Agriculture, Relative Price, and Climate Policy

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Abstract: I build a North-South Integrated Assessment Model (IAM) with an agriculture and non-agriculture sector, international trade, and Stone-Geary utility preference. The household preferences feature a subsistence consumption level for agricultural goods. Because the South/agriculture is more exposed to climate change, the relative price of agricultural goods will rise globally. The enumerative method, commonly used by the literature and based on fixed prices, cannot accurately capture the welfare implications of these price changes. By comparison, the less-developed, agriculture-importing South's climate-driven utility loss in terms of equivalent consumption, indicated by the price-adjusted integrated approach proposed by this paper, is 43% higher than that given by the enumerative approach, and the more-developed, agriculture-exporting North's loss is 92% lower. If the policymaker considers these relative price effects, a utilitarian world government would increase the magnitudes of the carbon abatement levels. However, under the Non-Cooperative Nash Equilibrium scenario, the North, facing lesser climate impacts, increases its emission levels.

Keywords: Climate Policy, Climate Change, Trade, Agriculture,

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I. Introduction

Even though agriculture only contributes around 4% of world GDP, its main product, food, is essential for human survival. Meanwhile, the agricultural sector is most exposed to climate change, with developing countries facing heightened vulnerability.[1] Therefore, climate change is expected to drive up the relative price of food worldwide by lowering agricultural productivity and changing consumer behavior and trade patterns among regions. Understanding the magnitudes and scale of these climate-induced relative-price changes and accounting for their welfare effects is essential to accurately assess the aggregate impacts of climate change on economies and design mitigation or adaptation policies that can appropriately alleviate its damage to human welfare. Yet, these price changes are usually ignored in Integrated Assessment Models.

In this paper, I build a North-South Integrated Assessment Model (IAM) with heterogeneous population dynamics and labor productivities in two regions. The household preferences are defined over final agricultural and non-agricultural goods. A non-homothetic subsistence level exists for the households' agricultural consumption (Stone-Geary). Such a setting highlights the importance of the agriculture sector and explains the high agricultural share of consumption in low-income countries. On the production side, a perfectly competitive firm in each sector in each region uses labor to produce intermediate goods. These firms' productivities are affected by climate damage and the costs of mitigation. First, the production activities of intermediate firms generate carbon emissions, which warm the planet and depress firms' productivity. The extent of these climate change impacts varies by region and sector. Meanwhile, these firms can reduce emissions by paying mitigation costs. Policymakers, whether operating on a global or local scale, can potentially set carbon emission abatement rates for firms to correct the negative externality brought on by carbon emissions and improve the intertemporal welfare of the household.

Building on the extension to the utility change decomposition technique by Tombe (2015), I demonstrate that utility changes caused by climate change can be decomposed into the physical

[1] See Dellink and Chateau (2019), Nath (2022)

effect driven by changes in production quantities and the relative price effect driven by changes in relative prices. The relative price effects can be further decomposed into the price income effect, the domestic price effect, the terms-of-trade effect, and the subsistence effect. A simulation of three centuries under a Business-as-Usual scenario shows significant relative price effects. In 2090, The relative price effects reduce the South utility by 2.23% since the less-developed South will need to pay more to maintain its food subsistence needs. In contrast, the North sees a 2.92% price-driven utility gain as increased prices for agricultural products lead to a rise in the North's nominal income and improve its terms-of-trade. In fact, climate change benefits the North in certain periods. Therefore, accounting for the relative price effects is essential for setting the socially optimal carbon abatement targets.

In contrast, previous research on climate impacts and optimal climate policies usually implements the "enumerative" approach (Tol 2009) and focuses solely on the physical impacts of climate change. These start by assuming that the relative values of goods in a counterfactual world without climate change can be accurately extrapolated to a world with climate damage. They then collect damage estimates from different studies and aggregate them based on their pre-damage market value. The enumerative approach further allows the researchers to formulate their models in a one-commodity neoclassical growth setting because, to aggregate several commodities, like agriculture goods and non-agriculture goods, into a one single notional commodity, the prices of the commodities have to be fixed. In this paper, I highlight the errors in these extrapolations and emphasize the importance of accounting for the relative price changes. Throughout this paper, I will use the "fixed-price enumerative method" to refer to the traditional loss inference approach and the "price-adjusted integrated method" to describe the utility loss inference that considers relative price effects.

The different damage estimates of the fixed-price enumerative method and the price-adjusted integrated method have important policy implications as they largely determine the policymaker's optimal levels of mitigation and adaptation efforts. This study calculates climate policies crafted by policymakers, such as world or regional governments, who acknowledge the welfare implications of climate-induced relative price shifts. This is done using a price-adjusted integrated approach. The carbon abatement targets determined through this method are then contrasted with those set by policymakers who employ the fixed-price enumerative method. This contrasts between optimal climate policies set by an "informed" and "uninformed" policymaker. The paper first studies the optimal carbon abatement levels under a utilitarian world government. Given the more populous South's amplified loss after accounting for the relative price effects, the planner would have increased the magnitude of carbon abatement levels in both the North and the South by about 209% and 21%, respectively, in 2015. A world government with a utility function that justifies the pre-climate-change North-South inequality would have increased the abatement levels, too. I then explore the Uncooperative Nash Equilibrium, where two regions determine their own carbon abatement levels while taking each other's levels as given. Under such an equilibrium, unsurprisingly, the magnitude of North's carbon emission reduction level in 2015 would have been 68% lower. While this paper focuses on the climate-driven agricultural relative price change's implication for the mitigation policy, a companion paper coauthored by Chen, Kirabaeva, and the author (2023) studies the optimal climate adaption investment of the public sector, using the framework proposed by this paper.

This paper is built upon and contributes two strands of literature. This paper first contributes to the literature examining the interplay between climate change, trade, and agriculture, as explored in works by Desmet and Rossi-Hansberg (2015), Costinot et al. (2016), Baldos et al. (2019), Gouel and Laborde (2021), Conte et al. (2021), and Rudik et al. (2021). This literature, in general, focuses on the impact of climate change on the comparative advantages of regions and addresses the roles of trade and migration as an adaptation mechanism. Nath (2020) builds a Ricardian trade model, where extreme temperature influences workers' productivity. He finds that, because of the existence of subsistence levels, many developing countries fail to re-specialize in non-agriculture to adapt to climate change, even though it is optimal to do so from a comparative advantage perspective. Nevertheless, Nath (2020) uses an exogenous climate module and says little about the implications of the food problem for climate policy. By contrast, this paper specifically discusses how the existence of food subsistence level affects the climate policy and the endogenous climate path for the next 300 years.

This paper also contributes to the well-established literature on optimal climate policy, including works by Nordhaus (1991), Yang and Nordhaus (1997), Nordhaus and Boyer (2000), and Golosov et al. (2014). The DICE/RICE integrates a climate model into a standard Ramsey social planner growth model with homogenous consumption goods or GDP. The policymakers internalize that carbon emissions lead to damaging higher global temperatures in the future. They face an intertemporal trade-off, which is whether to reduce carbon emissions today by adapting to "greener" but more expensive production processes. Economists, scientists, and policymakers already express concerns that the oversight of climate-driven relative price (scarcity) changes, especially the price of food and environmental goods, can potentially lead to bias in the efficient carbon abatement levels suggested by Integrated Assessment Models. For example, Stern and Stiglitz (2021) suspect that radical relative price changes driven by climate change will severely affect households and firms. Sterner and Persson (2008) argue that the elimination of global agricultural production would inevitably lead to a complete GDP loss, despite agriculture's current low contribution to GDP, as escalating food prices would cause agriculture's GDP share to approach 100%. They further criticize the IAMs' reliance on the assumption of perfect substitutability between impacted and impacted goods. National Academy of Sciences (2017) worries that climate policy models ignore the general equilibrium effects of "food storages." In response, there is a growing body of literature on the implication of relative price for climate policy. Many of these studies emphasize that climate change will significantly increase the relative scarcity of environmental, nonmarket goods (Heal and Sterner 2007; Drupp and Hansel 2021; etc.). Dietz and Lanz (2019) contribute to this discussion by developing a structural model with subsistence agriculture to investigate food demand under climate change and its policy implications. However, they do not address regional heterogeneity, as done in this paper.

II. The Economy

This section lays out the model structure and equilibrium conditions. Following the terminology of the trade literature, I will refer to the North and the South as separate countries, denoted by

$i \in \{1,2\}$ respectively. The North is a cold, developed country, and the South is a hot, developing country.

Households

Each country i is populated by a household of size $L_{i,t}$. Households' welfare is defined as an intertemporal population-weighted isoelastic utility function over utility $U_{i,t}$ over a finite time horizon T with discount factor β and elasticity of intertemporal substitution α:

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

In the model, each period t is five years. There is no capital or saving in the model. The households do not internalize the impacts of their decisions on climate. Therefore, even though the household wants to maximize the intertemporal welfare, its optimization problem reduces to a sequence of static problems to maximize utilities for each period. I use the Stone-Geary utility function over per-capita agricultural consumption $c_{i,A,t}$ and non-agricultural consumption $c_{i,N,t}$, where a subsistence level $\bar{a}$ exists for agricultural consumption. The households supply labor inelastically to the intermediate goods firms and earn wages $w_{i,t}$. Given final sectoral consumption price indexes $P_{i,A,t}$ and $P_{i,N,t}$, and wage $w_{i,t}$, the household in country i solves a sequence of static maximization problems

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

subject to income budget constraint

$$c_{i,A,t} P_{i,A,t} + c_{i,N,t} P_{i,N,t} = w_{i,t}.$$

The FOCs of the optimization problem give us the following equation:

$$\frac{\omega (c_{i,A,t} - \bar{a})^{-1}}{(1-\omega) c_{i,N,t}^{-1}} = \frac{P_{i,A,t}}{P_{i,N,t}}.$$

The population in each country is exogenously given by the population dynamics equation $L_{i,t} = L_{i,t-1} \left(\frac{L_i^{\infty}}{L_{i,t-1}} \right)^{\delta_i^L}$ and initial population $L_{i,0}$. Here L_i^{∞} denotes the asymptotic population in each country, and δ_i^L regulates the rate at which the current population converges to L_i^{∞}. The population dynamic here states that the population in each country is converging to L_i^∞ at rate δ_i^L.

Final Goods and International Trade

International trade is based on the Armington assumption. The intermediate goods produced by each country in each sector are differentiated. Each country imports and exports both agricultural and non-agricultural intermediate goods. In each sector, a perfectly competitive final goods producer purchases distinct intermediate goods from both countries to produce final consumption goods.

Let $Y_{i,j,k,t}$ be the intermediate goods in sector k shipped from country j to country i, $\tau_{i,j,k}$ be the iceberg cost to ship the intermediate goods from country j to country i. Given the final sectoral consumption price $P_{i,A,t}$ and $P_{i,N,t}$, and intermediate goods price $p_{1,A,t}, p_{1,N,t}, p_{2,A,t}$, and $p_{2,N,t}$, the final agricultural firm solves the profit maximization problem

$$\max_{Y_{i,i,A,t},Y_{i,j,A,t}} P_{i,A,t}L_{i,t}c_{i,A,t} - Y_{i,i,A,t}p_{i,A,t} - Y_{i,j,A,t}\tau_{i,j,A}p_{j,A,t}$$

subject to

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

while the final non-agricultural firm solves the maximization problem

$$\max_{Y_{i,i,N,t},Y_{i,j,N,t}} P_{i,A,t}L_{i,t}c_{i,N,t} - Y_{i,i,A,t}p_{i,A,t} - Y_{i,j,N,t}\tau_{i,j,N}p_{j,N,t}$$

subject to

$$L_{i,t}c_{i,N,t} = \left(Y_{i,i,N,t}^{\frac{\sigma_N-1}{\sigma_N}} + Y_{i,j,N,t}^{\frac{\sigma_N-1}{\sigma_N}}\right)^{\frac{\sigma_N}{\sigma_N-1}}.$$

Profit maximization behaviors and zero-profit conditions yield demand functions for intermediate goods and price indices:

$$Y_{i,i,A,t} = \left(\frac{p_{i,A,t}}{P_{i,A,t}}\right)^{-\sigma_A} C_{i,A,t}$$

$$Y_{i,j,A,t} = \left(\frac{\tau_{i,j,A}p_{j,A,t}}{P_{i,A,t}}\right)^{-\sigma_A} C_{i,A,t}$$

$$P_{i,A,t} = \left(p_{i,A,t}^{1-\sigma_A} + (\tau_{i,j,N} p_{j,A,t})^{1-\sigma_A}\right)^{\frac{1}{1-\sigma_A}}$$

$$Y_{i,i,N,t} = \left(\frac{p_{i,N,t}}{P_{i,A,t}}\right)^{-\sigma_N} C_{i,N,t}$$

$$Y_{i,j,N,t} = \left(\frac{\tau_{i,j,N} p_{j,N,t}}{P_{i,N,t}}\right)^{-\sigma_N} C_{i,N,t}$$

$$P_{i,N,t} = \left(p_{i,N,t}^{1-\sigma_N} + (\tau_{i,j,N} p_{j,A,t})^{1-\sigma_N}\right)^{\frac{1}{1-\sigma_N}}$$

Intermediate Goods

Perfectly competitive intermediate goods firms hire labor to produce intermediate goods and sell the products in both the domestic and foreign markets. Their labor productivities $MLP_{i,k,t}$ is a function of exogenously given pre-damage productivity $B_{i,k,t}$ as well as sector-specific climate damage $\Omega_{i,k,t}$, which both are functions of *global temperature* H_t:

$$MLP_{i,k,t} = \mathrm{B}_{i,k,t} \Omega_{i,k,t},$$

where

$$\Omega_{i,k,t} = \frac{1}{1 + a_{i,k} H_t^2}.$$

All firms in country i follow the country-specific mitigation policy, $\mu_{i,t}$, to reduce its carbon emission level $\mu_{i,t}$ at the cost of $\left(1 - \theta_{i,t} \mu_{i,t}^{\theta_2}\right)$ ($\theta_{i,t} > 0$ and $\theta_2 > 1$) of total intermediate goods. Mitigation cost $\theta_{i,t} \mu_{i,t}^{\theta_2}$ is a convex function and monotonically increasing in $\mu_{i,t}$. Over time, $\theta_{i,t}$ decreases to reflect the fact that green technology becomes relatively cheaper. Depending on the specific policy scenarios, the mitigation rate $\mu_{i,t}$ can either be exogenously given or endogenously set by a world or national country government, and the intermediate firms take them as given. **Section VI** discusses these policy scenarios. The mitigation policies $\mu_{i,t}$ can differ across countries but not agriculture and non-agriculture sectors. The assumption that mitigation rates are equal across sectors ensures that carbon abatement efforts do not affect the relative price of intermediate goods. Given the intermediate goods price $p_{i,k,t}$, unit labor productivity $MLP_{i,k,t}$ and wage $w_{i,t}$, the firm solves the optimization problem:

$$\max_{L_{i,k,t}} (Y_{i,i,k,t} + \tau_{i,j,k} Y_{i,j,k,t}) p_{i,k,t} - L_{i,k,t} w_{i,t}$$

subject to

$$(Y_{i,i,k,t} + \tau_{i,j,k} Y_{i,j,k,t}) = \left(1 - \theta_{1,t} \mu_{i,t}^{\theta_2}\right) MLP_{i,k,t} L_{i,k,t}$$

The FOCs, labor market clearing, and goods market-clearing conditions yield the equilibrium condition:

$$\frac{\mathrm{B}_{i,N,t}\Omega_{i,N,t}}{\mathrm{B}_{i,A,t}\Omega_{i,A,t}} Y_{i,i,A,t} + \tau_{j,i,A} \frac{\mathrm{B}_{i,N,t}\Omega_{i,N,t}}{\mathrm{B}_{i,A,t}\Omega_{i,A,t}} Y_{i,i,A,t} + Y_{i,i,N,t} + \tau_{j,i,N} Y_{i,i,N,t}$$
$$= \left(1 - \theta_{1,t} \mu_i^{\theta_2}\right) \mathrm{B}_{i,N,t} \Omega_{i,N,t} L_{i,t}$$

and

$$\frac{p_{i,A,t}}{p_{i,N,t}} = \frac{\mathrm{B}_{i,N,t}\Omega_{i,N,t}}{\mathrm{B}_{i,A,t}\Omega_{i,A,t}}.$$

The Static Equilibrium

A static market equilibrium at time t is defined by the set of endogenous variables in two countries $c_{1,A,t}, c_{1,N,t}, Y_{1,1,A,t}, Y_{2,1,A,t}, Y_{1,1,N,t}, Y_{2,1,N,t}, p_{1,N,t}, p_{1,A,t}, c_{2,A,t}, c_{2,N,t}, Y_{2,2,A,t}, Y_{1,2,A,t}, Y_{2,2,N,t}, Y_{1,2,N,t}, p_{2,N,t}$, $p_{2,A,t}$ that satisfy

$$\frac{\omega(c_{i,A,t} - \bar{a})^{-1}}{(1-\omega)c_{i,N,t}^{-1}} \frac{\left(Y_{i,i,N,t}^{\frac{\sigma_N - 1}{\sigma_N}} + Y_{i,j,N,t}^{\frac{\sigma_N - 1}{\sigma_N}}\right)^{\frac{1}{\sigma_N - 1}} Y_{i,i,N,t}^{\frac{-1}{\sigma_N}}}{\left(Y_{i,i,A,t}^{\frac{\sigma_A - 1}{\sigma_A}} + Y_{i,j,A,t}^{\frac{\sigma_A - 1}{\sigma_A}}\right)^{\frac{1}{\sigma_A - 1}} Y_{i,i,A,t}^{\frac{-1}{\sigma_A}}} = \frac{p_{i,A,t}}{p_{i,N,t}} \tag{1}$$

$$\frac{Y_{i,i,A,t}^{\frac{-1}{\sigma_A}}}{Y_{i,j,A,t}^{\frac{-1}{\sigma_A}}} = \frac{p_{i,A,t}}{p_{j,A,t}\tau_{j,A,t}} \tag{2}$$

$$L_{i,t} c_{i,A,t} = \left(Y_{i,i,A,t}^{\frac{\sigma_A - 1}{\sigma_A}} + Y_{i,j,A,t}^{\frac{\sigma_A - 1}{\sigma_A}}\right)^{\frac{\sigma_A}{\sigma_A - 1}} \tag{3}$$

$$\frac{Y_{i,i,N,t}^{\frac{-1}{\sigma_N}}}{Y_{i,j,N,t}^{\frac{-1}{\sigma_N}}} = \frac{p_{i,N,t}}{p_{j,N,t}\tau_{j,N,t}} \tag{4}$$

$$L_{i,t} c_{i,N,t} = \left(Y_{i,i,N,t}^{\frac{\sigma_N - 1}{\sigma_N}} + Y_{i,j,N,t}^{\frac{\sigma_N - 1}{\sigma_N}}\right)^{\frac{\sigma_N}{\sigma_N - 1}} \tag{5}$$

$$\frac{p_{1,A,t}}{p_{1,N,t}} = \frac{B_{i,N,t}\frac{1}{1+a_{i,N,t}H_t^2}}{B_{i,A,t}\frac{1}{1+a_{i,A,t}H_t^2}} \tag{6}$$

$$\begin{aligned} &\frac{B_{i,N,t}}{B_{i,A,t}\frac{1}{1+a_{i,A,t}H_t^2}} Y_{i,i,A,t} + \tau_{j,i,A}\frac{B_{i,N,t}}{B_{i,A,t}\frac{1}{1+a_{i,A,t}H_t^2}} Y_{i,i,N,t} + Y_{j,i,N,t} + \pi_{j,i,N} Y_{j,i,N,t} \\ &= \left(1-\theta_{1,t}\mu_i^{\theta_2}\right) B_{i,N,t}\frac{1}{1+a_{i,N,t}H_t^2} L_{i,t} \end{aligned} \tag{7}$$

$$Y_{2,1,A,t}p_{1,A,t}\tau_{2,A,t} + Y_{2,1,N,t}p_{1,N,t}\tau_{2,N,t} = Y_{1,2,A,t}p_{2,A,t}\tau_{1,A,t} + Y_{1,2,N,t}p_{2,N,t}\tau_{1,N,t} \tag{8}$$

Equation (1) shows the relative demand for domestic agricultural and non-agricultural products, respectively in country i. Equations (2) and (4) are the relative demand functions for domestic goods and foreign in each sector. Equations (3) and (5) are the production functions of the final goods packers. Equation (6) pins down the relative price of intermediate goods in each country. Equation (7) is the country-specific aggregate production function, and Equation (8) is the trade balance condition inferred directly from the household's budget constraint.

Climate Module

Intermediate goods production emits carbon into the atmosphere. Country's emission levels, $E_{i,t}$ are

$$E_{i,t} = (1-\mu_{i,t})\sigma_t^E \mathrm{B}_{i,N,t} L_{i,t}.$$

Since σ_t^E, $B_{i,N,t}$ and $L_{i,t}$ are exogenously given, the unmitigated emission $E_{i,t}^0 \equiv \sigma_t^E \mathrm{B}_{i,N,t} L_{i,t}$ is pre-determined. Total carbon emission at time t is the sum of emissions generated by both countries:

$$E_t = (1-\mu_{1,t})\sigma_t^E \mathrm{B}_{1,N,t} L_{1,t} + (1-\mu_{2,t})\sigma_t^E \mathrm{B}_{2,N,t} L_{2,t} \tag{9}$$

Ikefuji et al. (2019) proposes a simple climate system to describe the relation between carbon emission and temperature: the movement of total carbon stock M_t in the atmosphere is given by

$$M_{t+1} = \phi_1 M_t + E_t. \tag{10}$$

$0 < \phi_1 < 1$ because the ocean gradually absorbs carbon from the atmosphere.

The degree of global warming dynamics takes the form:

$$H_{t+1} = \eta_0 + \eta_1 H_t + \eta_2 \log(M_{t+1}). \tag{11}$$

In a nutshell, this climate module is calibrated to match the climate prediction model used by scientists.

III. Climate-Induced Utility Change versus the Enumerative Method

In this section, I first discuss how to decompose the relative utility change induced by climate change in the model. Then, I briefly discuss the fixed-price enumerative method and explain why this approach only partially captures the relative utility change. Time index t are omitted for notation convenience.

The Decomposition of Relative Utility Change

Using the techniques proposed by Tombe(2016), a household's utility between two scenarios, X and X', be exactly decomposed into

$$\begin{aligned}\frac{U_i'}{U_i} = & \underbrace{\frac{p_{i,A}Y'_{i,A} + p_{i,N}Y'_{i,N}}{p_{i,A}Y_{i,A} + p_{i,N}Y_{i,N}}}_{Production\ Income\ Effect} \times \underbrace{\frac{p'_{i,A}Y'_{i,A} + p'_{i,N}Y'_{i,N}}{p_{i,A}Y'_{i,A} + p_{i,N}Y'_{i,N}}}_{Price\ Income\ Effect} \\ & \times \underbrace{\left(1 - \frac{\bar{a}P'_{i,A}}{p'_{i,A}Y'_{i,A} + p'_{i,N}Y'_{i,N}}\right) \Big/ \left(1 - \frac{\bar{a}P_{i,A}}{p_{i,A}Y_{i,A} + p_{i,N}Y_{i,N}}\right)}_{Subsistence\ Effect} \times \underbrace{\frac{p_{i,A}^{\omega} p_{i,N}^{1-\omega}}{{p'}_{i,A}^{\omega} {p'}_{i,N}^{1-\omega}}}_{Domestic\ Price\ Effect} \\ & \times \underbrace{\frac{\left[\left(1 + \left(\frac{\tau_{j,i,A}p'_{j,A}}{p'_{i,A}}\right)^{1-\sigma_A}\right)^{\frac{1}{1-\sigma_A}}\right]^{\omega} \left[\left(1 + \left(\frac{\tau_{j,i,N}p'_{j,N}}{p'_{i,N}}\right)^{1-\sigma_N}\right)^{\frac{1}{1-\sigma_N}}\right]^{1-\omega}}{\left[\left(1 + \left(\frac{\tau_{j,i,A}p_{j,A}}{p_{i,A}}\right)^{1-\sigma_A}\right)^{\frac{1}{1-\sigma_A}}\right]^{\omega} \left[\left(1 + \left(\frac{\tau_{j,i,N}p_{j,N}}{p_{i,N}}\right)^{1-\sigma_A}\right)^{\frac{1}{1-\sigma_N}}\right]^{1-\omega}}}_{Terms\ of\ Trade\ Effect}\end{aligned} \tag{12}$$

The first and second terms $\frac{p_{i,A}Y'_{i,A}+p_{i,N}Y'_{i,N}}{p_{i,A}Y_{i,A}+p_{i,N}Y_{i,N}}$ and $\frac{p'_{i,A}Y'_{i,A}+p'_{i,N}Y'_{i,N}}{p_{i,A}Y'_{i,A}+p_{i,N}Y'_{i,N}}$ capture the change in nominal income together: $\frac{p_{i,A}Y'_{i,A}+p_{i,N}Y'_{i,N}}{p_{i,A}Y_{i,A}+p_{i,N}Y_{i,N}}$ is the change in nominal income changes driven by production quantity changes while and $\frac{p'_{i,A}Y'_{i,A}+p'_{i,N}Y'_{i,N}}{p_{i,A}Y'_{i,A}+p_{i,N}Y'_{i,N}}$ is the change driven by domestic relative price changes. The third term $\frac{1-\frac{\bar{a}P'_{i,A}}{p'_{i,A}Y'_{i,A}+p'_{i,N}Y'_{i,N}}}{1-\frac{\bar{a}P_{i,A}}{p_{i,A}Y_{i,A}+p_{i,N}Y_{i,N}}}$ captures the effect of the subsistence term $\bar{a}$. Regardless of the relative price of final agricultural consumption, the household always needs to spend a $\frac{\bar{a}P_A}{p_{i,A}Y_{i,A}+p_{i,N}Y_{i,N}}$ share of the total income on food. Net of the non-homothetic effect of the changes captured by the subsistence effect, the minimal cost of obtain a unit of utility is given by the real price index $\left[(p_{i,A}+(\tau_{j,i,A}p_{j,A})^{1-\sigma_A})^{\frac{1}{1-\sigma_A}}\right]^{\omega}\left[(p_{i,N}+(\tau_{j,i,N}p_{j,N})^{1-\sigma_A})^{\frac{1}{1-\sigma_N}}\right]^{1-\omega}$. This price index of the utility is both determined by the domestic price $p_{i,k}$ and the after-shipping cost foreign price $\tau_{j,i,k}p_{j,k}$. We can further decompose the changes in real price into the changes in the domestic goods' prices and the changes in terms-of-trade: the fourth term of Equation (12) captures the effect of domestic relative price changes, and the last term captures the terms-of-trade effect. Among all the five effects, the production income effect is solely driven by changes in physical quantities of goods produced. Instead, the other four effects are induced by relative price and nominal income changes. So, we can categorize these five effects into two groups: the physical effect and the price effect.

The Fixed-Price Enumerative Method

Per Tol's survey article (2009), Fankhauser (1995) was the first to implement the (fixed-price) enumerative method to compute the potential damage caused by climate change. This method involves collecting the estimates of climate change's "physical effects" and then giving these impacts a price and adding them up. If one wants to compute utility loss from agricultural production loss, "…, agronomy papers are used to predict the effect of climate on crop yield, and then market prices or economic models are used to value the change in output."

In DICE/RICE-2000, Nordhaus and Boyer (2000) implement the (fixed-price) enumerative method and weight climate impacts in each influenced sector by sector and country-specific *impact indexes* they chose. Regarding the agriculture sector, they use "the share of agricultural output in GDP" as the impact index. That is, they assume if a country loses 30% of agricultural production and the GDP share of agriculture in this country is 10%, then this country is willing to sacrifice 3% of revenue to avoid climate-induced agricultural damages, or this country suffers 3% climate utility loss because of climate-induced agricultural production change. The last step is to sum all these weighted impacts into an aggregate damage function in a certain year.

Thus, following DICE/RICE-2000's methodology, the enumerative damage should be:

$$\begin{aligned} Damage\ Ratio_i &= \text{Agr GDP Share} * \frac{Y'_{i,A}}{Y_{i,A}} + \text{Non Agr GDP Share} * \frac{Y'_{i,N}}{Y_{i,N}} \\ &= \frac{P_{i,A}Y_{i,A}}{GDP_i}\frac{Y'_{i,A}}{Y_{i,A}} + \frac{P_{i,N}Y_{i,N}}{GDP_{i,t}}\frac{Y'_{i,N}}{Y_{i,N}}. \end{aligned}$$

where $GDP_i = P_{i,A}Y_{i,A} + P_{i,N}Y_{i,N}$.

First, if we plug the definition of GDP_i into the Equation, we have

$$Damage\ Ratio_{i,t} = \frac{p_{i,A}Y'_{i,A}+P_{i,N}Y'_{i,N}}{p_{i,A}Y_{i,A}+P_{i,N}Y_{i,A}}.$$

This is the Laspeyres index that is used to compute real GDP. In other words, the enumerative method computes the real GDP loss valued by pre-climate-damage prices. Relative prices after climate change are entirely missing here. So, the relative price changes are entirely omitted by the enumerative approach. [2]

[2] If climate-induced relative agricultural prices change in two scenarios are sufficiently small: $\frac{p'_{i,A}}{p'_{i,N}} \approx \frac{p_{i,A}}{p_{i,N}}$ and $\bar{a} \approx 0$, then by (12), all effects but production income effect are close to 1, and the relative utility changes collapse to the production nominal income effect $\frac{U'}{U} \approx \frac{p_A Y'_A + p_N Y'_N}{p_A Y_A + p_N Y_N}$.

IV . Calibration

Table 1 shows a list of the values and sources of each parameter. Intertemporal preference parameters α and the discounting factor β, and time-varying mitigation cost $\theta_{1,t}$ and θ_2 are taken from the latest DICE-2016R directly (Nordhaus 2017). The upper bound for $\mu_{i,t}$ is 1 from 2015 to 2150 and 1.2 after 2150. A $\mu_{i,t}$ higher than 1 implies negative net emissions, which can be achieved by carbon capture and storage technologies. A long-run agricultural expenditure share of 1%, or setting $\omega = 0.01$, is a standard value in the literature and is consistent with the trend in developed countries. The subsistence level is chosen to set the South agricultural employment share to be 0.39, which is middle- and low-income countries' 2015 agricultural employment share documented by World Development Indicator. For each country, asymptotic population L_i^{∞} and the rate at which the population converges δ_i^L are jointly calibrated to match the U.N. population projection in 2030 and 2050. I also set Armington elasticity θ_k and the iceberg cost $\tau_{i,j,k}$ to be consistent with the estimation of Tombe (2015).

Catastrophic damages and sea level risings in the United States and India at 2.5 ℃ degrees of warming in the DICE-2007 (Nordhaus, 2007) are used to calibrate North and South non-agricultural damages. The agricultural damage parameters are calibrated such that the North and South agricultural productivity loss match the U.S. and India's projected agricultural productivity loss under 3.3℃ degrees of warming in Cline (2007)[3] and catastrophic and sea level risings damage at 2.5℃ degrees of warming. In particular, 2.5 ℃ degrees of warming cause the North to lose 4.3% of agricultural and 0.9% of non-agricultural productivity and the South to lose 27.2% and 1.78%, respectively. Note that this setting implies that the South is more vulnerable to climate change and agricultural production suffers more than non-agricultural production. The growth rate of carbon emission intensity also follows the calibration of DICE-2016R, which assumes that the intensity will decrease over time. The climate module follows Ikefuji et al. (2019), which simplifies the climate dynamics in the original DICE-2016 model.

[3] I use the estimate without the carbon fertilization effects. Admittedly, omitting the carbon fertilization effects implies that my baseline model may over-project climate-induced damages on agriculture. Hence, I examine the sensitivity of my results to projected agricultural loss in the appendix.

Table 1: The Calibrated Parameters

Parameter	Value	Source/Target	Parameter	Value	Source/Target
Intertemporal Preferences			Household Utility		
α	1.45	Nordhaus (2017)	ω	0.01	A Standard Value
β	0.985	Nordhaus (2017)	$\bar{a}^*$	840	Match Low-Middle Income Country Agriculture Employment Share
Population Dynamics			Goods Production		
$L_{1,0}$	1187	Match the UN Population Projection	σ_A	4.06	Tombe (2015)
L_1^{asym}	1255	Match the UN Population Projection	σ_N	4.63	Tombe (2015)
δ_1^L	0.40	Match the UN Population Projection	$B^*_{1,N,t}$	$B_{1,N,t-1} * 1.013^5$	World Development Indicator
$L_{2,0}$	6152	Match the UN Population Projection	$B^*_{1,A,t}$	$B_{1,N,t}\left(\frac{1.4}{0.99^{5t}}+1\right)^{-1}$	World Development Indicator
L_2^{asym}	8480	Match the UN Population Projection	$B^*_{2,N,t}$	$B_{1,N,t}\left(\frac{4.9}{0.98^{5t}}+1\right)^{-1}$	World Development Indicator
δ_2^L	0.21	Match the UN Population Projection	$B^*_{2,A,t}$	$B_{1,A,t}\left(\frac{14}{0.99^{5t}}+1\right)^{-1}$	World Development Indicator
Carbon Cycle			$a_{1,A}$	0.0073	Cline (2007)
ϕ_1	0.9942	Ikefuji et al. (2019)	$a_{1,N}$	0.0015	Cline (2007) and Nordhaus (2007)
$\sigma^E_{i,0}$	0.0167	Match Global Emission in 2020	$a_{1,A}$	0.060	Cline (2007)
$\sigma^E_{1,t}$	$\sigma^E_{i,t-1}\mathrm{e}^{-g_{\sigma^E}(1-\delta_{\sigma^E}}$	Nordhaus (2017)	$a_{1,N}$	0.0029	Cline (2007) and Nordhaus (2007)
g_{σ^E}	0.0152	Nordhaus (2017)	$\tau_{1,2,A}$	4	Tombe (2015)
δ_A	0.001	Nordhaus (2017)	$\tau_{1,2,N}$	3	Tombe (2015)
M_0	851	Ikefuji et al. (2019)	$\tau_{2,1,A}$	4	Tombe (2015)
Temperature Dynamics			$\tau_{2,1,N}$	3	Tombe (2015)
η_0	-2.86	Ikefuji et al. (2019)	$\theta_{1,0}$	0.0741	Nordhaus (2017)
η_1	0.8954	Ikefuji et al. (2019)	$\theta_{1,t}$	$\theta_{1,i-1}(1-\delta_\theta)\sigma^E_t$	Nordhaus (2017)
η_2	0.4622	Ikefuji et al. (2019)	δ_θ	0.025	Nordhaus (2017)
H_0	0.85	Ikefuji et al. (2019)	θ_2	2.6	Nordhaus (2017)

* Joint calibration of subsistence level and productivity levels to match agricultural employment shares and relative GDP per capita in high income countries and low- and- middle-income countries generate similar results.

The productivity in each sector is set such that, at time t, the price of domestic agricultural products relative to non-agricultural price is higher in the South and real wage is higher in the North. By ignoring the fact that two countries produce distinct goods and slightly abusing the terminology, we may conclude that the North has absolute advantages in both sectors and "comparative advantage" in the non-agriculture sector. To be more specific, the North-South agricultural productivity gap is larger than the non-agricultural productivity gap. Over time, both the sector productivity gap and North-South productivity gaps are shrinking. Hence, the productivity gaps will eventually close as $t \to \infty$. The three productivity gaps match the 2015 gap in the value-added per worker in the agriculture and industry sector in 2015 after accounting for climate damages in 2015. Their growth/gap shrinkage rates are calibrated to match the average value-added per worker growth rate from 1997 to 2019.

V. Quantitative Results

This section reports the results for the model and its implications. I proceed with the following steps. First, I compute a Business-as-Usual (BAU) equilibrium with $\mu_1 = \mu_2 = 0.02$ for 300 years and a counterfactual no-climate-change (NCC) equilibrium with $H_t = 0.85 \; \forall \; t$ and compare the utility loss implied by the Fixed-Price Enumerative Method and the Price-Adjusted Integrated Method. Second, using the results in BAU and NCC, we can compute the damage functions implied by the Fixed-Price Enumerative Method. Third, I evaluate my model's policy implications under several policy equilibriums.

Table 2: The Steps of the Analysis

Step 1	Simulate the BAU and NCC equilibrium
Step 2	Construct Fixed-Price Enumerative Damage Functions
Step 3	Discuss the Policy Implication of Relative Price Effects under several policy equilibriums.

Step 1: Simulate the BAU and NCC equilibriums

In both BAU and NCC, mitigation levels are set exogenously. In BAU, $\mu_{i,t} = 0.02 \; \forall \; t$, which reflects the curent level of carbon abatement. In NCC, $\mu_{i,t} = 0.0 \; \forall \; t$ since carbon abatement is costly and unnecessary. By comparing BAU and NCC equilibriums, we can learn the impacts of climate change and construct the fixed-price enumerative damage functions. Figure 1 demonstrates the path of several endogenous economics and climate variables of interest under BAU and NCC.

Figure 1-A shows, under BAU, the carbon stock in the atmosphere reaches 2169 trillion tons, and the degree of warming reaches 4.31 ℃ by 2095. This temperature projection roughly matches RCP 8.5, the high emissions scenario projected by the Intergovernmental Panel on Climate Change.

In Figures 1-B and 1-C, we observe that the South labor share in agricultural sector decreases gradually across time in both scenarios from subplot 2. As income increases in the South, the subsistence level becomes less relevant. By contrast, under BAU but not NCC, the North agricultural labor share increases before 2095. It reflects the North's gain in non-agriculture's comparative advantage from climate change. From subplot 3-6, we find that the South mainly exports non-agricultural goods in exchange for agricultural goods and, under BAU, the South increases their agricultural imports to substitute climate-induced domestic production loss. The increased demand from the South boosts the North's export-oriented agricultural production even though its agricultural labor productivity is also harmed.

Table 3 provides a breakdown of the welfare impacts on the North and South regions in 2020, 2060, and 2095, based on Equation (12). The North is subject to a complex interplay of effects: negative impacts from production income, relative price, and subsistence, counterbalanced by positive price income and terms-of-trade effects. In 2060, the North's utility, U, is affected in various ways: a decrease of 0.91% due to production income, an increase of 0.32% from price nominal effects, a decrease of 0.03% from domestic prices, an increase of 0.02% from terms-of-trade, and a decrease of 0.03% from subsistence. Even though the North's productivities are reduced by climate change, the North is temporarily benefiting from it because of the strong positive relative price effects dominate the physical effect of climate change. By contrast, in the South, the effects of production and price nominal income, relative price, and subsistence collectively lead to a reduction in utility. In 2060, these impacts are quantified as follows: the production income effect decreases the flow utility of the South by 3.01%, the price nominal effect by 5.46%, the domestic price effect increases it by 7.57%, the terms-of-trade effect decreases it by 0.06%, and the subsistence effect further reduces it by 2.90%. Because the South is less developed relative to the North, the South's household agricultural consumption share $\frac{\bar{a}P_{i,A}}{p_{i,A}Y_{i,A}+p_{i,N}Y_{i,N}}$ is high. As a result, the increase in agricultural product prices leads to a substantial negative subsistence effect.

TABLE 3— THE DECOMPOSITION OF RELATIVE WELFARE CHANGE BETWEEN BAU AND NCC

	The North			The South		
Relative Effects (%)	2020	2060	2095	2020	2060	2095
Production Income Effect	-0.07	-0.91	-3.07	-0.60	-3.01	-4.83
Price Income Effect	0.02	0.32	1.34	-0.22	-5.46	-12.54
Domestic Price Effect	0.00	-0.03	-0.09	0.72	7.57	14.86
Terms-of-Trade Effect	0.05	0.02	1.73	-0.01	-0.06	0.06
Subsistence Effect	-0.01	-0.03	-0.07	-0.82	-2.90	-2.69
Total Effect	-0.01	0.02	-0.23	-0.94	-4.30	-6.91

From Section II, we learn that the fixed-price enumerative damage function is identical to the production nominal income effect. Hence, simulation results are sufficient for us to compute the "real" utility change and the fixed-price enumerative utility change. For the North, the fixed-price enumerative approach predicts a utility reduction of 0.91%, but the actual loss is much smaller at 0.23%. In contrast, the South's utility loss is underestimated by the enumerative approach, which estimates a 4.83% loss compared to the actual 6.91% loss.[4] In other words, the enumerative method significantly over-estimate the cost of climate change in the North and under-estimate it in the South: climate-driven non-agricultural utility loss in terms of equivalent non-agricultural consumption goods in the South is 43% higher after accounting for the price effects. Conversely, the North experiences a 92% decrease in utility loss.[5] These comparisons highlight the importance of accounting for the relative price effects for accurately accounting for the climate change's impacts.

Step 2: Construct the Fixed-price enumerative Damage Function

Nordhaus and Boyer (2000) only compute climate damage at the end of the 21st century. Based on the projected global temperature in that year, they calibrate an exponential damage function

$$\Omega_{i,t} = \frac{1}{1 + a_{i,FP} H_t^2}$$

to match each region's projected damages. I follow this procedure and compute climate damage in North and South in 2095 to be

$$Enumerative\ Damage_{i,2095} = \frac{1}{1+a_{i,BU}H_{2095}^2} = \frac{P_{i,A,2095}^{NCC} Y_{i,A,2095}^{NCC}}{GDP_{i,2095}^{NCC}} \frac{Y_{i,A,2095}^{BAU}}{Y_{i,A,2095}^{NCC}} + \frac{P_{i,N,2095}^{NCC} Y_{i,A,2095}^{NCC}}{GDP_{i,2095}^{NCC}} \frac{Y_{i,N,2095}^{BAU}}{Y_{i,N,2095}^{NCC}}$$

And the then calibrate $a_{i,FP}$ such that

$$\frac{1}{1 + a_{i,FP} H_{2090}^2} = Enumerative\ Damage_{i,2095}.$$

Step 3: Compute the endogenous policies under the Fixed-Price Enumerative Method and the Price-Adjusted Integrated Method

[4] Both the Passche Index and Fisher Index tend to infer a loss higher than the real loss in the North and lower in the South.

[5] The change in utility can be easily normalized in terms of equivalent non-agricultural consumption by the formula $c'_{N,equivalent}/c_{N,equivalent} = (U'/U)^{\frac{1}{1-\omega}}$

In an Integrated Assessment Model (IAM), a policymaker sets the optimal carbon emission abatement rates given a damage function. The optimal policy set by the policymaker depends on which method she is implementing to infer the damage function. Here, I demonstrate the optimal climate policies in two types of models: the fixed-price enumerative model, in which the damage function of the policymaker is inferred from the fixed-price enumerative method, and the price-adjusted integrated model in which the effects of price changes are accounted. Three policy scenarios are addressed: the utilitarian world government, the uncooperative Nash equilibrium, and a "fair" government with time-varying weights on two countries.

Scenario 1: The Utilitarian World Government

This scenario assumes that an utilitarian world government imposes a mitigation rate in each country to maximize the population-weighted utility for the next 300 years while internalizing how the market will respond to the mitigation policy.

In the fixed-price enumerative model, the policymaker's optimization problem is:

$$\max_{\mu_{1,t},\mu_{2,t}} \Sigma_{t=0}^{T}\beta^t \Bigg\{ L_{1,t}\frac{\Big((1-\theta_{1,t}\mu_1^{\theta_2})\Omega_{1,t}GDP_{1,t}^{NCC}\Big)^{1-\alpha}-1}{1-\alpha} + L_{2,t}\frac{\Big((1-\theta_{1,t}\mu_1^{\theta_2})\Omega_{2,t}GDP_{2,t}^{NCC}\Big)^{1-\alpha}-1}{1-\alpha}\Bigg\}$$

subject to

$$\Omega_{i,t} = \frac{1}{1+a_{i,FP}H_t^2}$$

$$M_{t+1} = \phi_1 M_t + (1-\mu_1)E_{1,t}^0 + (1-\mu_2)E_{i,t}^0$$

$$H_{t+1} = \eta_0 + \eta_1 H_t + \log(M_{t+1})$$

$$0 \le \mu_{i,t} \le \overline{\mu_t}.$$

In this problem, that the world government ignores the relative price effect of climate change. As I argue above, such a government relies on the projected Laspeyres GDP indexes to measure utility loss induced by climate change in each period.

In the price-adjusted integrated model, the policymaker instead solves a more complex problem by choosing mitigation rates $\{\mu_{1,t}, \mu_{2,t}\}$, agriculture and non-agriculture labor shares $\{l_{1,A,t}, l_{2,A,t}\}$, agriculture and non-agriculture export rates $\{x_{1,2,A,t}, x_{1,2,N,t}, x_{2,1,A,t}, x_{2,1,N,t}\}$ in each country, and South non-agricultural intermediate product prices $\{p_{2,N,t}\}$ to maximize population-weighted CRRA utility subject to implementability constraints (1) - (6), (8)[6] and the law of climate system (9) - (11) $\forall \ \ 0 \le t \le T$:

$$\max_{\mu_{i,t}, \ \ l_{i,A,t}, \ \ x_{i,j,k,t}, \ \ p_{2,N,t}} \Sigma_{t=0}^{T} \beta^t \left\{ L_{1,t} \frac{(c_{1,t})^{1-\alpha} - 1}{1-\alpha} + L_{2,t} \frac{(c_{2,t})^{1-\alpha} - 1}{1-\alpha} \right\}$$

subject to

$$Y_{i,i,k,t} = l_{i,k,t}(1 - x_{j,i,k,t}) L_{i,t} B_{i,k,t} \Omega_{i,k,t} \Omega_{i,C,t} (1 - \theta_{1,t} \mu_{i,t}^{\theta_2})$$

$$Y_{j,i,A,t} = l_{i,A,t}(x_{j,i,A,t}) L_{i,t} B_{i,k,t} \Omega_{1,k,t} \Omega_{1,C,t} \frac{1}{\tau_{j,i,k}} (1 - \theta_{1,t} \mu_{i,t}^{\theta_2})$$

$$c_{i,t} = (c_{i,A,t} - \bar{a})^{\omega} c_{i,N,t}^{1-\omega}$$

(1) - (6), (8) -(11)

and mitigation bounds

$$0 \le \mu_{i,t} \le \overline{\mu_t}.$$

Figures 2-A, 2-B, and 2-C show the two models' mitigation $\mu_{i,t}$, climate paths, and mitigation costs $\theta_{1,t}\mu_{i,t}^{\theta_2}$ under the utilitarian world government. Since the social planner has the incentive to equalize the per-capita consumption of North and South, it imposes most of the carbon abatement burden on the North. Mitigation rates gradually increase over time and reach the upper bound after decades. However, higher South utility loss driven by relative price changes in the two-sector model implies more radical initial mitigation rates and higher mitigation costs than in the fixed-price enumerative model: at $t = 0$, the North mitigation level is about 209%

[6] The aggregate production constraints do not appear here because it is replaced by labor and export shares.

higher, and that in South 21% higher. Moreover, the North reaches zero emissions about 30 years earlier in the two-sector model than in the fixed-price enumerative model (Figure 2-A). Therefore, in 2095, the carbon concentration is 5.9% lower, and the degree of warming is 0.2℃ lower (Figure 2-B). We also can notice from 2-C that the North bears higher mitigation costs because it is richer than the South under both approaches.

In scenario 1, because the South is populous and less-developed, the policymaker will have a strong tendency to re-allocate the income from the North to the South to equalize the marginal utility of the North and the South. Even though direct consumption redistribution is not feasible for her because of the binding income budget constraint, she still will impose most of the mitigation burdens on the North. So, as we can see from Figure 2-A, the mitigation rates in the North is much higher than the mitigation rates in the South. Therefore, the North is worse off under this scenario because the mitigation costs of North even outweigh its welfare losses under Business-as-Usual.

Scenario 2: Non-Cooperative Nash Equilibrium

The Nash equilibrium assumes a policymaker in each country that sets her country's mitigation rates to maximize household intertemporal welfare in her country. Each policymaker internalizes how the market responds to her mitigation policy and takes the other country's climate policy as given.

In the fixed-price enumerative model, each policymaker solves an optimization problem to maximize her home country's GDP while taking the other policymaker's policy paths as given:

$$\max_{\boldsymbol{\mu_{i,t}}} \Sigma_{t=0}^{T} \beta^t \left\{ \begin{matrix} \omega L_{1,t} \dfrac{\left(\left(1-\theta_{1,t}\mu_1^{\theta_2}\right)\Omega_{1,t} GDP_{1,t}^{NCC}\right)^{1-\alpha} - 1}{1-\alpha} + \\ (1-\omega) L_{2,t} \dfrac{\left((1-\theta_{1,t}\mu_1^{\theta_2})\Omega_{2,t} GDP_{2,t}^{NCC}\right)^{1-\alpha} - 1}{1-\alpha} \end{matrix} \right\}$$

subject to

$$\Omega_{i,t} = \frac{1}{1 + a_{i,F}\ \ H_t^2}$$

$$M_{t+1} = \phi_1 M_t + (1-\mu_{1,t})E_{1,t}^0 + (1-\mu_{2,t})E_{i,t}^0$$

In the price-adjusted integrated model, the Nash Equilibrium is instead characterized by the following problem solved by each country's policymaker while taking the other policymaker's policy paths as given:

$$\max_{\boldsymbol{\mu_{i,t}},E_{i,t},M_{t+1},H_{t+1},c_{i,k,t},Y_{i,j,k,t},p_{i,k,t}} \Sigma_{t=0}^{T}\beta^t \left\{ L_{i,t}\frac{((c_{i,A,t}-\bar{a})^{\omega}c_{i,N,t}^{1-\omega})^{1-\alpha}-1}{1-\alpha}\right\}$$

subject to (1) to (8) and

$$M_{t+1} = \phi_1 M_t + (1-\mu_{1,t})\sigma_t^E \mathrm{B}_{1,N,t}L_{1,t} + (1-\mu_{2,t})\sigma_t^E \mathrm{B}_{1,N,t}L_{2,t}$$
$$H_{t+1} = \eta_0 + \eta_1 H_t + \log(M_{t+1})$$
$$0 \leq \mu_{i,t} \leq \bar{\mu}_t.$$

Figures 3-A and 3-B demonstrate the mitigation and climate path in the two models under the Nash equilibrium. In both models, the magnitude of mitigation levels in both countries are considerably lower than the equilibriums with a centralized social planner. We observe less carbon efforts in the North and more efforts in the South in the price-adjusted integrated model compared to the fixed-price enumerative model. To be specific, in year 2015, the North reduces its carbon abatement level by 68%, while the South slightly increases the mitigation level by 21% (Figure 3-A). In the end, the relative price and fixed-price enumerative models' climate paths are practically identical (Figure 3-B). It is worth noticing that the carbon abatement levels under the Nash equilibrium are much lower than those under the world government because of free-riding problems.

Scenario 3: A "Fair" World Government

In scenario 3, the world government weighs the utilities of the North and the South by the inverse of their NCC utilities each period. Unlike scenario 1, the world government under such welfare weights treats the NCC world as the optimal world because, according to this world government's utility function, the marginal benefits of the North and South's consumption are equalized under the NCC scenario. [7] In this case, this world government tries to replicate this NCC world.

[7] You may also regard this social planner as "unfair".

In the fixed-price enumerative model, the policymaker's optimization problem is:

$$\max_{\mu_{1,t},\mu_{2,t}} \Sigma_{t=0}^{T}\beta^t \Bigg\{ \frac{(GDP_{1,t}^{NCC})^\alpha}{\left(GDP_{1,t}^{NCC}\right)^\alpha + \left(GDP_{2,t}^{NCC}\right)^\alpha} L_{1,t} \frac{\left((1-\theta_{1,t}\mu_1^{\theta_2})\Omega_{1,t}GDP_{1,t}^{NCC}\right)^{1-\alpha} - 1}{1-\alpha}$$

$$+ \frac{(GDP_{1,t}^{NCC})^\alpha}{\left(GDP_{1,t}^{NCC}\right)^\alpha + \left(GDP_{2,t}^{NCC}\right)^\alpha} L_{2,t} \frac{\left((1-\theta_{1,t}\mu_1^{\theta_2})\Omega_{2,t}GDP_{2,t}^{NCC}\right)^{1-\alpha} - 1}{1-\alpha} \Bigg\}$$

subject to

$$\Omega_{i,t} = \frac{1}{1 + a_{i,FP}H_t^2}$$

$$M_{t+1} = \phi_1 M_t + (1-\mu_{1,t})E_{1,t} + (1-\mu_{2,t})E_{i,t}$$

$$H_{t+1} = \eta_0 + \eta_1 H_t + \log(M_{t+1})$$

$$0 \leq \mu_{i,t} \leq \bar{\mu}_t.$$

The price-adjusted integrated model is represented by the optimization problem:

$$\max_{\mu_{i,t},\ l_{i,A,t},\ x_{i,j,k,t},\ p_{2,N,t}} \Sigma_{t=0}^{T}\beta^t \Bigg\{ L_{1,t} \frac{(c_{1,t}^{NCC})^\alpha}{\left(c_{1,t}^{NCC}\right)^\alpha + \left(c_{2,t}^{NCC}\right)^\alpha} \frac{(c_{1,t})^{1-\alpha} - 1}{1-\alpha}$$

$$+ L_{2,t} \frac{(c_{2,t}^{NCC})^\alpha}{\left(c_{1,t}^{NCC}\right)^\alpha + \left(c_{2,t}^{NCC}\right)^\alpha} \frac{(c_{2,t})^{1-\alpha} - 1}{1-\alpha} \Bigg\}$$

subject to

$$Y_{i,i,k,t} = l_{i,k,t}(1 - x_{j,i,k,t})L_{i,t}B_{i,k,t}\Omega_{i,k,t}\Omega_{i,C,t}(1-\theta_{1,t}\mu_{i,t}^{\theta_2})$$

$$Y_{j,i,A,t} = l_{i,A,t}(x_{j,i,A,t})L_{i,t}B_{i,k,t}\Omega_{1,k,t}\Omega_{1,C,t}\frac{1}{\tau_{j,i,k}}(1-\theta_{1,t}\mu_{i,t}^{\theta_2})$$

$$c_{i,t} = (c_{i,A,t} - \bar{a})^\omega c_{i,N,t}^{1-\omega}$$

(1) - (6), (8) -(11)

and mitigation bounds

$$0 \leq \mu_{i,t} \leq \overline{\mu_t}.$$

One twist here is that the welfare weights of the social planner are different under the price-varying enumerative method and the price-adjusted integrated method. Therefore, I also solve the social planner problem under the Enumerative Method using the welfare weights under the relative price approach:

$$\max_{\mu_{1,t},\mu_{2,t}} \Sigma_{t=0}^{T}\beta^t \Bigg\{ \frac{(c_{1,t}^{NCC})^\alpha}{\left(c_{1,t}^{NCC}\right)^\alpha + \left(c_{2,t}^{NCC}\right)^\alpha} L_{1,t} \frac{\left((1-\theta_{1,t}\mu_1^{\theta_2})\Omega_{1,t}GDP_{1,t}^{NCC}\right)^{1-\alpha} - 1}{1-\alpha}$$

$$+ \frac{(c_{2,t}^{NCC})^\alpha}{\left(c_{1,t}^{NCC}\right)^\alpha + \left(c_{2,t}^{NCC}\right)^\alpha} L_{2,t} \frac{\left((1-\theta_{1,t}\mu_1^{\theta_2})\Omega_{2,t}GDP_{2,t}^{NCC}\right)^{1-\alpha} - 1}{1-\alpha} \Bigg\}$$

subject to

$$\Omega_{i,t} = \frac{1}{1 + a_{i,BU}H_t^2}$$

$$M_{t+1} = \phi_1 M_t + (1-\mu_{1,t})E_{1,t} + (1-\mu_{2,t})E_{i,t}$$

$$H_{t+1} = \eta_0 + \eta_1 H_t + \log(M_{t+1})$$

$$0 \le \mu_{i,t} \le \bar{\mu}_t.$$

We can observe the results of three social planner problems in Figure 4. At $t = 0$, the magnitudes of mitigation levels in the North and the South are about 30% higher. Still, the North reaches zero emissions about 30 years earlier in the relative price model than in the fixed-price enumerative model (Figure 4-A). Nevertheless, if the world government is assigned to the price-adjusted weights in the fixed-price enumerative approach, then the magnitude of the South carbon abatement level is higher. The consequence of more radical carbon abatement efforts in the North is that the carbon concentration is 13.3% lower, and the degree of warming is 0.27℃ lower at the end of this century under the relative price approach relative to the fixed-price enumerative approach. (Figure 4-B).

VI. Conclusion

I build a North-South Integrated Assessment Model with an explicit agriculture sector, trade, and a Stone-Geary utility function featuring a subsistence food consumption level. The results of the commonly used fixed-price enumerative method and the price-adjusted integrated method show significant discrepancies in the implied climate-induced utility loss: the former method suggests a higher utility loss in the richer, more resilient, agriculture-exporting North but a lower loss in the poorer, more vulnerable, non-agriculture-exporting South under the Business-as-Usual equilibrium. Consequently, acknowledging the climate-driven food price change leads to lower carbon emission levels under a utilitarian world government's optimal climate policy. However, it results in higher emission levels under the Uncooperative Nash Equilibrium.

I conclude with several suggestions for future research. The framework proposed in the paper can be easily extended as more countries and sectors can be added. Although capital and land are not included in the current model, they may have significant welfare implications. First, the limited supply of land can potentially curb marginal worker productivity in agriculture, reducing the welfare gain of North's potential specialization in agriculture. Second, capital accumulation in the South might be affected by the food problem since more workers are allocated to produce food to meet the subsistence level instead of producing capital goods. I also make a convenient assumption that mitigation cost is constant across sectors. In the real world, they might be different. So, the carbon abatement efforts can also change the relative price between agricultural and non-agricultural prices and therefore affect welfare through relative price channels. While this paper focuses on the policy implication for the mitigation policy, the optimal adaptation policy is addressed in a companion paper. (Chen et al. 2023) The role of endogenous population growth may also be of interest. Furthermore, while the role of migration is extensively discussed in the literature (Desmet and Rossi-Hansberg 2015; Rudik et al. 2021), it is not addressed in this paper.

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Appendix: Sensitivity Analysis

In this section, I perform a sensitivity analysis for how the difference between the fixed-price enumerative method and the price-adjusted integrated approach depends on the model's key parameters. To be more specific, I examine how the difference between the utility cost in 2095, implied by the fixed-price enumerative method and the price-adjusted integrated method, changes with respect to changes of four parameters: the subsistence level $\bar{a}$, the agricultural damage parameter $a_{A,i}$, and iceberg cost τ.

Subsistence Level

From (12), we learn that $\bar{a}$ is the key driver for the subsistence effect. Figure 5 depicts the effects of varying the subsistence level $\bar{a}$. Unsurprisingly, a higher subsistence level implies a higher non-homotheticity. So, the difference between the two methods is larger. In the North, a high subsistence level leads to a high agricultural GDP share and amplifies the nominal income and terms-of-trade effects. Since the North is much richer, the adverse subsistence level effect is negligible. In the much poorer South, the subsistence level effect is much larger such that it drives the South utility loss up.

Agricultural Damages

The climate-induced relative price changes are mainly determined by climate's impacts on agricultural productivity. Figure 6 demonstrates how the difference between the two approaches responds to the agricultural damages in the two countries. As long as the agricultural damage is zero, the relative price change is trivial such that the fixed-price enumerative method and the price-adjusted integrated method tell us a practically identical utility loss in the North. It is worth noting that a small relative price change does not imply a small subsistence effect in the South as long as the nominal income I changes. As the agricultural damage parameter increases, the difference between the implied utility losses increases.

Decline Rate of Labor Productivity Growth

In the baseline model, I assume that the labor productivity growth rate is constant in the "benchmark" sector, the most advanced North non-agricultural sector. This subsection examines how the results change if the growth rate declines over time (Figure 7). In general, slower productivity growth implies a larger expenditure share in 2095. These give us larger price effects and subsistence level effects that are not reflected in the fixed-price enumerative approach.

Iceberg Cost

Trade plays a key role in the welfare cost of climate change. So, I examine how the level of iceberg cost affects the differences between the two methods (Figure 8). We observe that, as iceberg cost increases, the differences first increase and then decline. These results demonstrate the importance of trade on the relative price channel of climate change's welfare costs.

Tables and Figures

Figure 1-A: The Path of Endogenous Economic Variables in BAU and NCC (Constant Y-Axis Scale)

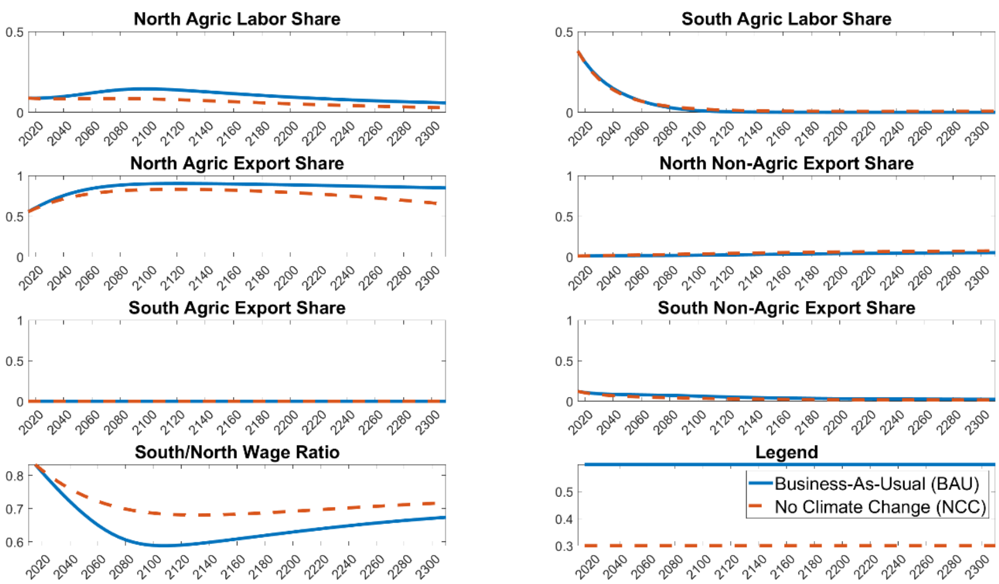

Figure 1-B: The Path of Endogenous Economic Variables in BAU and NCC (Varying Y-Axis Scale)v

Figure 1-C: The Path of Carbon Stock and Global Temperature under BAU

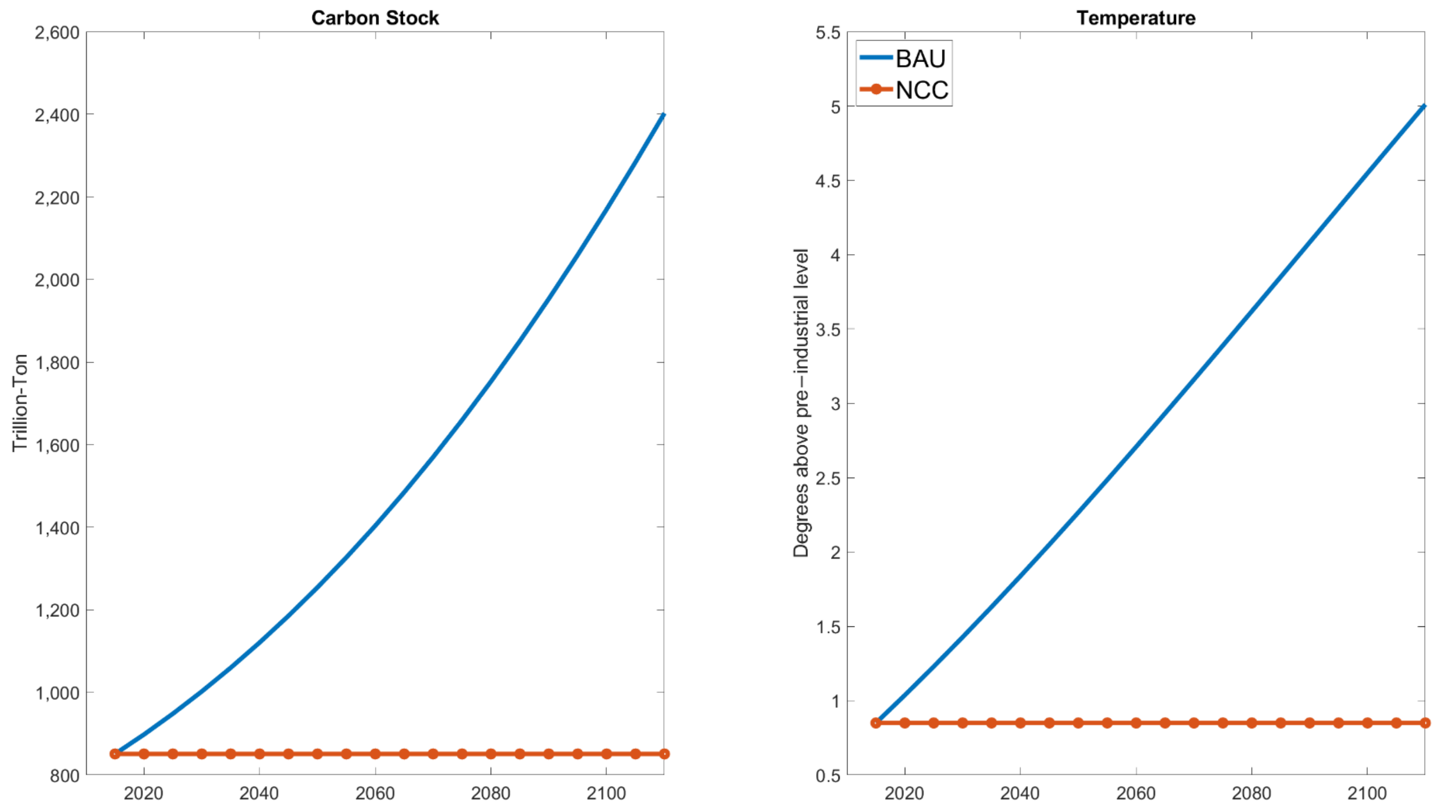

Figure 2-A: The Mitigation Paths under the Utilitarian World Government.

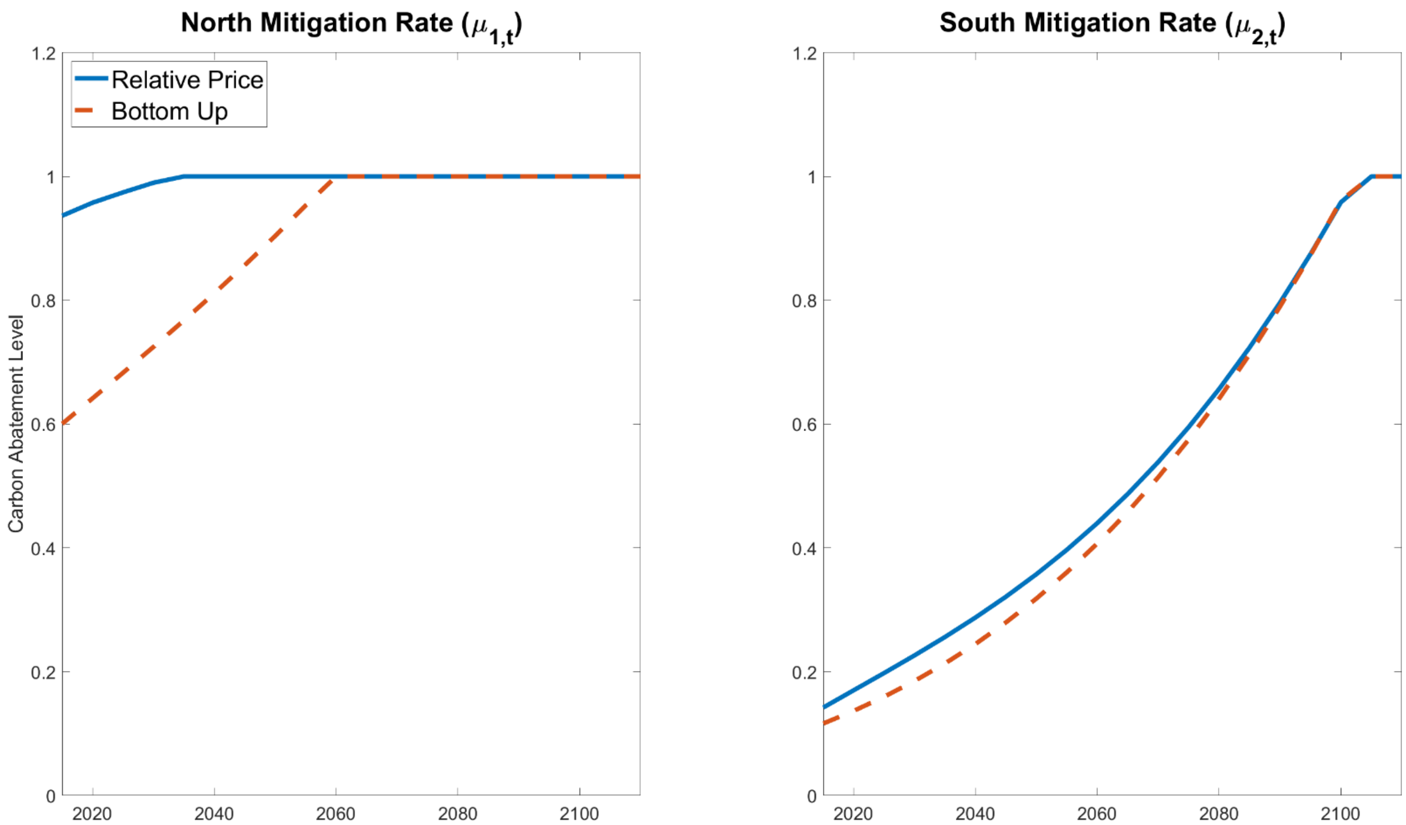

Figure 2-B: The Climate Path under the Utilitarian World Government.

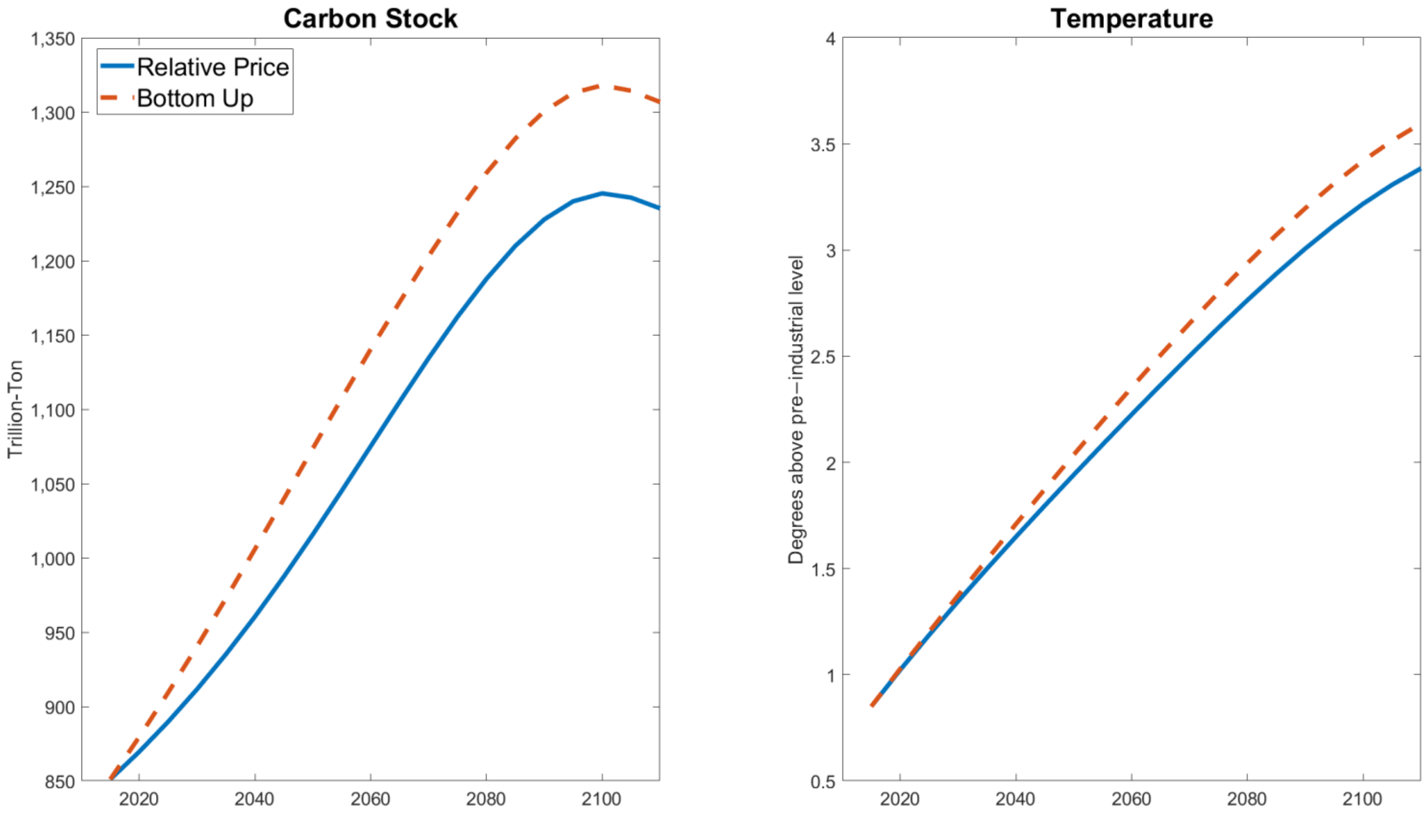

Figure 2-C: The Mitigation Cost Paths under the Utilitarian World Government.

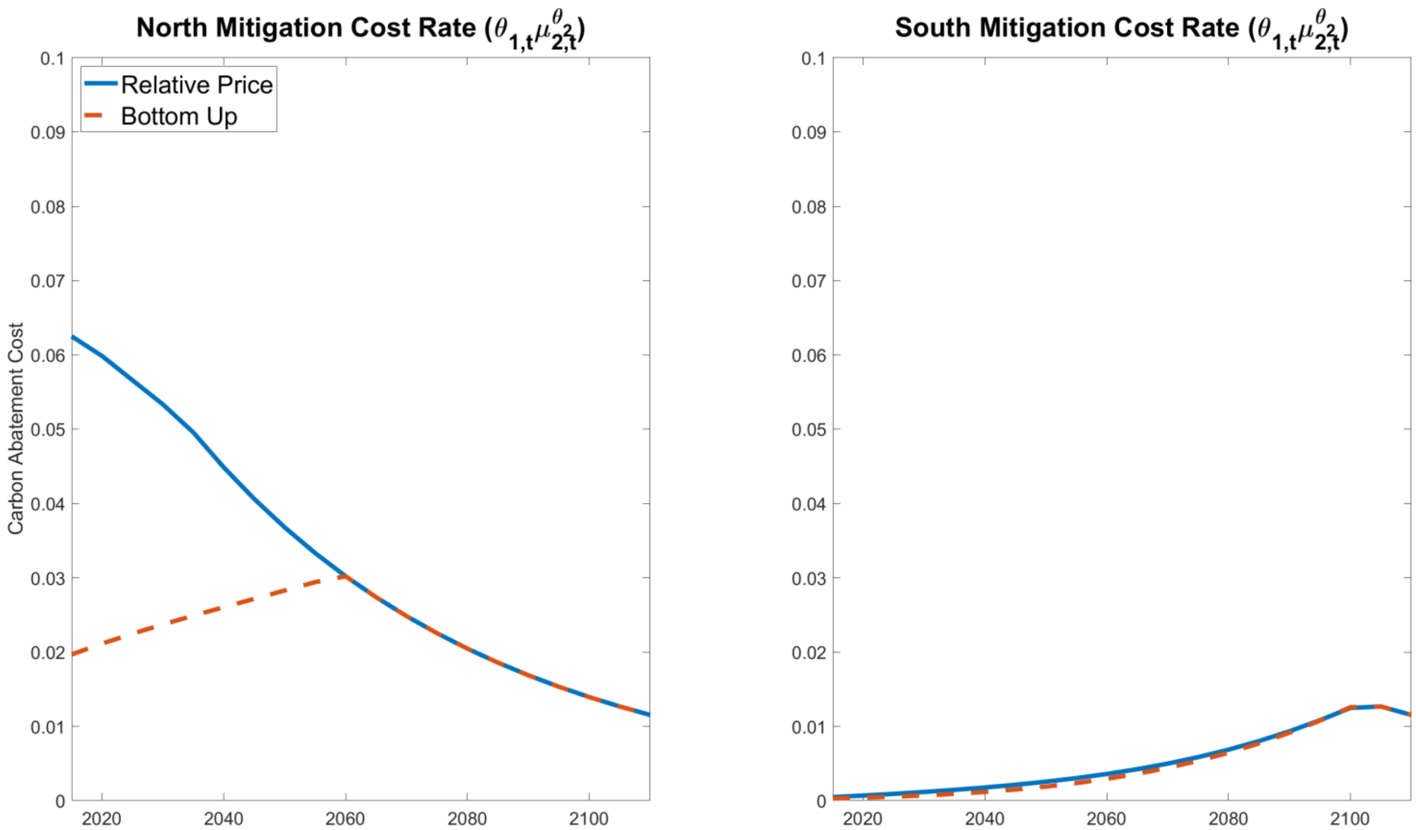

Figure 3-A: The Mitigation Paths under the Nash Equilibrium.

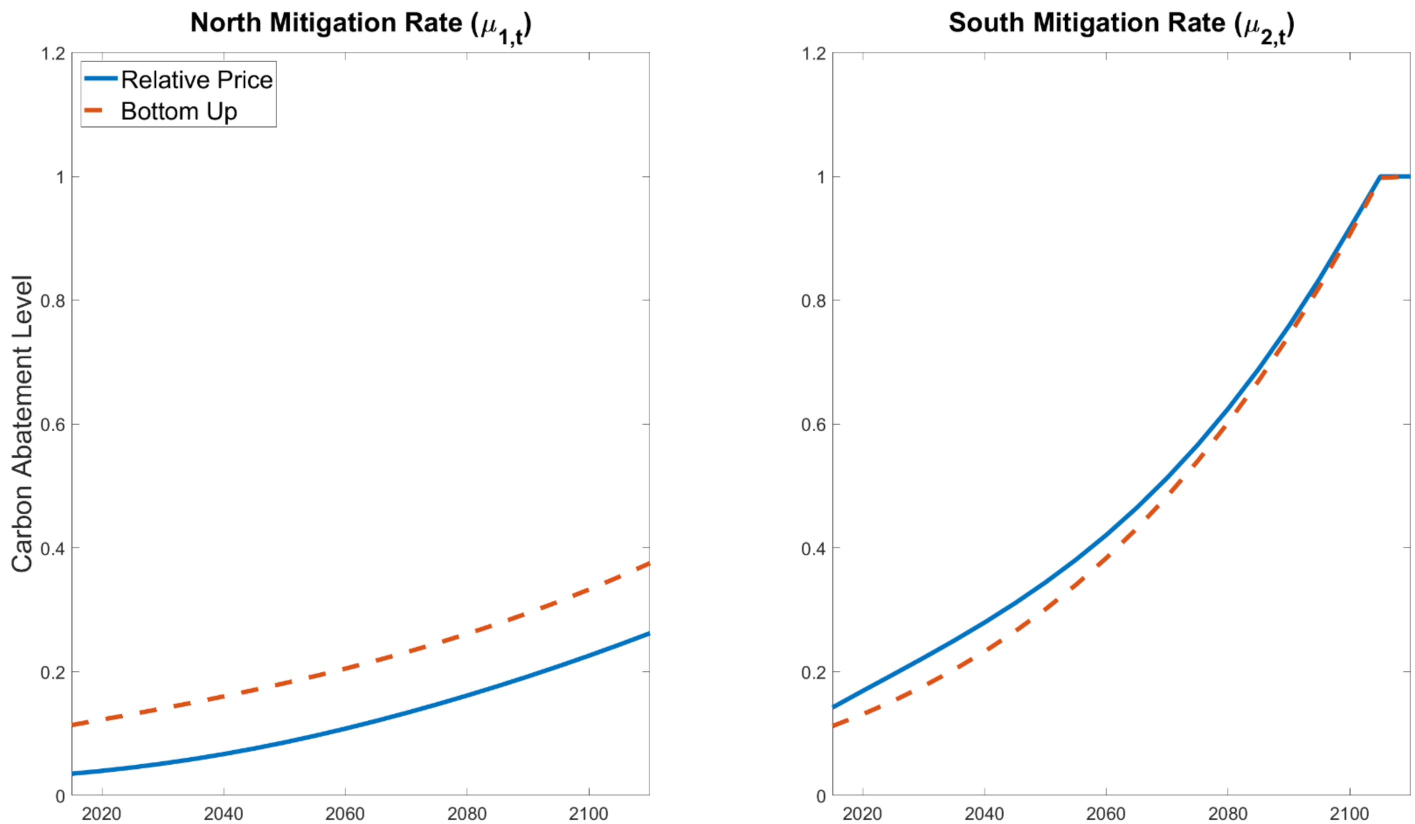

Figure 3-B: The Climate Path under the Nash Equilibrium.

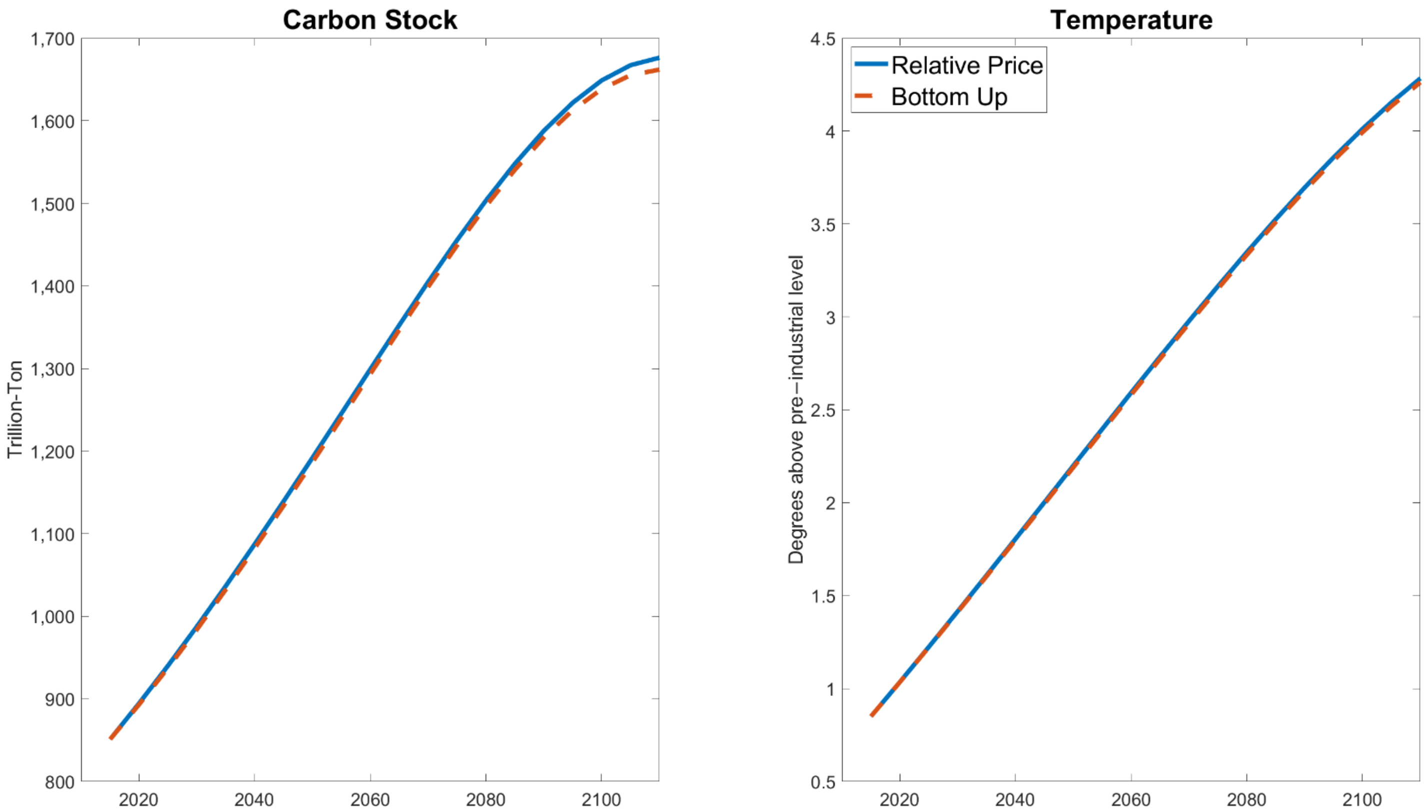

Figure 3-C: The Mitigation Cost Paths under the Nash Equilibrium

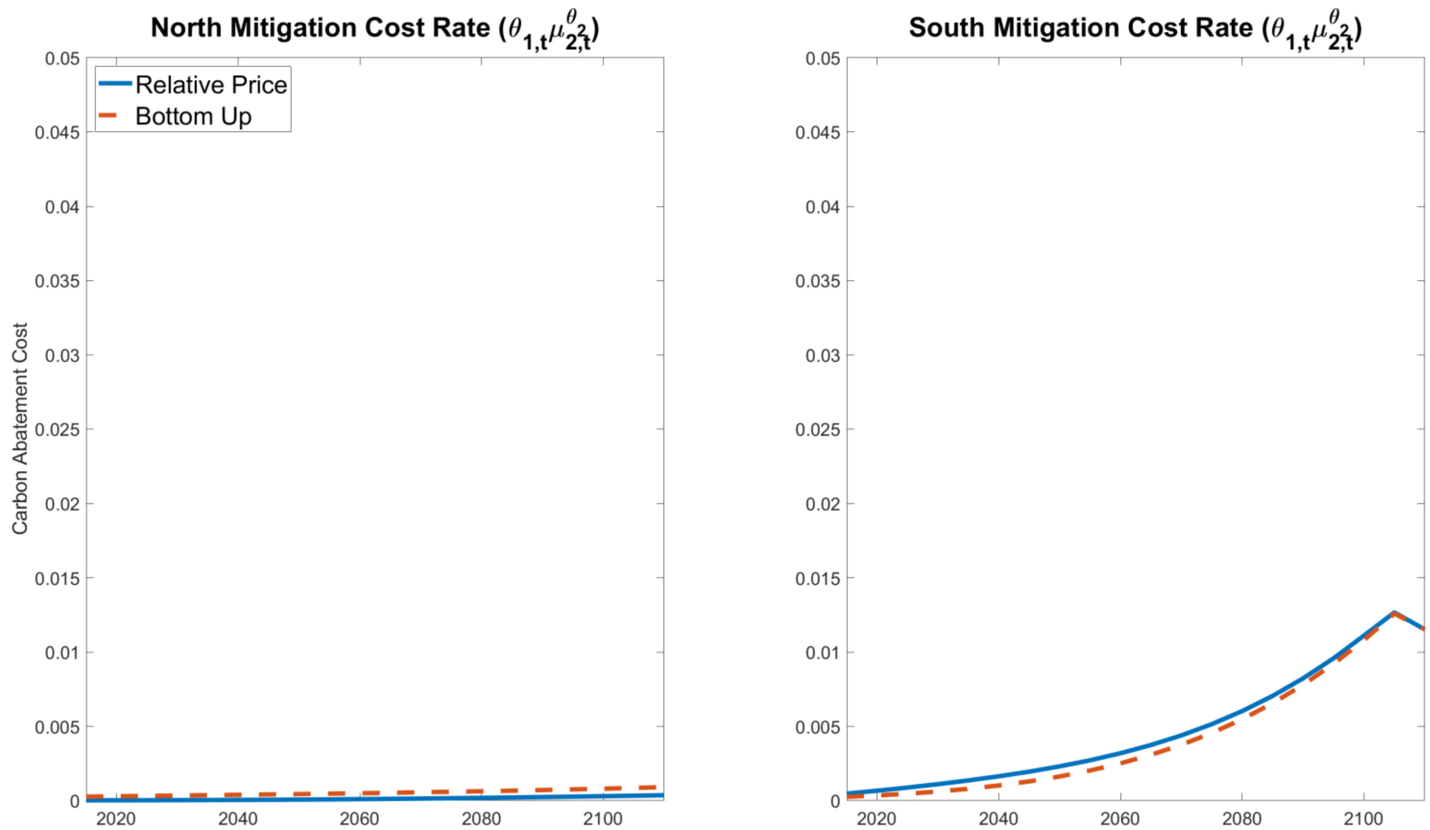

Figure 4-A: The Mitigation Paths under the "Fair" Government

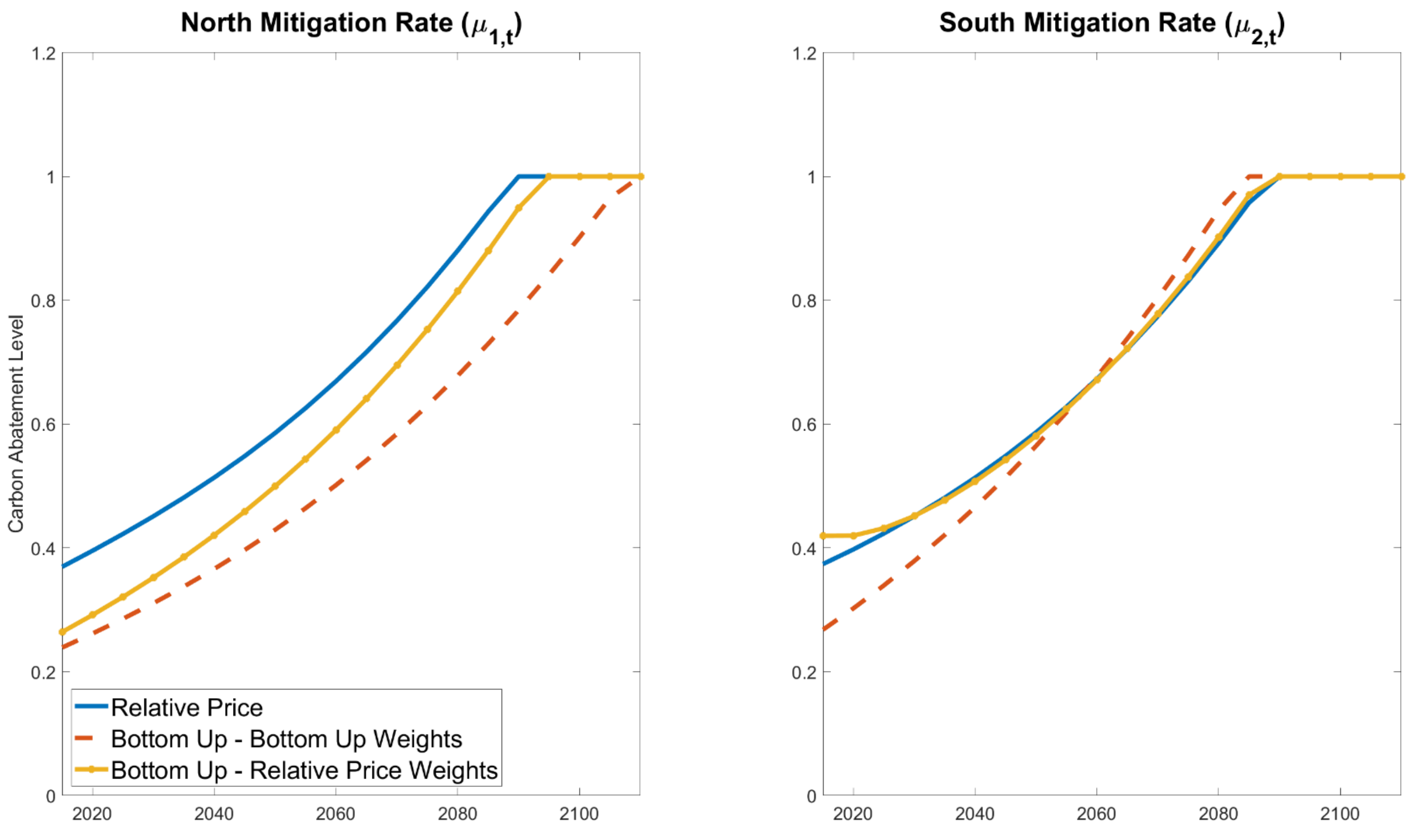

Figure 4-B: The Climate Path under the “Fair” Government

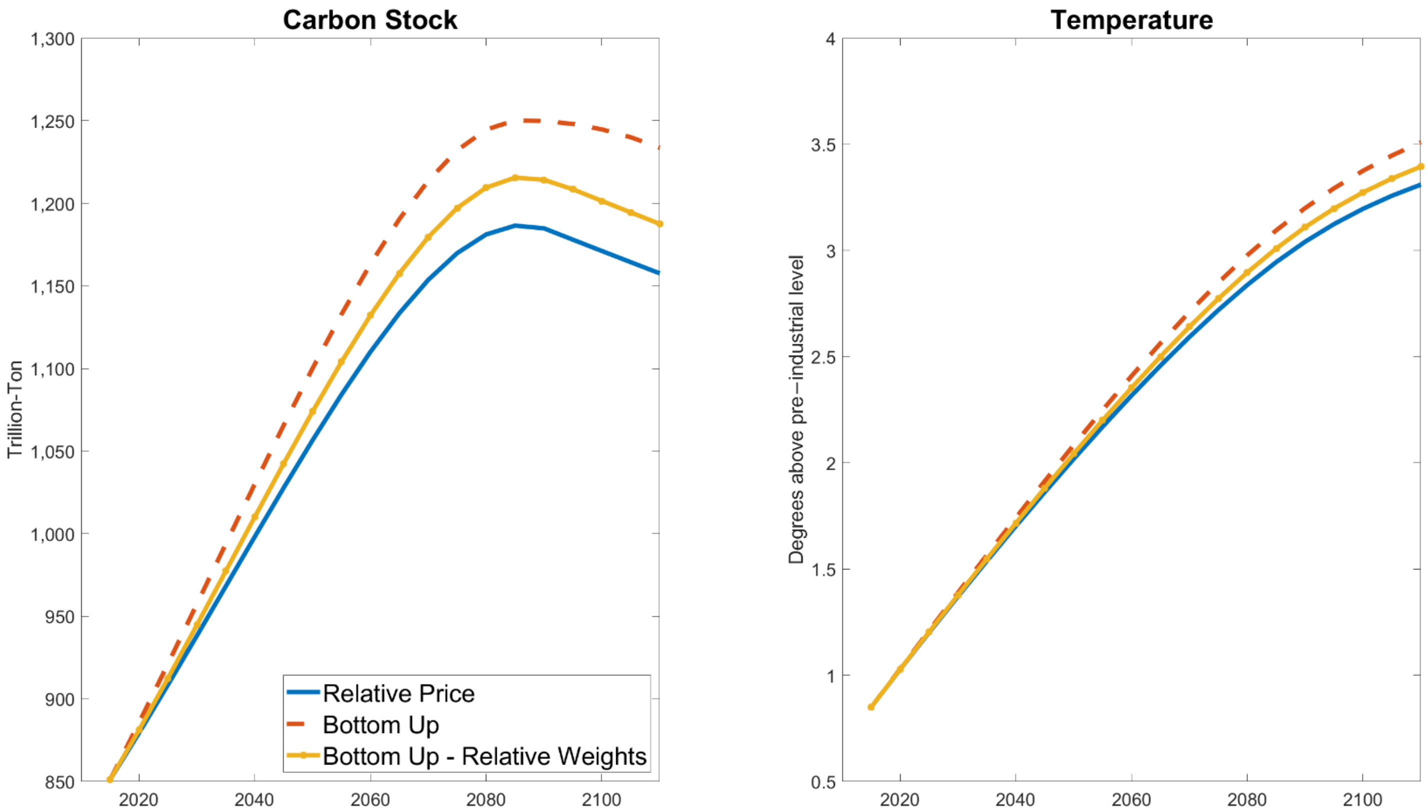

Figure 4-C: The Mitigation Cost Paths under the "Fair" World Government

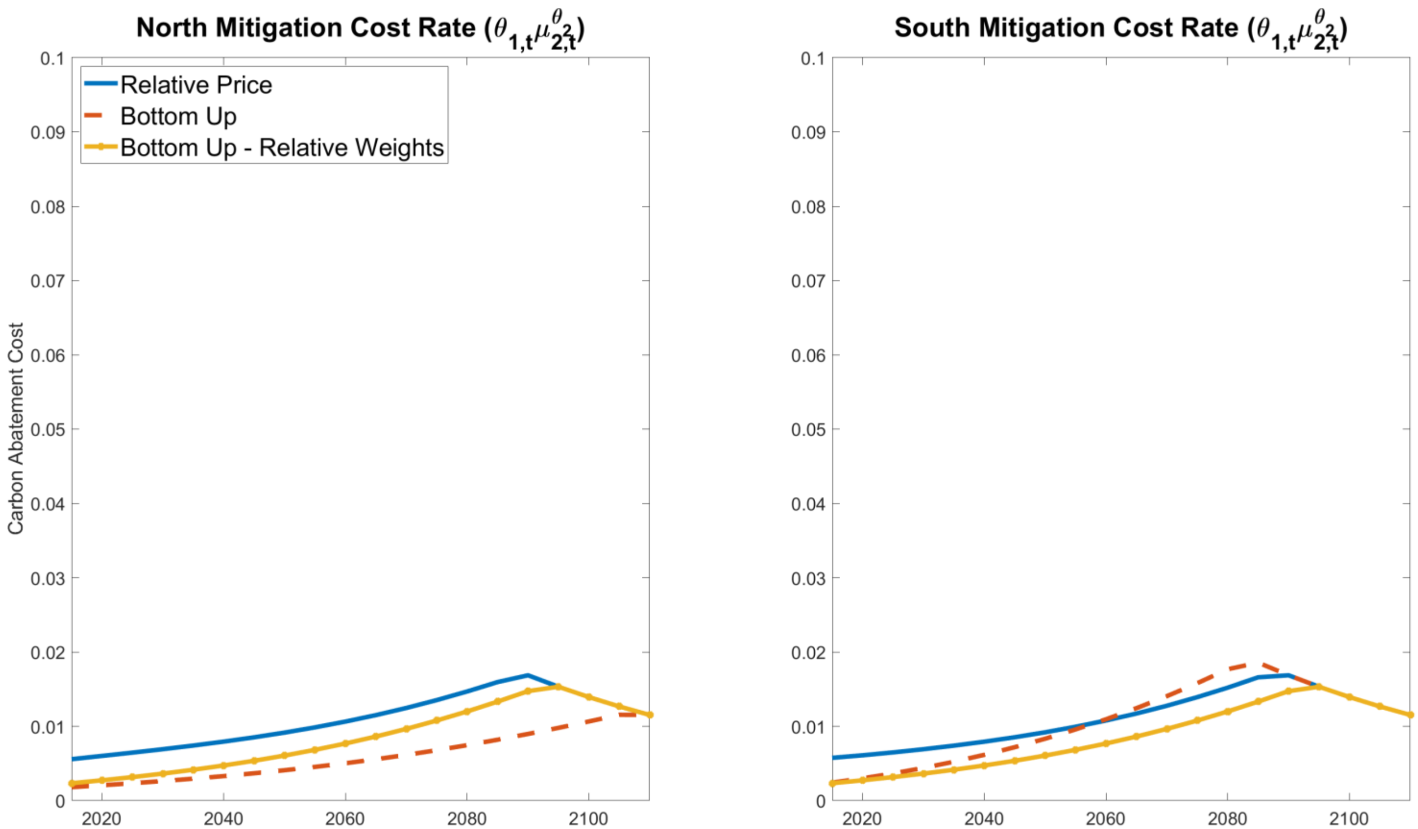

Figure 5: Sensitivity Analysis: Subsistence Level

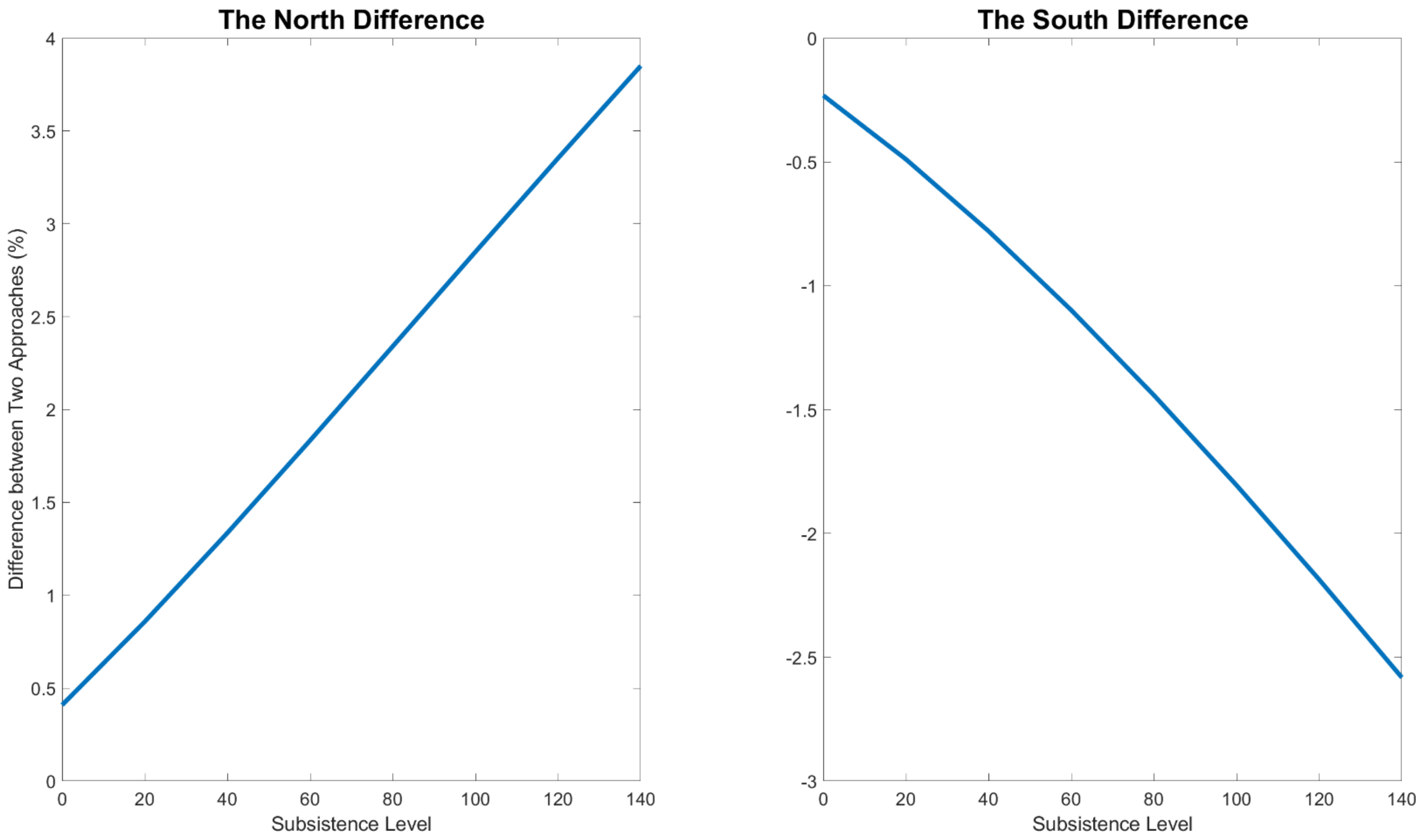

Figure 6: Sensitivity Analysis: Agricultural Damages

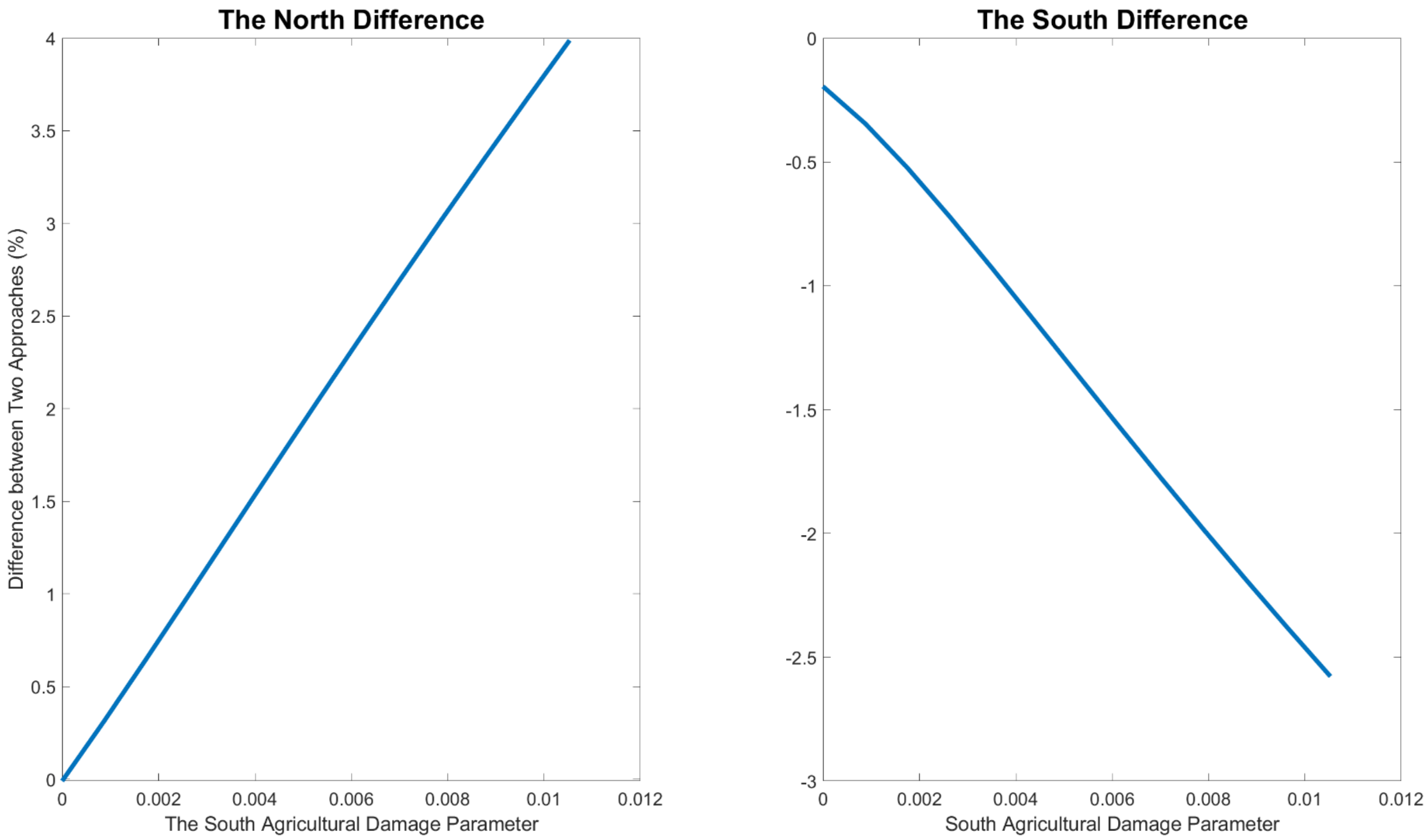

Figure 7: Sensitivity Analysis: Decline Rate of Labor Productivity Growth