surprisingly, they worsen food insecurity and have ambiguous effects on GHG emissions when they target producers (supply). Previous pollution pricing theories not accounting for trade found supply and demand taxes to have identical effects. My results have important implications for climate change mitigation, environmental justice, and environmental economic theory.

Introduction

Climate change has numerous negative implications and must be mitigated. Food must be considered in any mitigation strategy because food systems contribute a large fraction of global greenhouse gas (GHG) emissions (Foley et al., 2011). A preferred policy tool of economists for addressing climate change is a carbon tax (Akerlof et al., 2019). A concern regarding carbon taxes is that they could raise food prices and thereby raise food insecurity for the poor (Golub et al., 2013). To address these competing concerns, my thesis explores the idea of implementing a carbon tax on only rich countries. The rationale I hypothesize is that this could lower global food prices by reducing rich-country demand, and consequently reduce food insecurity rather than worsening it.

I explore this possibility in two models. One is a simple, stylized, analytical model of two hypothetical countries, one 'rich', one 'poor', which trade with each other. The other is the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE) model, which is a computational model of agricultural production, emissions, and trade, which is calibrated to real data.

Background

Climate impacts of the global food system

The negative effects of climate change are widely known and studied. The disastrous impacts of climate change range further than an increase in temperature- it has broader implications. Habitat destruction and subsequent biodiversity loss, melting glaciers & ice caps threatening coastlines, and increased ocean acidity are all consequences of climate change (IPCC, 2021). For a long time, the United Nations (UN) and other organizations have warned about these impacts and attempt to mitigate it. The UN Intergovernmental Panel on Climate Change (IPCC) is charged with synthesizing the scientific literature to inform global mitigation targets through the UN. Recent IPCC reports have made it abundantly clear that global emissions must be drastically reduced, as quickly as possible, to avoid the most catastrophic effects of climate change (IPCC, 2021). While the cause of climate change is the result of global emissions production, the negative impacts are disproportionately felt by low-income communities and other marginalized groups. Such impacts are exacerbated by a lack of global regulation and cooperation to address climate change, including the lack of incentives for high-income countries to reduce their carbon footprint. While the 2015 Paris Agreement set an aspirational target of limiting warming to 1.5℃ by 2100, climate action by individual nations is entirely voluntary (IPCC, 2018). Nations must voluntarily take steps to reduce emissions via policy, lifestyle, or cultural changes, such as reductions in fossil fuel use or meat consumption.

Food systems are responsible for a third of global emissions (Crippa et al., 2021). However, 'food'; is a broad category. When considering the environmental impact of 'food' we are considering land use, agricultural production, the supply chain, and post-retail. Land use includes emissions from deforestation, soil cultivation, fires, and peatland degradation. Agricultural production refers to emissions from both natural and synthetic fertilizers, running and fueling farm machinery, aquaculture, and methane from livestock and certain crops. The supply chain umbrella refers to the emissions from processing, packaging, retail refrigeration, and transportation. Finally, post-retail emissions are emissions from consumer food waste as well as energy used by consumers in preparing food such as cooking or refrigeration (Ritchie, 2021). From all these categories, land use accounts for the largest relative amount of greenhouse gas emissions by far–accounting for about 71% of emissions related to food which already accounts for a third of global emissions (Crippa et al., 2021).

Opportunities to reduce food system emissions

Meeting global climate targets requires mitigating food-system emissions. In fact, even if we completely stopped using fossil fuels but did not mitigate food emissions, we would not be able to meet the IPCC's target of limiting warming to 1.5°C by 2050 (Clark et al., 2020). Thus, we must clearly do something to mitigate the emissions from food, while continuing to provide this very basic necessity of life. There have been a variety of potential mitigation measures analyzed including shifting towards a more plant-based diet, improving technologies, and limiting food waste. None of these is a 'silver-bullet' solution and must be implemented in tandem with numerous other mitigation efforts to produce a positive effect on emissions mitigation (Springmann et al., 2018).

One option that could potentially be effective is a tax placed on GHG emissions; following basic economic principles- implementing a tax raises prices which reduces demand, which decreases the activity. However, there must be barriers to prevent 'leakages', whereby producers offshore their production to avoid the tax, and also to ensure that some larger 'players' cannot pay to continue polluting. There have been some analyses into the potential to mitigate our carbon intensive food industries through emissions pricing/taxing (Springmann et al., 2016). One study by Springmann et al. (2016) showed the potential positive mitigation effects of a carbon tax on emissions if 'designed appropriately'. The main concern with ascribing a price to food emissions is the increase in price that may exacerbate food insecurity in some areas. In fact, a study regarding emissions pricing found that there were strong negative impacts on income and food consumption globally. This outlines the risks associated with ascribing a price to food emissions (Golub et al., 2012).

Global food security, food inequity, and malnutrition

When ascribing a carbon price to carbon-intensive foodstuffs, prices will increase, which can have a negative effect on food security in some regions. Globally, around 16% of the population suffers from chronic hunger; about one billion people suffer even though there is enough food, the issue is inequitable access (Mc Carthy et al., 2018). Current estimates predict the need to scale global food production by 70% by 2050 with already limited resources if we continue on our current consumption (Mc Carthy et al., 2018). Despite this, there are also some parts of the world in which obesity is on the rise, in addition to one third of food produced being ultimately wasted or lost (Schmidt-Traub et al., 2019). Thus, food insecurity could be reduced by more equitable allocations of food already produced, in addition to producing more.

While meat consumption has generally been rising globally, over the past few decades it has been a largely inequitable increase. Less developed countries have largely increased their meat consumption in recent years which has put a larger strain on their environments- this rapid growth has had negative effects on land use change and livestock emissions. Although consumption is growing rapidly in underdeveloped nations, developed nations still consume a largely disproportionally large amount of meat (Whitnall & Pitts, 2021). A sobering comparison of the meat consumption in developed and developing nations outlines this truth. The average American consumes 101.1 kilograms of meat per year while the average Indian consumes 4.4 kilograms of meat per year and the average Nigerian consumes only 3.5 kilograms of meat per year (Hansen & Syse, 2021). This inequitable consumption of meat and inequitable distribution of emissions due to the distribution of meat consumption outlines the necessity to mitigate emissions from food proportionally. Aside from the inequitable distribution, meat consumption comes with a number of negative environmental impacts. Chief of which is the increased emissions stemming from the processes that go into raising and consuming meat ranging from feed fertilizers to methane from the animals themselves. Furthermore, meat consumption also has a negative impact on water scarcity, water pollution, and general water footprint. Alongside the negative environmental impacts, there are also a number of health risks associated with excessive meat consumption- red meat is a potential carcinogen, processed meat is definitely a carcinogen, and meat as generally being related to virus infections (especially ‘wild’ meat) (González et al., 2020).

There are numerous negative consequences of food insecurity and its inequities that directly worsen quality of life– effects which will only be exaggerated as the planet warms with increasing emissions output (Schmidt-Traub et al., 2019). Food insecurity and the accompanying malnutrition affect many of the body’s normal physiological functions. Malnutrition causes declines in muscle function & mass which can have dire implications for tissue function. Moreover, malnutrition reduces cardio-respiratory function due to the reduction in cardiac muscle mass. In addition, gastrointestinal functions are negatively affected, the colon loses its functionality to absorb electrolytes, and diarrhea is a common symptom which can be fatal in severe cases. Immune function is also negatively affected and makes malnourished individuals much more prone to infection as well as have delayed wound healing (Saunders & Smith, 2010). Malnutrition also has psychological and psychosocial effects; it can lead to apathy, self-neglect, anxiety, and depression (Saunders & Smith, 2010). Malnutrition also leads to growth and development stunting which directly leads to negative intellectual effects. This improper development from a dearth of proper nutrition results in decreased productivity and has larger consequences for populations and economies as a whole (Seipel, 1999).

Improper nutrition and subsequent poor development can have intellectual implications. Several studies in South America have concluded that malnutrition leads to reduced mental and physical development. This has much broader implications for a nation’s overall well-being and development as economic development is born from the improvement of skills and knowledge of its people (Latham & Cobos, 1971). Well-nourished children have better relative cognitive abilities which translate to higher productivity in their adult life- directly leading to an improved quality of life. Furthermore, well-nourished individuals are simply more physically capable and are more productive (Lomborg et al., 2013). This outlines how malnutrition not only has negative health effects, but can also have devastating social effects.

In summary, there is a need to reduce emissions from food systems, as well as a need to reduce food insecurity. One way to accomplish both goals might be to induce less consumption of carbon-intensive foods in rich countries and more redistribution of such foods to poorer countries. To this end, I explore imposing a carbon tax on only richer countries.

Methods

To gain some insight into the food security implications of emissions pricing I employed two models: a simple, conceptual model of supply and demand between two hypothetical countries, and the SIMPLE model (Baldos & Hertel, 2012).

Analytical model

The analytical model consists of linear supply and demand curves in each of a ‘rich’ country and a ‘poor’ country. I assumed that the markets of these two countries were perfectly integrated through trade with no transaction costs, such that the ‘law of one price’ applied, meaning consumers must face the same pre-tax price in both countries at equilibrium. From this, I calculated the pre-tax equilibrium quantities in each region and price, in algebraic terms, using Mathematica (Appendix A). Then, I added a tax per unit quantity to either supply or demand in the rich country, simulating taxing either consumers or producers, and recalculated the equilibrium quantities and price. When demand is taxed, I assume that consumers in the rich country are taxed regardless of which country they buy in. When supply is taxed, I assume that producers in the rich country are taxed regardless of which country they sell in. This is the key qualitative difference in the assumptions. I compared the pre- and post-tax equilibria (Appendix A) to see if it was possible to prove that quantity consumed in the poor country would go up, which would reduce food insecurity, and whether total quantity produced would go down, which would mean reductions in emissions most likely. I also analyze this linear model graphically in Figure 1.

SIMPLE model

To further explore a carbon tax on carbon-intensive foods, I use the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE model). The SIMPLE model is a partial equilibrium model that utilizes global price and quantity values in addition to other economic variables (e.g., efficiency factors) to understand the drivers that influence the global food system and their resulting effects on long run agricultural land use, production, prices, GHG emissions, and food consumption. By ‘shocking’ different exogenous variables in the model, SIMPLE can be used to predict the effects of varying tax levels on different income regions. Essentially, the SIMPLE model is a balanced system of equations; it is unbalanced via a shock, and the model rebalances itself and, subsequently, the equations. The outputs are generated by finding the after-shock equilibrium and comparing it to the pre-shock equilibrium. Using the SIMPLE model, I impose a tax on food products in high-income regions via a shock to the Hicks Neutral Efficiency variable. In simple terms, the Hicks Neutral Efficiency variable (AOCROPr) represents the efficiency of input use for a given output. Shocking this Hicks Neutral Efficiency variable for crops in the SIMPLE model decreases the efficiency of crop production and thus, serves as a proxy for increasing the price of crops via a tax. Note that this shock affects the efficiency of production and therefore, serves as a supply side shock rather than a demand side shock within the SIMPLE model.

There are 15 regions and/or individual countries in the SIMPLE model. These include Eastern Europe, North Africa, Sub-Saharan Africa, South America, Brazil, Australia & New Zealand, the European Union (EU), South Asia, Central America, South Africa, South-East Asia, Canada, the United States of America (US), China, the Middle East, Japan & Korea, and Central Asia. Regions can be characterized by income according to the World Bank. I shocked the efficiency of production in the following high-income regions/countries: the United States, Canada, the EU, Australia, New Zealand, Japan, and South Korea. I have chosen these regions as these high-income regions have disproportionate meat consumption and production rates.

Unfortunately, the SIMPLE model does not allow me to directly apply a carbon price because the regional price of different agricultural commodities is endogenous in the model. However, shocking the efficiency of crop production as previously mentioned allows me to indirectly influence the price via a supply side shock. First, I calculated the proper efficiency shocks using the initial price from the model ($157 per MT of crops) which I obtained by dividing the regional crop value by regional quantity of crops. Then, using data from FAOSTAT (FAO, 2022), I determined the carbon efficiency of crop production for each region of the model. I then obtained a range of feasible carbon prices from existing literature (Ricke et al., 2018; Nordhaus, 2017; Wagner, 2021) and calculated that regional tax over a range of carbon prices ranging from $50 to $275 per MT of CO2 eqv. Using the emissions intensity and the carbon prices, I was able to determine the increase in regional carbon price for each carbon price measured in increments of $25. The new price of carbon per high-income region (United States, Canada, the EU, Australia, New Zealand, Japan, and South Korea) was calculated by adding the original global carbon price of $157 per MT crop and adding the new carbon price imposed by the tax and relative emission intensity of the region. The production shock was then calculated by finding the difference before and after the carbon tax for each of the regions for each of the carbon tax price points. I conducted ten simulations based on the comparative ratios between the shocked regions, using that relative difference, I was able to conduct ten simulations with the relative differences between the high-income regions and shocking the efficiency variable. I used the Australia & New Zealand region as my baseline and shocked its efficiency variable increasing by 5% starting from 5% (Sim 1) till 50% (Sim 10) and calculating the correct relative efficiency variables for the rest of the taxed regions. I had to stop at ten simulations because of the model's accuracy, after ten simulations the results were no longer as accurate. I determine the effects of different supply side tax shocks by analyzing several important output variables, including emissions, malnutrition, food prices, and consumption quantities across all 15 model regions.

Results

Analytical model

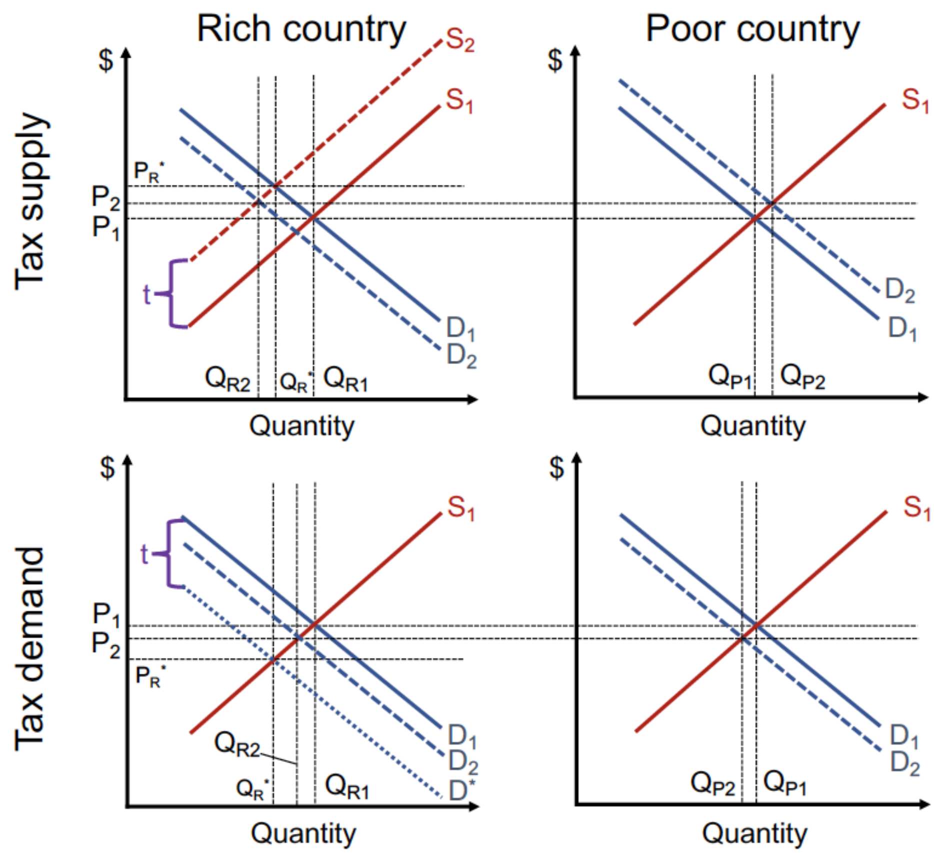

Figure 1. Effects of a tax on supply and a tax on demand on a stylized 'rich' and 'poor' country. 'D' refers to the demand, 'S' refers to the supply, 'P' refers to price, 'Q_R' refers to the rich country's quantity, 'Q_P' refers to the poor country's quantity, and 't' represents the tax. S_1, D_1, P_1, and their respective quantities refer to before the tax. D^* & P_R^* refer to intermediaries after tax but before trade. S_2, D_2, P_2 and their respective quantities refer to after tax and trade.

In the analytical model, there is an important difference between taxing supply and taxing demand (Figure 1). When consumers are taxed in the rich country, they cannot pay less by importing, so they simply buy less. This causes the price to go down, and the quantity consumed to go up for consumers in the poor country. However, the quantity produced goes down in both countries, meaning that emissions must also go down (Figure 1; Appendix A). In other words, when demand is taxed, emissions go down, but food access in the poor country goes up, which is the desired effect.

When producers are taxed, the result is different (Figure 1; Appendix A). Since the tax is now tied to production in the rich country, but not consumption, consumers in the rich country import food produced in the poor country to avoid the tax. However, this drives prices up and consumption down in the poor country, and therefore harms food security. Producers in the poor country produce more, though, in order to meet the demand from the rich country. As a result, production goes up in the poor country and down in the rich country. If the poor country produces more emissions per unit food produced than the rich country, it is possible for overall emissions to go up in this scenario. In other words, the effect of the supply tax is ambiguous on emissions and unambiguously negative on food security in the poor country (Figure 1; Appendix A).

SIMPLE model simulations

The results from the ten simulations ran in the SIMPLE model show that prices increase globally across crops (Figure 2 & Figure 3), livestock, and processed foods with the most dramatic increase in the taxed regions.

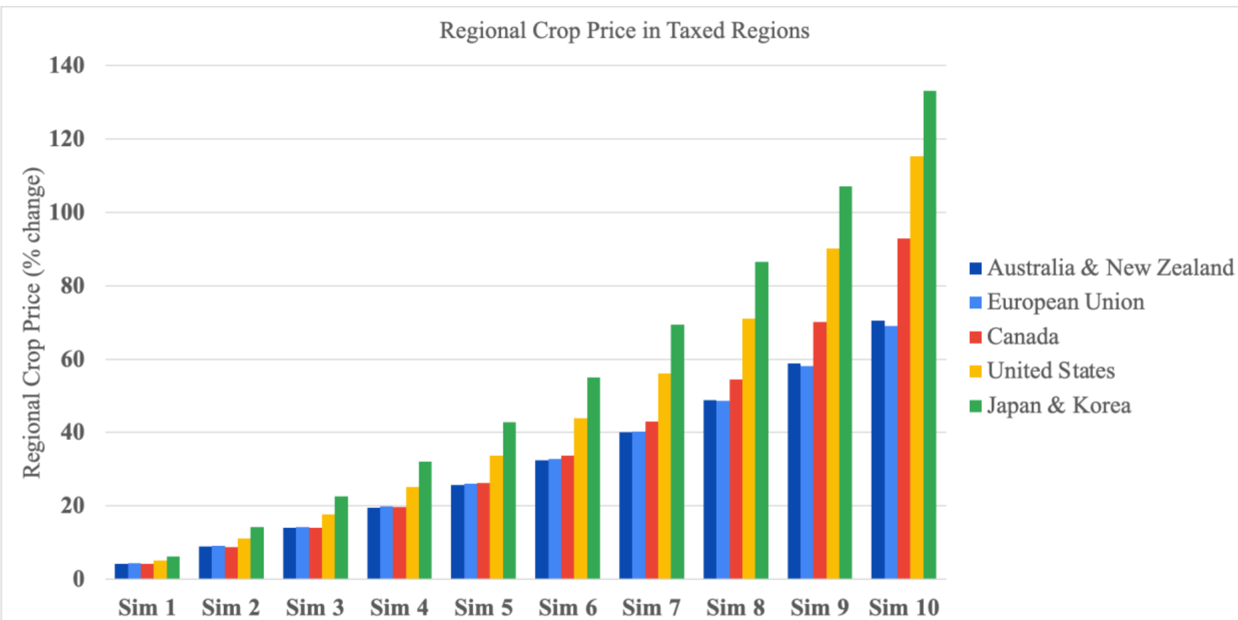

Figure 2. Percent change in Crop Price across high income regions including the United States, Canada, Australia & New Zealand, Japan& Korea, and the EU. Simulation 1 represents the lowest shock and carbon price while simulation 10 represents the highest shock and carbon price across high-income regions.

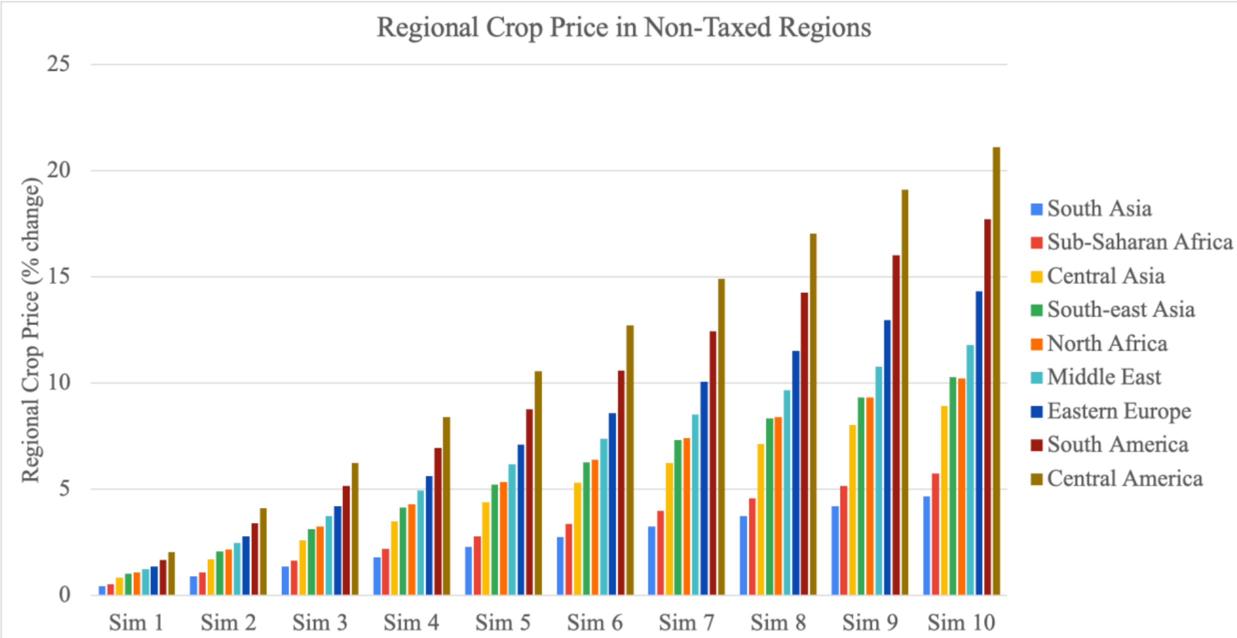

Figure 3. Percent change in Crop Price across low- and middle-income regions including sub-Saharan Africa, South Asia, South America, Central America, the Middle East, Central Asia, South-East Asia, North Africa, and Eastern Europe. Simulation 1 represents the lowest shock and carbon price while simulation 10 represents the highest shock and carbon price across high-income regions.

Emissions from crops (Figure 4 & Figure 5), croplands, land use changes, and non-land inputs all decreased in the taxed regions, but actually increased in all the other, untaxed regions. However, the emissions from livestock decreased in all the regions with the most significant decreases in the regions of South Asia, Australia & New Zealand, North Africa, the EU, Central America, Middle East, the United States, and Japan & Korea in order of severity of emissions decrease. The emissions from non-feed inputs increased in all regions.

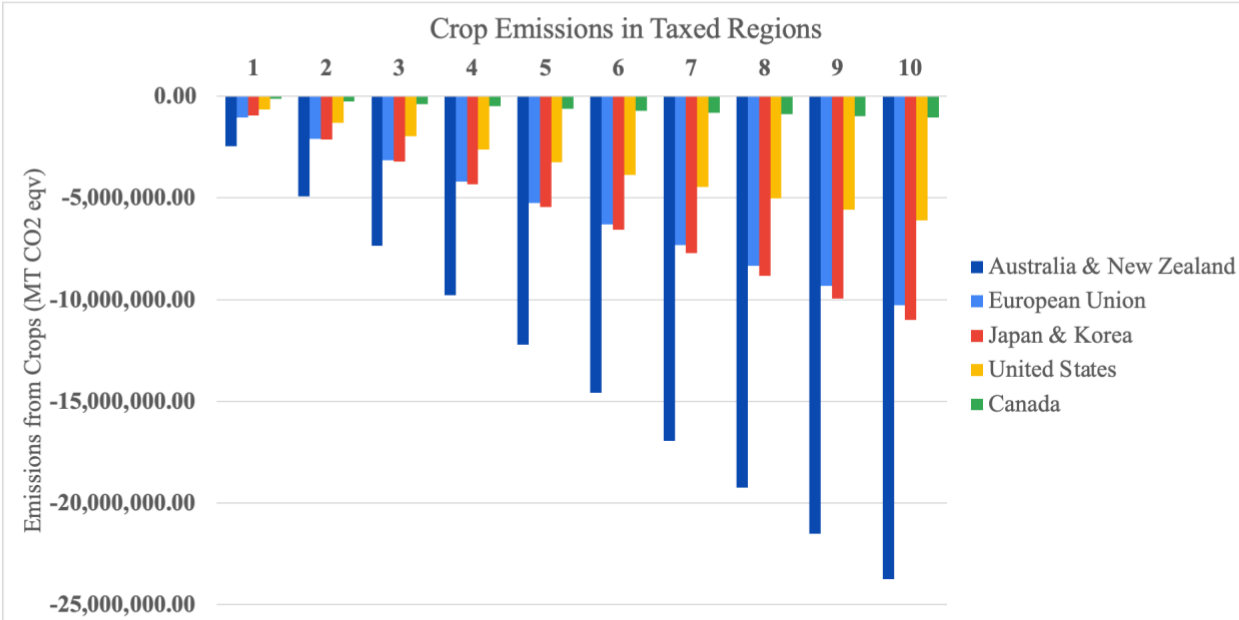

Figure 4. Change in Emissions from Crops across high income regions including the United States, Canada, Australia & New Zealand, Japan& Korea, and the EU. Simulation 1 represents the lowest shock and carbon price while simulation 10 represents the highest shock and carbon price across high-income regions.

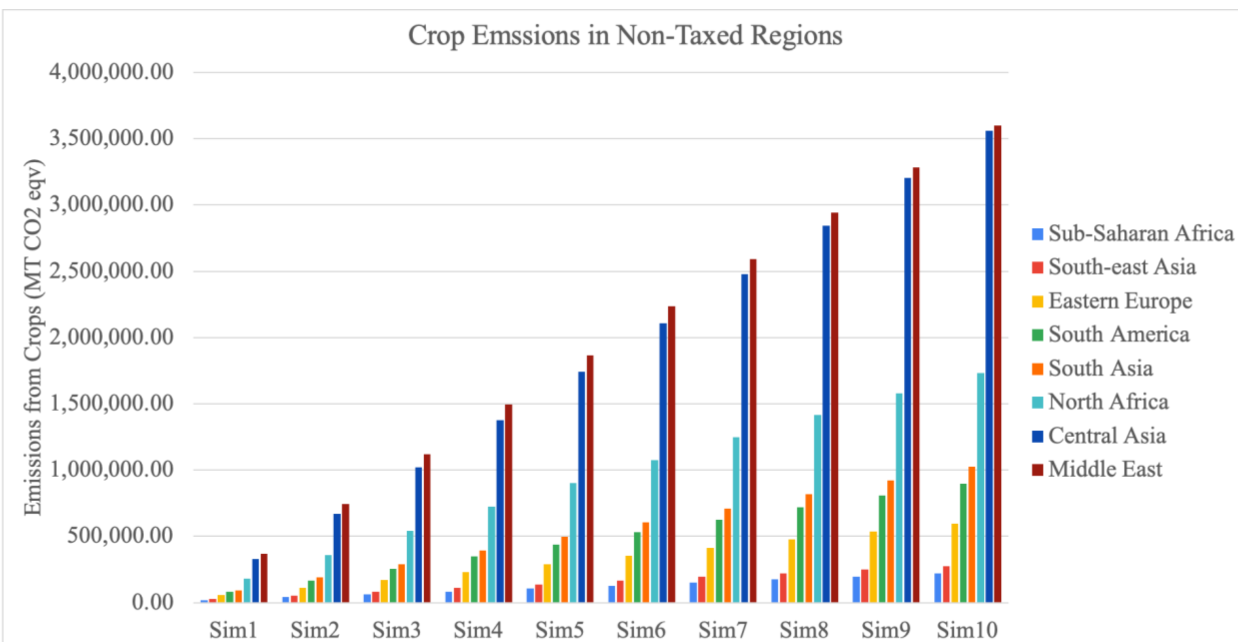

Figure 5. Change in Emissions from Crops across low- and middle-income regions including sub-Saharan Africa, South Asia, South America, Central America, the Middle East, Central Asia, South-East Asia, North Africa, and Eastern Europe. Simulation 1 represents the lowest shock and carbon price while simulation 10 represents the highest shock and carbon price across high-income regions.

Unfortunately, the tax yielded negative effects for malnutrition (Figure 6 & Figure 7) and food security. The number of malnourished individuals increased in every region, with the most profound effect in the untaxed regions. Starting from the largest relative changes to malnutrition after the implementation of emissions pricing, malnutrition increased in Eastern Europe, North Africa, South-East Asia, Central Asia, the Middle East, Central America, South America, South Asia, and Sub-Saharan Africa.

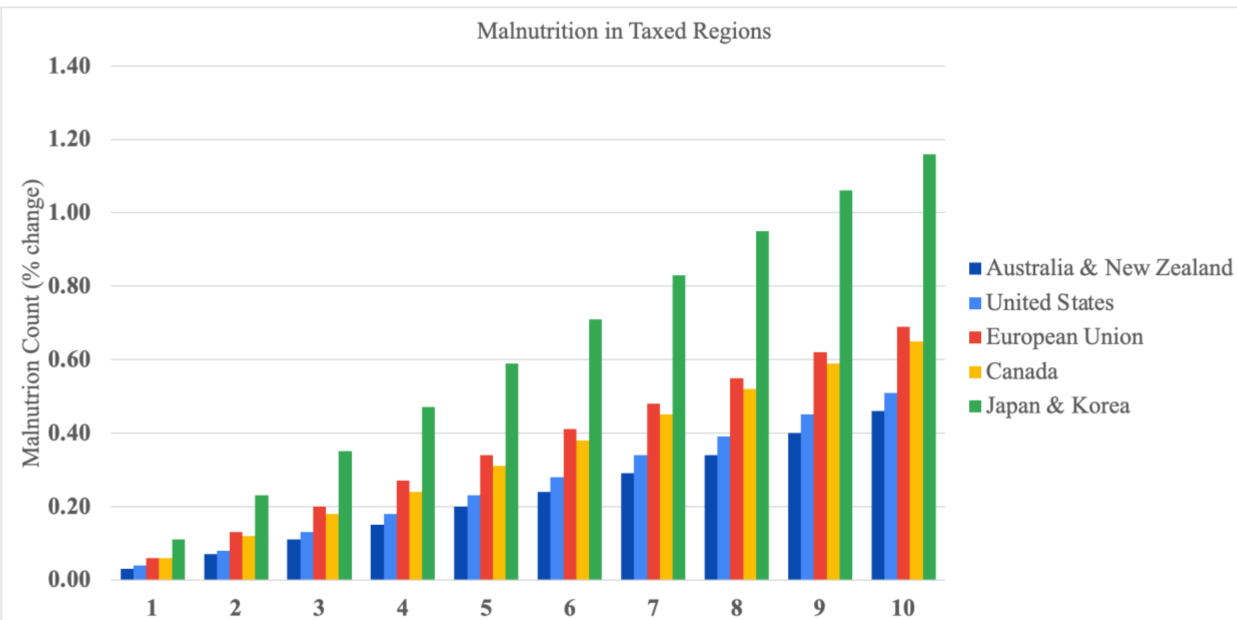

Figure 6. Percent change in Malnutrition Count across high income regions including the United States, Canada, Australia & New Zealand, Japan& Korea, and the EU. Simulation 1 represents the lowest shock and carbon price while simulation 10 represents the highest shock and carbon price across high-income regions

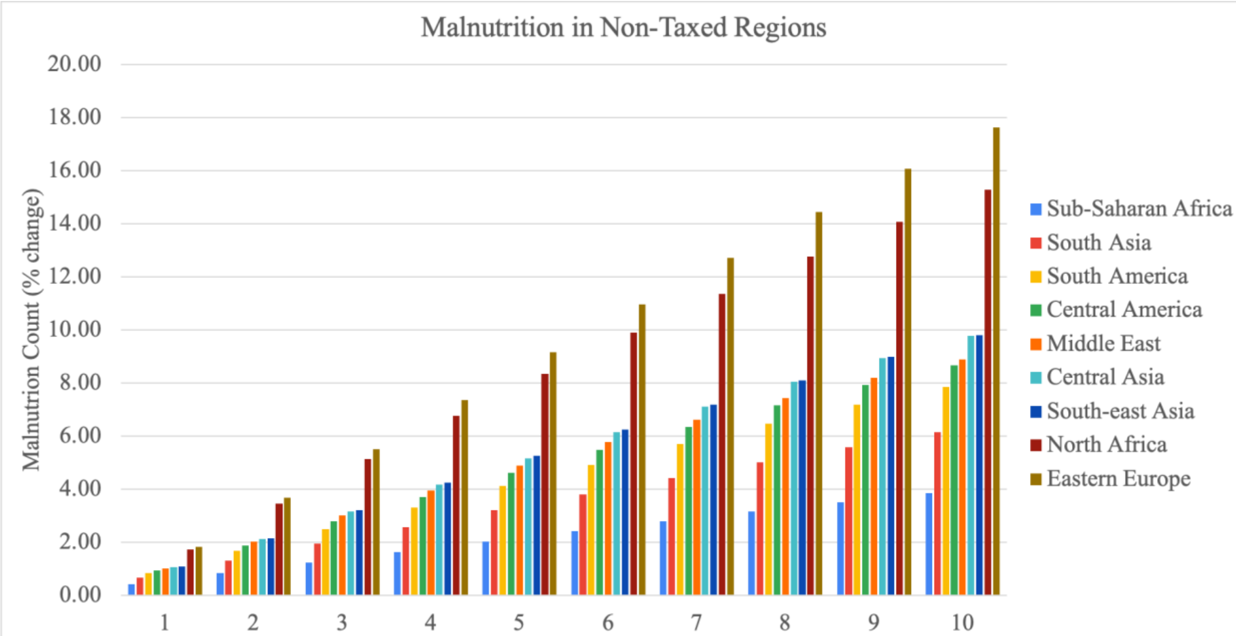

Figure 7. Percent change in Malnutrition Count across low- and middle-income regions including sub-Saharan Africa, South Asia, South America, Central America, the Middle East, Central Asia, South-East Asia, North Africa, and Eastern Europe. Simulation 1 represents the lowest shock and carbon price while simulation 10 represents the highest shock and carbon price across high-income regions.

Discussion

My results reveal counterintuitive findings about the effects of a supply and demand side tax in rich countries on carbon emissions and food security. The purpose of the analytical model was to conceptually compare a demand-side and a supply-side tax on food products in high-income countries. I then used the SIMPLE model to test the efficacy of a supply side tax using empirical data. Using these methods, I find that a supply side tax is potentially less effective and more harmful for food security outcomes than a demand side tax.

The supply side tax had unexpected negative impacts on food security and carbon emissions. First, from the analytical model the results showed a negative effect on food security and an unambiguous effect on emissions. Since the supply-side tax is tied to production instead of consumption, rich country consumers simply import to circumvent the tax. As a result, production increases in the poor country while consumption decreases to 'fill the gap' caused by the producer tax in the rich country. In short, the analytical model highlights the negative and unambiguous effect of a supply side tax. In the SIMPLE model, total global emissions decreased, while food insecurity increased. Although the intended effects of lower global emissions was achieved, it is not an equitable distribution. It ended up with the nations who had polluted the most through history, enjoying the least emissions and 'cleanest air' as production shifted to the more 'efficient' lower developed nations following the production efficiency shock in the SIMPLE model. Furthermore, the prevalence of malnutrition increased worldwide, directly worsening the quality of life. This effect was especially profound in the less-developed regions where I initially thought would have improved food security as a result of the tax.

In contrast, results from the demand-side tax had the intended results I initially hypothesized. First, the analytical model predicts that a demand-side tax will reduce consumption in rich countries while simultaneously increasing consumption in poor countries. Consequently, decreased demand leads to decreased food production in rich countries resulting in lower emissions. Since rich countries' consumers are facing a demand tax no matter where the food product is sourced from, the quantity exported from poor to rich countries decreases while poor countries simultaneously benefit from lower food prices. As a result, my study suggests that a demand-side tax is more effective for decreasing emissions from food production and eliminating negative effects on food insecurity as seen with the supply side tax. Thus, a demand side tax likely has positive implications for environmental justice and overall well-being in poor countries, who are home to some of the world's most vulnerable and disproportionately impacted individuals of climate change. However, the political feasibility of a demand side tax in high-income countries may be limited and thus, such benefits may be left unrealized without drastic social and cultural changes.

My results have proven to me that a supply-side tax is an ineffective food emission mitigation strategy. It would actually harm food security in lower developed regions which is not worth the slightly lower global emissions, especially considering the inequitable distribution of lowered emissions which in itself raises even more environmental justice concerns. In essence, the supply-side tax on carbon intensive foods is more harmful than helpful. This is also important from a theoretical perspective also, since pollution taxing on the supply and demand sides are equivalent without trade.

The change in the emissions sources across carbon prices for the supply side tax in the SIMPLE model was also interesting. After the first simulation, the emissions decreased in all the taxed areas (United States, Canada, the EU, Australia, New Zealand, Japan, and South Korea) yet increased everywhere else. This effect only became more pronounced as the carbon price increased through the simulations. This is clearly outlined when examining the emissions from simulation 1, 5, and 10 which show the emissions continuing to decrease in the taxed, higher income regions and continue to increase in the non-taxed, lower-income regions (Appendix B).

The order of severity of malnutrition increase was interesting and somewhat counterintuitive as well. In order of severity, malnutrition increased in Eastern Europe, North Africa, South-East Asia, Central Asia, the Middle East, Central America, South America, South Asia, and Sub-Saharan Africa'. I hypothesized that Sub-Saharan Africa would have been the worst off and Eastern Europe would have been the best off, based on their relative incomes. However, this result illustrates subtleties caused by trade and the integration of the different markets that future studies could explore further. A notable difference between the SIMPLE model and the analytical model is that the SIMPLE model assumes partially integrated markets while the analytical model assumes perfectly integrated markets.

Based on my results, my policy recommendation is to implement a carbon tax in rich countries on the demand side, which requires ensuring that imports are tariffed commensurately to ensure that the tax cannot be avoided by consumers. These tariffs are a form of border adjustments designed to reduce inefficiencies. Border adjustments prevent leakages such as shifts in location of adjustments (Kortum & Weisbach, 2017). Future research should explore additional ways to pursue environmental justice via proportional mitigation strategies, where rich and poor countries reduce their carbon footprint relative to their respective emissions. Such studies should explore ways to mitigate inequitable barriers to poor country development and security of necessities. Future research should consider the potential of increasing food security through productivity enhancements in poor countries, such as those that increase yield. Such enhancements could increase yield and potentially fill the gap caused by trade in response to a tax on producers and avoid the inequity. More research would be worthwhile into expanding productivity while hopefully limiting negative impacts of land use change and agriculture. It would also be worthwhile to explore the effects of decreasing agricultural subsidies instead of implementing a supply side tax in high-income regions, since such subsidies sometimes support otherwise unprofitable, unhealthy, and harmful production methods.

Conclusion

When considering the reality of climate change and food's contribution to emissions, food emissions must be mitigated. Food emissions include land use, agricultural production, the supply chain, and post-retail. Using a carbon tax on high income regions to reduce emissions while reducing food insecurity is a good idea in theory; however, the results from the analytical model and SIMPLE model had interesting results. The intended effect of a targeted carbon tax on higher income countries was to reduce global emissions while improving food security. This was the case for a demand side tax, but not a supply side tax. The difference between the two models I have used highlight the supremacy of a demand side tax over a supply side tax for such intended effects. Considering this, future research should continue looking into demand side carbon taxes as viable carbon emission mitigation strategies that do not endanger food security. Imposing the carbon tax on only high-income regions (such as the United States, Canada, Australia & New Zealand, Japan & Korea, and the EU) on the demand side had positive implications for both emissions and food security.

Resources

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Appendix A: Mathematical Supply and Demand Model, Mathematica Code and Output

Before shock

Equations before shock:

In[1]:=
```
Qdr = adr - bdr p + g; Qdp = adp - bdp p - g; Qsr = asr + bsr p; Qsp = asp + bsp p;
```

Equilibrium before shock:

In[2]:=
```
equilibriumbefore = Flatten[Solve[{Qdr == Qsr, Qdp == Qsp}, {p, g}]] // Simplify
Print["Quantity in rich country"]
QuantityRichBefore = Qdr /. equilibriumbefore // Simplify
Print["Quantity in poor country"]
QuantityPoorBefore = Qdp /. equilibriumbefore // Simplify
```

Out[2]= $\left\{p \to \frac{adp + adr - asp - asr}{bdp + bdr + bsp + bsr},\ g \to \frac{-adr\ (bdp + bsp) + asr\ (bdp + bsp) + (adp - asp)\ (bdr + bsr)}{bdp + bdr + bsp + bsr}\right\}$

Quantity in rich country

Out[4]= $\frac{asr\ (bdp + bdr + bsp) + (adp + adr - asp)\ bsr}{bdp + bdr + bsp + bsr}$

Quantity in poor country

Out[6]= $\frac{(adp + adr - asr)\ bsp + asp\ (bdp + bdr + bsr)}{bdp + bdr + bsp + bsr}$

Supply shock

Equations after supply shock, t:

In[7]:=
```
Qsrshocked = asr + bsr (p - t);
```

Equilibrium after supply shock:

In[8]:=
```
equilibriumaftersupply =
  Flatten[Solve[{Qdr == Qsrshocked, Qdp == Qsp}, {p, g}]] // Simplify
Print["Quantity in rich country"]
QuantityRichAfterSupply = Qdr /. equilibriumaftersupply // Simplify
Print["Quantity in poor country"]
QuantityPoorAfterSupply = Qdp /. equilibriumaftersupply // Simplify
```

Out[8]= $\left\{p \to \frac{\text{adp} + \text{adr} - \text{asp} - \text{asr} + \text{bsr t}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}},\ g \to -\left(\left(-\text{adp bdr} + \text{asp bdr} + \text{adr}\ (\text{bdp} + \text{bsp}) - \text{asr}\ (\text{bdp} + \text{bsp}) - \text{adp bsr} + \text{asp bsr} + \text{bdp bsr t} + \text{bsp bsr t}\right) / (\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr})\right)\right\}$

Quantity in rich country

Out[10]= $\left(\text{asr}\ (\text{bdp} + \text{bdr} + \text{bsp}) + \text{bsr}\ (\text{adp} + \text{adr} - \text{asp} - \text{bdp t} - \text{bdr t} - \text{bsp t})\right) / (\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr})$

Quantity in poor country

Out[12]= $\frac{\text{asp}\ (\text{bdp} + \text{bdr} + \text{bsr}) + \text{bsp}\ (\text{adp} + \text{adr} - \text{asr} + \text{bsr t})}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$

Rich country comparison:

Quantity produced:

In[13]:=
```
(QuantityRichAfterSupply - QuantityRichBefore) // Simplify
```

Out[13]= $-\frac{(\text{bdp} + \text{bdr} + \text{bsp})\ \text{bsr t}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$

Domestic supply:

In[14]:=
```
(((adr - bdr p) /. equilibriumaftersupply) - ((adr - bdr p) /. equilibriumbefore)) //
  Simplify
```

Out[14]= $-\frac{\text{bdr bsr t}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$

Price:

In[15]:=
```
((p /. equilibriumaftersupply) - (p /. equilibriumbefore)) // Simplify
```

Out[15]= $\frac{\text{bsr t}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$

Poor country comparison:

Quantity produced:

In[16]:=
```
(QuantityPoorAfterSupply - QuantityPoorBefore) // Simplify
```

Out[16]= $\frac{\text{bsp bsr t}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$

Domestic supply:

In[17]:=
```
(((adp - bdp p) /. equilibriumaftersupply) - ((adp - bdp p) /. equilibriumbefore)) //
 Simplify
```

Out[17]= $-\frac{\text{bdp bsr t}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$

Total Quantity:

In[18]:=
```
(QuantityRichAfterSupply + QuantityPoorAfterSupply -
   QuantityRichBefore - QuantityPoorBefore) // Simplify
```

Out[18]= $-\frac{(\text{bdp} + \text{bdr})\ \text{bsr t}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$

Demand shock

Equations after demand shock, t:

In[19]:=
```
Qdrshocked = adr - bdr (p + t) + g;
```

Before quantities, expressed as supply Qs:

In[20]:=
```
QuantityRichBeforeS = Qsr /. equilibriumbefore // Simplify
QuantityPoorBeforeS = Qsp /. equilibriumbefore // Simplify
```

Out[20]= $\text{asr} + \frac{(\text{adp} + \text{adr} - \text{asp} - \text{asr})\ \text{bsr}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$

Out[21]= $\text{asp} + \frac{(\text{adp} + \text{adr} - \text{asp} - \text{asr})\ \text{bsp}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$

Equilibrium after supply shock:

In[22]:=
```
equilibriumafterdemand =
  Flatten[Solve[{Qdrshocked == Qsr, Qdp == Qsp}, {p, g}]] // Simplify
Print["Quantity in rich country"]
QuantityRichAfterDemand = Qsr /. equilibriumafterdemand // Simplify
Print["Quantity in poor country"]
QuantityPoorAfterDemand = Qsp /. equilibriumafterdemand // Simplify
```

Out[22]=
$$\left\{p \to \frac{\text{adp} + \text{adr} - \text{asp} - \text{asr} - \text{bdr}\ t}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}},\ g \to \frac{1}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}} \left(\text{adp bdr} - \text{asp bdr} - \text{adr} \left(\text{bdp} + \text{bsp}\right) + \text{asr} \left(\text{bdp} + \text{bsp}\right) + \text{adp bsr} - \text{asp bsr} + \text{bdp bdr}\ t + \text{bdr bsp}\ t\right)\right\}$$

Quantity in rich country

Out[24]=
$$\text{asr} - \frac{\text{bsr} \left(-\text{adp} - \text{adr} + \text{asp} + \text{asr} + \text{bdr}\ t\right)}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$$

Quantity in poor country

Out[26]=
$$\text{asp} - \frac{\text{bsp} \left(-\text{adp} - \text{adr} + \text{asp} + \text{asr} + \text{bdr}\ t\right)}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$$

Rich country comparison:

Quantity produced:

In[27]:=
```
(QuantityRichAfterDemand - QuantityRichBeforeS) // Simplify
```

Out[27]=
$$-\frac{\text{bdr bsr}\ t}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$$

Domestic supply:

In[29]:=
```
(((adr - bdr (p + t)) /. equilibriumafterdemand) -
    ((adr - bdr p) /. equilibriumbefore)) // Simplify
```

Out[29]=
$$-\frac{\text{bdr} \left(\text{bdp} + \text{bsp} + \text{bsr}\right) t}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$$

Price:

In[31]:=
```
((p /. equilibriumafterdemand) - (p /. equilibriumbefore)) // Simplify
```

Out[31]=
$$-\frac{\text{bdr}\ t}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$$

Poor country comparison:

Quantity produced:

In[34]:=
```
(QuantityPoorAfterDemand - QuantityPoorBeforeS) // Simplify
```

Out[34]=
$$-\frac{\text{bdr bsp t}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$$

Domestic supply:

In[35]:=
```
(((adp - bdp p) /. equilibriumafterdemand) - ((adp - bdp p) /. equilibriumbefore)) //
 Simplify
```

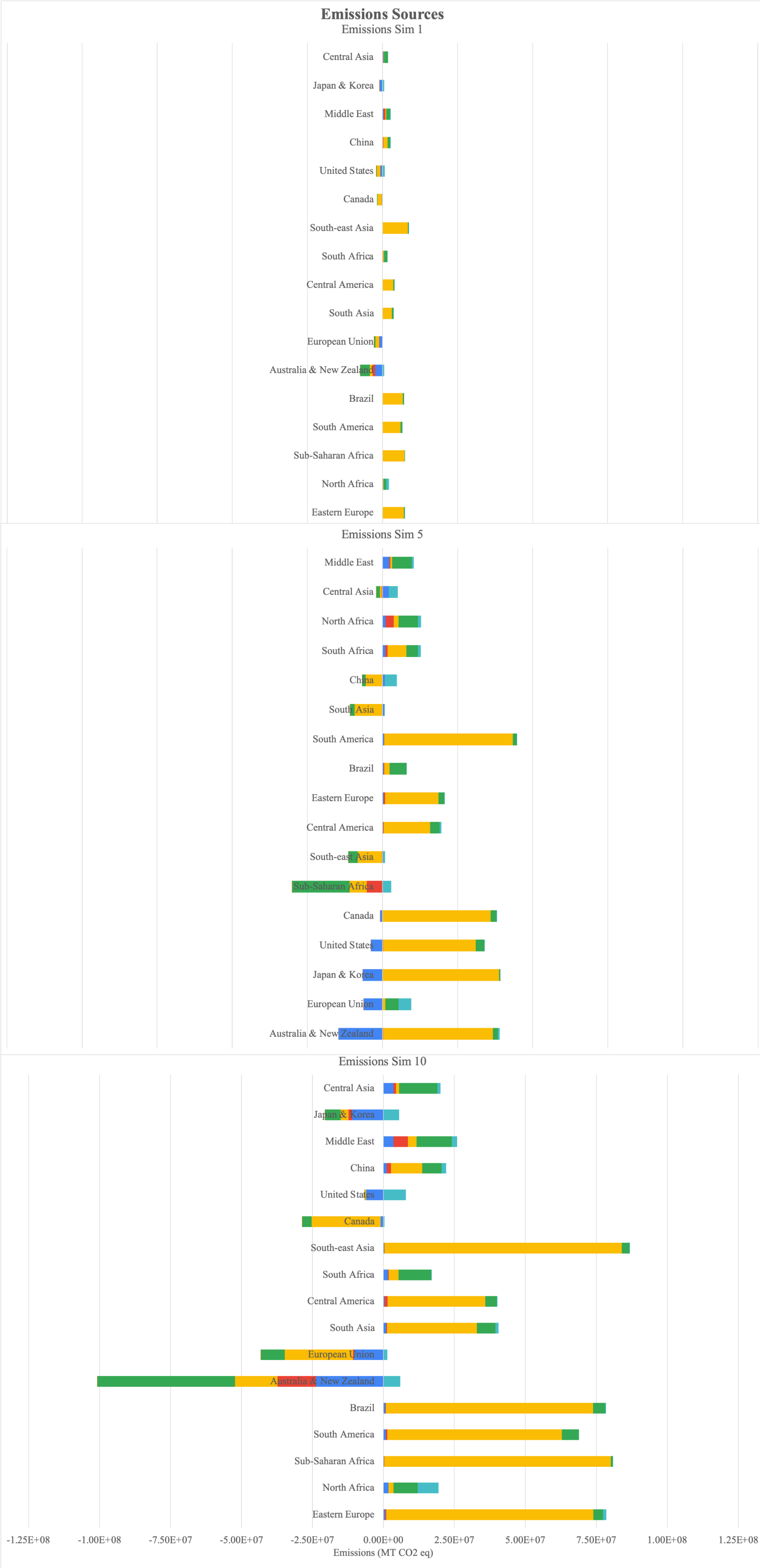
Out[35]=
$$\frac{\text{bdp bdr t}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$$

Total Quantity:

In[36]:=
```
(QuantityRichAfterDemand + QuantityPoorAfterDemand -
   QuantityRichBefore - QuantityPoorBefore) // Simplify
```

Out[36]=
$$-\frac{\text{bdr } (\text{bsp} + \text{bsr}) \text{ t}}{\text{bdp} + \text{bdr} + \text{bsp} + \text{bsr}}$$

Appendix B



Emissions Sources
Emissions Sim 1
Central Asia
Japan & Korea
Middle East
China
United States
Canada
South-east Asia
South Africa
Central America
South Asia
European Union
Australia & New Zealand
Brazil
South America
Sub-Saharan Africa
North Africa
Eastern Europe
Emissions Sim 5
Middle East
Central Asia
North Africa
South Africa
China
South Asia
South America
Brazil
Eastern Europe
Central America
South-east Asia
Sub-Saharan Africa
Canada
United States
Japan & Korea
European Union
Australia & New Zealand
Emissions Sim 10
Central Asia
Japan & Korea
Middle East
China
United States
Canada
South-east Asia
South Africa
Central America
South Asia
European Union
Australia & New Zealand
Brazil
South America
Sub-Saharan Africa
North Africa
Eastern Europe
-1.25E+08
-1.00E+08
-7.50E+07
-5.00E+07
-2.50E+07
0.00E+00
2.50E+07
5.00E+07
7.50E+07
1.00E+08
1.25E+08
Emissions (MT CO2 eq)
Crops
Crop land
Land use change
Nonland
Livestock
Nonfeed