Agriculture, Relative Price, and Climate Policy in a North-South Model

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Abstract: I build a North-South Integrated Assessment Model (IAM) with an agriculture and non-agriculture sector, and international trade. Household preferences feature subsistence consumption for agricultural goods. Because agriculture is more exposed to climate change, the relative price of agricultural goods will rise globally. The enumerative method, which is based on fixed prices and commonly used by IAMs, cannot capture the welfare implications of these price changes. To assess these effects, I propose a price-adjusted integrated approach. By comparison, the South's climate-driven utility loss in terms of equivalent consumption, indicated by the price-adjusted integrated approach, is 43% higher than that given by the enumerative approach. The utility loss of the North is 92% lower. A utilitarian world government that takes account of these relative price effects will further reduce global carbon emissions. Under the Non-Cooperative Nash Equilibrium, the North, which benefits from the climate-induced relative price changes, increases its emissions.

Keywords: Integrated Assessment Models, Climate Change, Trade, Agriculture, Welfare

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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. Unfortunately, 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. Understanding the directions and magnitudes of these climate-induced relative-price changes and their welfare consequences is essential for accurately assessing the aggregate impacts of climate change on economies and designing mitigation and adaptation policies that can appropriately alleviate climate change's damages.

In this paper, I build a North-South Integrated Assessment Model (IAM) with heterogeneous population and labor productivity dynamics across the two regions. Household preferences are defined over final agricultural and non-agricultural goods. A subsistence level exists for the households' agricultural consumption (Stone-Geary). Doing so elevates the importance of the agriculture sector and explains the high share of agricultural consumption in low-income countries (Herrendorf et al. 2014). 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 damages and the costs of mitigation. Production activities of these firms generate carbon emissions, which warm the planet. A higher degree of global warming depresses firms' productivity. The extent of these climate damages varies by region and sector. Meanwhile, 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 caused by carbon emissions and improve welfare.

Building on Tombe (2015), I demonstrate that utility changes caused by climate change can be decomposed into its physical effects driven by changes in production quantities and relative price effects driven by changes in relative prices of sectoral goods. Relative price effects can be further decomposed into a price income effect, a domestic price effect, a terms-of-trade effect, and a subsistence effect. A simulation spanning three centuries shows quantitatively significant relative price effects. Under the Business-as-Usual, where carbon emissions are minimally curbed and global warming remains unchecked, the magnitude of climate-driven South utility loss, in terms of equivalent consumption, is 43% higher when considering the relative price. The main reason for this higher loss is that the South will need to pay more to maintain its food subsistence needs. In contrast, the North sees a significant 92% reduction in the magnitude of its utility loss, as increased prices for

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

agricultural products lead to a rise in the North's income and improve its terms of trade. In fact, climate change can benefit the North in certain periods.

In contrast, previous research on climate impacts and optimal climate policies usually implements the so-called "enumerative" approach (Tol 2009), which focuses solely on the impacts of climate change has on production quantities (the physical effects), to assess the welfare consequences of climate change. This approach assumes that the relative prices of goods in a counterfactual world without climate change can be accurately extrapolated to a world with climate damage. [2] It involves collecting damage estimates from different studies and aggregating these damages based on their pre-damage value or their GDP shares.[3] In this paper, I study the errors in these extrapolations and assess the importance of accounting for the effects of relative price changes in addition to the physical effects. Throughout this paper, I will use the "fixed-price enumerative method" to refer to this traditional loss inference approach and the "price-adjusted integrated method" to describe the method that considers relative price effects.

The alternative damage estimates of the fixed-price enumerative method and the price-adjusted integrated method have important policy implications as the damage estimates largely determine the policymaker's optimal levels of mitigation and adaptation efforts. I evaluate climate policies devised by policymakers who are aware of the welfare impacts caused by climate-driven price changes using the price-adjusted integrated framework. The carbon reduction goals established through this approach are then compared with those derived by policymakers using the fixed-price enumerative method. This comparison is to evaluate the differences in optimal climate policies as determined by policymakers who are "informed" about the impacts of these price changes versus those who are "uninformed." I study 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 policymaker 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 consistent with the pre-climate-change North-South inequality would have also increased the abatement levels. I then explore the carbon abatement rates under the non-cooperative Nash Equilibrium, where each region determines its own carbon abatement levels while taking each other's climate policy as given. Under such an equilibrium, unsurprisingly, the North's

[2] By implementing this enumerative approach, the researchers can further formulate their models in a one-commodity neoclassical growth setting. Only when prices are fixed can we aggregate several disaggregated damages, like damages on agricultural and non-agricultural goods, into one aggregate damage function on the one single notional commodity.
[3] The aggregations based on pre-damage market values and pre-damage GDP shares are shown to be equivalent in the Section III.

emission level in 2015 would have been 32% higher. While I focus 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. It first contributes to the literature aimed at 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 some of them further address the roles of trade and migration as an adaptation to climate change. To the best of my knowledge, this paper is the first to study the optimal climate policies in a global model with explicit international trade between sectoral goods. Nath (2020) builds a three-sector Ricardian trade model, where extreme temperature influences workers' productivity. He finds that, due to subsistence food consumption requirements, developing countries fail to specialize in non-agriculture to adapt to climate change, even though it is optimal to do so from a comparative advantage perspective. He uses an exogenous climate module and says little about this "food problem's" implication for climate policy. By contrast, this paper explicitly discusses how the existence of food subsistence levels affects climate policies and climate paths.

This paper also contributes to the well-established literature on Integrated Assessment Models and the cost-benefit analysis of climate policies. Seminal works in this field include Nordhaus (1991), Yang and Nordhaus (1997), Nordhaus and Boyer (2000), Golosov et al. (2014), and Barrage (2020). A typical model in this field integrates a climate model into a standard Ramsey social planner growth model with a homogenous consumption good. Policymakers internalize that carbon emissions will lead to damaging higher global temperatures in the future. They, therefore, face an intertemporal trade-off about whether to reduce carbon emissions today by adapting to "greener" but more expensive production processes. Much research in this literature relies on the fixed-price enumerative method to evaluate welfare effects. The international trade as an adaption to climate change is often modelled implicitly. Economists, scientists, and policymakers have already expressed concerns that such 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 these Integrated Assessment Models. Stern and Stiglitz's (2021) predict that these 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 nearly 100% 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 many IAMs' reliance on the assumption of perfect substitutability between more-impacted and less-impacted goods. National Academy of Sciences (2017) worries that current climate policy models ignore the general equilibrium effects of "food storages." In response, there is a growing literature on the implication of relative price changes for the climate policy. Many of these studies emphasize that climate change will significantly increase the relative scarcity of environmental, non-market goods (Heal and Sterner 2007; Drupp and Hansel 2021; etc.). Dietz and Lanz (2019) and Casey et al. (2021) contribute to this discussion by developing a structural model with subsistence agriculture. However, they do not address regional heterogeneity, as done in this paper.

This paper is structured as follows. Section II lays out the model. Section III explains how to decompose the utility impacts of climate change and discusses the enumerative method. Section IV describes the model calibration strategy. Section V reports the quantitative results and Section VI concludes.

II. The Economy

This section lays out the model structure and equilibrium conditions. Following the terminology of the trade literature, I refer to the North and South as separate countries, denoted by $i \in \{1,2\}$, respectively. The North is cold, developed, and the South is hot, developing.

Households

Each country i is populated by a household of size $L_{i,t}$. Household welfare is defined as an intertemporal population-weighted isoelastic utility function over the flow utility $U_{i,t}$ over a finite time horizon T, with discount factor β and elasticity of intertemporal substitution α:

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

Each period t is five years. There is no capital or saving. 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. Consumers gain utility from 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. Households supply labor inelastically to the intermediate goods firms in the home country and earn wage $w_{i,t}$. 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

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

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 yields the following equation:

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

The population in each country is exogenously given by the population dynamics $L_{i,t} = L_{i,t-1}\left(\frac{L_i^{\infty}}{L_{i,t-1}}\right)^{\delta_i^L}$ 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:

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

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

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

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

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

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

Intermediate Goods

Perfectly competitive intermediate goods firms hire labor from households in the home country to produce intermediate goods and sell the products in both the domestic and foreign markets. The pre-mitigation cost labor productivity of the intermediate firm in sector k in country i at time t $MLP_{i,k,t}$ is a function of exogenously given pre-damage productivity $B_{i,k,t}$ and sector-specific climate damage $\Omega_{i,k,t}$, which is a function of *global degree of warming* 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 benevolent world or national government, and the intermediate firms always take them as given. Section VI discusses these policy scenarios. The mitigation policies $\mu_{i,t}$ can differ across countries but not across 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:

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

subject to

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

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

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

and

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

Here, since $\Omega_{i,A,t}$ and $\Omega_{i,N,t}$ are both functions of the degree of warming H_t, the relative price $\frac{p_{i,A,t}}{p_{i,N,t}}$ is determined by the H_t, too.

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

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

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

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

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

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

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

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

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

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. A country *i*'s emission level at time t, $E_{i,t}$, is

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

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:

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

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

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

with $0 < \phi_1 < 1$ 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.

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 review the fixed-price enumerative method and explain why this traditional approach only partially captures the climate-induced relative utility change. Time index t is omitted here for notation convenience.

The Decomposition of Relative Utility Change

Using the techniques proposed by Tombe (2015), 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. The first term $\frac{p_{i,A}Y'_{i,A}+p_{i,N}Y'_{i,N}}{p_{i,A}Y_{i,A}+p_{i,N}Y_{i,N}}$ is the change in nominal income driven by different production quantities. It also equals the Laspeyres index used to compute the real GDP. The second term $\frac{p'_{i,A}Y'_{i,A}+p'_{i,N}Y'_{i,N}}{p_{i,A}Y'_{i,A}+p_{i,N}Y'_{i,N}}$ is the income change driven by different domestic relative prices for the products the household produces. 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 to meet its subsistence needs. Net of the non-homothetic effect of the changes that are already captured by the subsistence effect, the minimal cost of obtaining a unit of utility is given by the price index

$$P_i = \left[\left(p_{i,A} + \left(\tau_{j,i,A}p_{j,A}\right)^{1-\sigma_A}\right)^{\frac{1}{1-\sigma_A}}\right]^{\omega}\left[\left(p_{i,N} + \left(\tau_{j,i,N}p_{j,N}\right)^{1-\sigma_A}\right)^{\frac{1}{1-\sigma_N}}\right]^{1-\omega}.$$

This price index of the utility is both determined by the domestic price $p_{i,k}$ and the after-shipping-cost foreign price $\tau_{j,i,k}p_{j,k}$. So, we can further decompose the change in this price index into the changes in the domestic goods' prices and the changes in terms-of-trade, which are the fourth and fifth terms in Equation (12). The five terms in Equation (12) can be divided into two distinct categories: physical and relative price effects. The production income effect stands out as it is exclusively influenced by climate-induced changes in the physical quantities of goods produced. In contrast, the other four effects stem from changes in relative prices and incomes.

The Fixed-Price Enumerative Method

Per Tol's survey article (2009), the (fixed-price) enumerative method is widely used 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. For example, 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 by weighting 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. They then 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:

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

where $GDP_i = P_{i,A}Y_{i,A} + P_{i,N}Y_{i,N}$. If we plug the definition of GDP_i into the above equation, we have:

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

The damage ratio turns out to be equivalent to the production income effect in Equation (12). It only computes the physical impacts of climate change. Relative prices after climate change and their utility effects are entirely missing here as the enumerative method values the goods based on their pre-damage market prices $p_{i,k}$ instead of the after-damage prices $p'_{i,k}$.[4] If these missing effects are non-trivial, the enumerative damage estimates would be biased.[5]

IV. Calibration

Table 1 shows a list of the values and sources of each parameter. The values of 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. The long-run agricultural expenditure share ω is set to be 0.01. This value is consistent with the historical trends and is commonly used in the literature (Herrendorf et al. 2014). 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

[4] The aggregations based on pre-damage market values and pre-damage GDP shares are therefore equivalent.

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

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).

Table 1: The Calibrated Parameters[6]

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)
$\sigma_{i,0}^E$	0.0167	Match Global Emission in 2020	$a_{1,A}$	0.060	Cline (2007)
$\sigma_{1,t}^E$	$\sigma_{i,t-1}^E e^{-g_{\sigma^E}(1-\delta_{\sigma^E})}$	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)	$\theta_{1,t}$	$\theta_{1,i-1}(1-\delta_\theta)\sigma_t^E$	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)

Notes: Lists model parameters that are calibrated from 2015 data or taken from the literature.

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)[7] and catastrophic and sea level risings damage at 2.5℃ degrees

[6] 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.
[7] 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.

of warming (Nordhaus 2007). In particular, 2.5 °C 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. As a result, the relative price of agricultural goods will rise globally because of climate change by Equation (6).

The growth rate of carbon emission intensity σ also follows the calibration of DICE-2016R, which assumes that the intensity will decrease over time. The climate module and its calibration follow Ikefuji et al. (2019), which simplifies the climate dynamics in the original DICE-2016R model.

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 the 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

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 scenarios.

This section reports the results of the model. I proceed with the following steps. First, I simulate 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 report the scale of five climate-induced utility effects per Equation (12). I then compare the utility loss implied by the Fixed-Price Enumerative Method and the Price-Adjusted Integrated Method and highlight their differences. Second, I calibrate the damage functions implied by the Fixed-Price Enumerative Method. Third, I evaluate climate policies formulated by policymakers who fail to recognize the welfare impacts of climate-driven price fluctuations by employing the fixed-price enumerative approach. The carbon reduction levels derived from this approach are then compared with those established using the Price-Adjusted Integrated method.

Step 1: Simulate the BAU and NCC equilibriums

In both BAU and NCC, mitigation levels $\mu_{i,t}$ are set exogenously. In BAU, $\mu_{i,t} = 0.02\ \forall\ t$, which reflects the current level of carbon abatement. In NCC, $\mu_{i,t} = 0.0\ \forall\ t$ since carbon abatement is costly and unnecessary. 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 °C by 2095. This temperature projection in general 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 the agricultural sector decreases gradually across time in both scenarios from subplot 2. As income increases in the South, the subsistence level becomes less relevant, leading to a declining share of agricultural employment. 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 compensate for climate-induced domestic production losses. The increased demand from the South boosts the North's export-oriented agricultural production even though its agricultural labor productivity is also harmed by climate change.

Table 3 provides a breakdown of the welfare impacts of climate change 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 effects, relative price effects, and subsistence effects, are counterbalanced by positive price income and terms-of-trade effects. In 2095, the North's utility is affected in various ways: a decrease of 3.07% due to the production income effect, an increase of 1.34% from the price nominal effect, a decrease of 0.09% from the domestic prices effect, an increase of 1.73% from the terms-of-trade effect, and a decrease of 0.03% from the subsistence effect. In 2095, climate change decreases the North's welfare. However, in certain periods like 2060, even though the North's productivity is damaged by climate change, this region will temporarily benefit from climate change because 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, and subsistence collectively lead to a reduction in utility. In 2095, these effects are quantified as follows: the production income effect decreases the flow utility of the South by 4.83%, the price nominal effect by 12.54%, the domestic price effect increases it by 14.86%, the terms-of-trade effect increases it by 0.06%, and the subsistence effect further reduces it by 2.69%. 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, increased agricultural product prices lead 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

Notes: Displays a breakdown of the welfare impacts of climate change on the North and South regions in 2020, 2060, and 2095, based on Equation (12).

Section III shows that the fixed-price enumerative damage estimate equals the production nominal income effect. Hence, results from Table 3 are sufficient for us to compare the price-adjusted integrated utility change and the fixed-price enumerative utility change as we can compare the production income effects and the total effects. For the North in 2090, 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 in 2095 is underestimated by the enumerative approach, which estimates a 4.83% loss compared to the actual 6.91% loss.[8] In other words, the enumerative method greatly 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

[8] The Production Income Effects are shown to be equivalent to the Laspeyres GDP index. Both the Passche Index and Fisher Index infer a loss higher than the real loss in the North and lower in the South.

experiences a 92% decrease in utility loss.[9] These comparisons highlight the importance of accounting for the relative price effects for accurately accounting for the impacts of climate change.

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 aggregate 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

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

And then calibrate a fixed-price enumerative damage function $\Omega_{i,t}$ with $a_{i,FP}$ 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

In this sub-section, policymakers set 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 of climate change. 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: a utilitarian world government, the uncooperative Nash equilibrium, and a "fair" government with time-varying weights on two countries.

Scenario 1: A Utilitarian World Government

This scenario assumes that a 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.

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[9] 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 the fixed-price enumerative model, the policymaker's optimization problem is:

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

subject to

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

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

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

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

In this problem, 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 isoelastic utility subject to implementability constraints (1) - (6), (8)[10] and the law of climate system (9) - (11) $\forall\ 0\le t\le T$:

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

subject to (1) - (6), (8), and

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

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

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

$$M_{t+1}=\phi_1 M_t+\left(1-\mu_{1,t}\right)\sigma_t^E \mathrm{B}_{1,N,t}L_{1,t}+\left(1-\mu_{2,t}\right)\sigma_t^E \mathrm{B}_{1,N,t}L_{2,t}$$

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

and mitigation bounds

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

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

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. Mitigation rates gradually increase over time and reach the upper bound after decades under both models. Higher South utility loss driven by relative price changes in the price-adjusted integrated 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% 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°C lower (Figure 2-B).

In scenario 1, because the South is populous and has a lower consumption level, the policymaker has a tendency to reallocate 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 because she faces the binding income budget constraint (8), she still can impose most of the mitigation burdens on the North. As shown in Figure 2-A and 2-C, the mitigation rates and mitigation costs in the North are much higher than those in the South. Therefore, the North is worse off under this scenario because the mitigation costs of the 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 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:

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

subject to

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

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

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

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

subject to (1) to (8) and

$$M_{t+1}=\phi_1 M_t+\left(1-\mu_{1,t}\right)\sigma_t^E \mathrm{B}_{1,N,t}L_{1,t}+\left(1-\mu_{2,t}\right)\sigma_t^E \mathrm{B}_{1,N,t}L_{2,t}$$

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

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

Figures 3-A and 3-B demonstrate the mitigation and climate path in the two models under the Nash equilibrium. In both models, the magnitudes of mitigation levels in both countries are considerably lower than those under a centralized world government because of the free-riding problem. We observe fewer carbon efforts in the North and more efforts in the South in the price-adjusted integrated model compared to the fixed-price enumerative model. Specifically, in 2015, the North reduces the magnitude of its carbon abatement level by 68%, while the South slightly increases the magnitude of its mitigation level by 21% (Figure 3-A). These change mitigation levels are because the North utility loss is lower, and the South utility loss is higher under the price-adjusted integrated model. In the end, the climate paths of the relative price and fixed-price enumerative models are practically identical because the carbon abatement rates are both trivial under both models (Figure 3-B).

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. This setting follows the spirit of the time-varying Negishi weight method proposed by Nordhaus and Yang (1997). Here, the world government treats the NCC world as the optimal world despite the North-South inequality under the NCC. Hence, this world government would try to replicate the NCC world. The reason is that, according to this world government's utility function, the marginal benefits of the North and South's consumption are equalized under the NCC scenario. Compared to the world government in Scenario 1, this government is fairer as it tends to allocate the burden of carbon abatements more uniformly across the North and

South.[11] Because its policies are Pareto-improving for each region, the optimal mitigation rates set by this world government are more feasible in the real world.

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

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

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

subject to

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

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

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

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

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

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

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

subject to

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

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

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

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

and mitigation bounds

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

One twist here is that the welfare weights of the world government are different under the price-varying enumerative method and the price-adjusted integrated method. So, the different policies under the two models may be driven by the different welfare weights instead of their

[11] You may also regard this world government as "unfair".

different damage estimates. Therefore, I also solve the world government Ramsey problem under the Enumerative Method using the welfare weights under the relative price approach:

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

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

subject to

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

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

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

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

We can observe the results of three Ramsey problems in Figure 4. At $t=0$, the magnitudes of mitigation levels in the North and the South are about 30% higher under the price-adjusted integrated model than those under the fixed-price enumerative model. 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, the difference between the mitigation rates under the fixed-price model and the price-adjusted model would be smaller because the magnitude of South mitigation rates will be 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°C 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. I further show that climate change can influence households' utility through its physical and relative price effects. While the IAM literature typically focuses on climate change's effects on quantities, I show that its relative price effects are also quantitatively important. Hence, the results of the commonly used fixed-price enumerative method and the price-adjusted integrated method proposed by this paper 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, agriculture-importing South. If a utilitarian world government begins to account for these relative price effects, the optimal magnitude of the carbon abatement levels would be higher. However, under the non-cooperative Nash Equilibrium, the North, facing lesser climate impacts, increases its carbon emissions.

I conclude with several suggestions for future research. The framework proposed in the paper can be 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. The limited land supply can potentially curb marginal worker productivity in agriculture, reducing the global welfare gain of the North's potential specialization in agriculture. Also, capital accumulation in the South might be affected by the food problem since more workers might be allocated to produce food to meet the subsistence level instead of producing capital goods, delaying the capital accumulation in the less-developed South. 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, affecting welfare through relative price channels. 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. 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)

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Appendix: Sensitivity Analysis

In this section, I perform a sensitivity analysis for the scale of the relative price effects, that is, the difference between the fixed-price enumerative loss and the price-adjusted integrated loss. To be more specific, I examine how the magnitudes of the relative price effects changes with respect to changes of four parameters: the subsistence level $\bar{a}$, the agricultural damage parameter $a_{A,i}$, and icerberg cost τ.

Subsistence Level

From Equation (12), we learn that the subsistence level $\bar{a}$ is the key driver for the subsistence effect. Figure 5 depicts the effects of varying the subsistence level $\bar{a}$. A higher subsistence level implies a higher non-homotheticity. So, the relative price effects become 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 total relative price effects respond 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 practically identical utility losses in the North. It is worth noting that a small relative price change does not necessarily mean a negligible subsistence effect in the South as long as the nominal income changes. As the agricultural damage parameter increases, the difference between the implied utility losses increases.

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 total relative price effects (Figure 7). We observe that, as iceberg cost increases, the magnitudes of the relative price effects increase, too. These results demonstrate the importance of trade as an adaptation to alleviate climate change's welfare costs.