Climate Policy and International Risk Sharing*

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Abstract

We study the strategic interaction among heterogeneous countries in a stochastic growth model of climate change. Each country is exposed to exogenous fundamental and endogenous climate risk determined by global temperature. We analyze alternative market arrangements determining the extent of trade and international capital flows as well as the scope for risk sharing through financial markets. We provide analytical characterizations of optimal climate policies under non-cooperation, and full cooperation and show how these policies depend on the underlying market structure. Numerical simulations quantify the welfare gains from trade and financial risk sharing, as well as from cooperation in addressing the climate externality. In the absence of cooperation, introducing risk-sharing opportunities through financial markets tends to benefit countries that are less exposed to climate change, while more exposed countries gain only when direct international capital investment is feasible. Quantitatively, we find that the combined gains from financial market openness and capital trade are substantially larger than those achieved through cooperation under international climate agreements.

JEL classification: E62; H21; H23; Q52; Q54

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1 Introduction

Climate change will almost certainly induce substantial damages in many countries. The exact magnitude and timing of these damages, however, is highly uncertain, differs across countries, and also correlates with other sources of economic fluctuations. Crucially, the scale of climate damages depends on climate policy: the more ambitiously countries cut global emissions, the lower the risks induced by climate change. Beyond the global climate, countries are also linked through global markets, where trade of goods, capital, and financial assets offer opportunities to diversify and share risks. This raises the question of how the market structure interacts with policy cooperation in shaping countries' incentives to mitigate emissions, and their ability to manage residual climate risk.

In this paper, we explore the links between climate risk, climate policy, and the global market structure by addressing the following questions: i) Can countries use international markets to insure against climate risks? ii) Do all regions benefit from a more complete market structure consisting of additional financial assets and trade opportunities? iii) To what extent does enhanced risk-sharing via international markets lower the urgency for internationally coordinated climate policy?

To answer these and a number of related questions, we develop a stochastic growth model of climate change with multiple heterogeneous regions and endogenous climate risk. Using this framework, we study the equilibrium effects of alternative market arrangements as well as optimal climate policies under cooperation and non-cooperation both theoretically and with the help of numerical simulations.

Theoretical results

Comparing the equilibrium restrictions under different market structures allows us to identify the efficiency gains from risk-sharing via financial markets and international trade of capital. A first set of results studies the stochastic properties of regional consumption and the world consumption distribution under alternative market scenarios and how it depends on regional and global risk factors. We employ various notions of efficiency to determine the gains from a more complete market structure and demonstrate how it leads to harmonization of prices for internationally traded goods and assets. Moreover, a general insight is that international financial markets give rise to a synchronization mechanism affecting also the prices and returns of region-specific assets even if they are not traded across countries.

Secondly, to assess the value from international coordination of climate policy, we provide an analytical characterization of optimal climate policies under cooperation and non-cooperation and show how its structure is shaped by the underlying market structure. We demonstrate that despite identical risk preferences, the market structure determines the (stochastic) discount factors by which countries discount future damages while the degree of cooperation determines which of these damages are internalized. Heterogeneous discount factors under incomplete financial markets therefore lead to disagreement about optimal carbon pricing even if countries agree on the damages to be internalized. Conceptually, these findings extend the deterministic results on optimal climate policy from Hillebrand (2025) to the present model of a stochastic economy. We also extend the separability result from Hillebrand and Hillebrand (2019) and derive an aggregation result that has direct virtue for the computation of equilibrium allocations under complete financial markets.

Quantitative results
For each of the market scenarios considered, we use global functional methods to recursively determine policy and transition functions defined on a common state space generating all equilibrium variables. Our regional structure distinguishes vulnerable regions facing severe climate damages and resilient regions less exposed to climate risk. The main quantitative findings are as follows: First, global financial markets disproportionately benefit resilient regions: vulnerable regions face capital devaluation effects that overcompensate the positive risk-sharing effects of consumption insurance. Second, capital mobility benefits vulnerable regions: the induced efficiency gains allows vulnerable countries to lower precautionary capital investment and increase their relative lifetime income. The combined gains of financial market openness and capital mobility are strictly positive for all countries, eliminating the need for direct Pareto-improving transfers across countries. Finally, cooperation gains are positive for the vulnerable region but tend to be negative for resilient regions. The resilient region faces lower climate damages and attracts more of the fossil-fuel intensive production, resulting in both adverse incentives for the internalization of climate damages and an inefficient allocation of fossil fuel inputs.

Relation to the literature
With these results, our paper contributes to three different strands of the literature. Firstly, there is a large recent literature that uses dynamic general equilibrium models of climate change with multiple regions to study optimal climate policy under cooperation and non-cooperation. Examples are Hambel et al. (2021), Hassler and Krusell (2012), Hassler et al. (2026) or Hillebrand and Hillebrand (2019). These papers make different assumptions about trade between countries, ranging from merely trade of fossil fuels in Hassler and Krusell (2012) to frictionless international trade of commodities and production factors in Hillebrand and Hillebrand (2019). A major contribution of our paper is that it permits to explicitly evaluate the role of the underlying market structure and its consequences for climate policy and welfare. Moreover, all the previous studies are deterministic, and our results generalize them to a stochastic setup.

Our work also contributes to the literature on climate change and risk as studied, e.g., in Barnett, Brock, and Hansen (2020), Hambel and van der Ploeg (2025), or Fried et al. (2022). Specifically, these studies emphasize the transition risk associated with moving from a high-carbon to a low-carbon economy. Such risks can be due to policy changes, technological shifts, and asset revaluation, and this literature typically analyzes how alternative transition paths affect capital values, asset prices, and other macroeconomic aggregates. We connect to this line of research by treating climate policy and emissions as endogenous and by explicitly examining how different market arrangements, both in terms of asset trade and international capital mobility, shape the importance of physical risks and the associated welfare consequences.

With respect to our specific goal of analyzing international risk-sharing in the spirit of Corsetti, Dedola, and Leduc (2008), there appear to be relatively few applications in the context of climate change. A notable exception is Kübler (2025) who studies the welfare effects of sharing climate risk via financial markets in a multi-region model of climate change with capital trade. He finds that introducing a more complete asset market structure is always beneficial for all countries. The analysis in our paper is closely aligned with this perspective, but we explore alternative market structures and also incorporate the role of optimal climate policy and cooperation in our setup which is not considered in Kübler (2025). As a result, the welfare effects that we obtain are quite different and not necessarily positive for all countries.

Lastly, we contribute to the literature on game-theoretic aspects of climate policy as studied in Harstad (2012, 2016), Battaglini and Harstad (2016), or Okada (2023). These studies tend to use rather stylized economic models, while we employ a full-fledged dynamic growth model with different sources of risk and international trade to study optimal climate policy under cooperation and non-cooperation. Here, our paper offers a novel conceptual approach also used in Hillebrand (2025) to reconcile strategic choices of regional emissions with price-taking behavior on international markets.

Structure of the paper
The paper is organized as follows. Section 2 introduces the model. Section 3 studies the decentralized equilibrium and its properties under different market structures for given climate policies. Sections 4 and 5 derive optimal climate policies under non-cooperation and full cooperation, respectively. Section 6 presents quantitative results from numerical simulations. Section 7 concludes, proofs for our main results and details on the numerical solution of the model are placed in Appendices A and B.

2 Model

2.1 Setup and notation

Time and regional structure
Time evolves in discrete periods $t = 0, 1, 2, \dots$ where $t = 0$ is the initial period. The world economy is divided into $L \geq 2$ politically autonomous regions indexed by $\ell \in \mathbb{L} := \{1, ..., L\}$. A superscript ℓ indexes region-specific variables while a bar-superscript is used to denote summations of this variable over all regions. For example, C_t^ℓ will be consumption in region $\ell \in \mathbb{L}$ at time t while $\overline{C}_t := \sum_{\ell \in \mathbb{L}} C_t^\ell$ denotes global consumption.

Exogenous states and probabilistic structure
Exogenous uncertainty in period t is represented by a random state s_t drawn from the

finite set $\mathbb{S} = \{1,...,S\}$, $S \geq 2$. The initial state $s_0 = \bar{s}_0 \in \mathbb{S}$ fixed and known. The sequence of random variables $(s_t)_{t\geq 0}$ is a time-homogenous Markov process with time-invariant transition probability $M : \mathbb{S} \times \mathbb{S} \to]0,1]$ where $M(s,s')$ is the probability that $s_{t+1} = s'$ given $s_t = s$. Denote by $s^t := (s_0,...,s_t)$ the history of states observed up to period t. By a slight abuse of notation, write $s^t = (s^{t-1}, s_t)$. Let $\mathbb{S}_t$ denote the set of all possible histories in period t defined recursively as $\mathbb{S}_0 := \{\bar{s}_0\}$ and $\mathbb{S}_t := \mathbb{S}_{t-1} \times \mathbb{S}$ for $t = 1,2,3,....$ The Markov structure of states permits to recursively construct probability functions $\mu_t : \mathbb{S}_t \to]0,1]$ over histories s^t for all t by setting $\mu_0(s_0) := 1$ and $\mu_t(s^t) := \mu_{t-1}(s^{t-1}) \cdot M(s_{t-1}, s_t)$ for $t = 1,2,3\ldots$ The value $\mu_t(s^t) > 0$ is the probability of observing a particular history $s^t \in \mathbb{S}_t$. Note that we assume all histories to have strictly positive probability.[1]

Processes of endogenous variables

All endogenous variables determined in period t are random variables that can depend on all exogenous states observed up to and including period t. A sequence of random variables $(\xi_t)_{t\geq 0}$ with values in Ξ is an *adapted stochastic process* if each ξ_t depends only on the history s^t up to time t, i.e., $\xi_t : \mathbb{S}_t \longrightarrow \Xi, s^t \mapsto \xi_t(s^t)$. Our subsequent notation will typically suppress the dependence of endogenous variables on histories. Equalities and inequalities between endogenous variables are therefore understood to hold for all histories. For example, $C_t^\ell \geq 0$ is a short-hand for $C_t^\ell(s^t) \geq 0$ for all $s^t \in \mathbb{S}_t$.

Unconditional and unconditional expectation

The probability functions $(\mu_t)_{t\geq 0}$ over histories permit to define the (unconditional) expectation of a generic random variable $\xi_t : \mathbb{S}_t \to \Xi$ determined in period t as

$$\mathbb{E}[\xi_t] := \sum_{s^t \in \mathbb{S}_t} \mu_t(s^t) \cdot \xi_t(s^t). \tag{1}$$

This definition extends to infinite sums of random variables $(\xi_t)_{t\geq 0}$ by setting

$$\mathbb{E}\left[\sum_{t=0}^{\infty} \xi_t\right] := \lim_{T\to\infty} \mathbb{E}\left[\sum_{t=0}^{T} \xi_t\right] = \lim_{T\to\infty} \sum_{t=0}^{T} \mathbb{E}[\xi_t]. \tag{2}$$

The conditional expectation of random variable ξ_{t+1} determined in $t+1$ conditional on information in period t is denoted and defined as

$$\mathbb{E}_t[\xi_{t+1}] := \sum_{s\in\mathbb{S}} \frac{\mu_{t+1}(s^t, s)}{\mu_t(s^t)} \cdot \xi_{t+1}(s^t, s) = \sum_{s\in\mathbb{S}} M(s_t, s) \cdot \xi_{t+1}(s^t, s). \tag{3}$$

Note that $\mathbb{E}_t[\xi_{t+1}]$ is itself a random variable that depends on the history $s^t \in \mathbb{S}_t$.

Using the previous probabilistic structure, the following subsections describe the major building blocks of the model consisting of the production and consumption sector in each region $\ell \in \mathbb{L}$ as well as a global climate model.

2.2 Production sector

Production technology

In each region $\ell \in \mathbb{L}$ a single representative firm produces consumable output $Y_t^\ell \geq 0$ in

[1] This assumption can easily be relaxed by restricting the sets $\mathbb{S}_t$ to the support of μ_t.

period t using capital $K_t^\ell \geq 0$ and fossil fuels $X_t^\ell \geq 0$ as inputs. The latter subsumes all kinds of fossil fuels (coal, oil, etc.) and can be extracted at constant unit cost $c_x > 0$. There is no explicit resource constraint implying that fossil fuels are abundant. Capital is formed endogenously using final output and depreciates at constant rate $0 < \delta_K \leq 1$. The production technology of region ℓ takes the general form

$$Y_t^\ell = Z_t^\ell \cdot (1 - D_t^\ell) \cdot F_t^\ell(K_t^\ell, X_t^\ell). \tag{4}$$

Here, Z_t^ℓ denotes country-specific total factor productivity (TFP) while $D_t^\ell \in [0,1]$ denotes endogenous climate damages further specified below. Regional TFP is generated by the map $\theta^\ell : \mathbb{S} \to \mathbb{R}$ such that

$$Z_t^\ell(s_t) := \exp(\theta^\ell(s_t)). \tag{5}$$

Since regional TFP depends only on the current state s_t, the process $(Z_t^\ell)_{t\geq 0}$ mirrors the exogenous state process $(s_t)_{t\geq 0}$ but can be region-specific in terms of its size and the co-movements across regions. This specification is sufficient to capture the magnitude and correlations of exogenous business cycle fluctuations in each country $\ell \in \mathbb{L}$.

Properties of the production technology
The sequence of production functions $(F_t^\ell)_{t\geq 0}$ is deterministic and independent of exogenous states. Time-dependence of $F_t^\ell(\cdot)$ captures both population growth as well as exogenous technological progress. The following assumption imposes standard restrictions on production functions.

Assumption 1
The function $F_t^\ell : \mathbb{R}_+^2 \to \mathbb{R}_+$ satisfies $F_t^\ell(0,0) = 0$ and is strictly increasing, strictly concave, and continuously differentiable on $\mathbb{R}_{++}^2$. The partial derivatives satisfy

$$\lim_{K \searrow 0} \partial_K F_t^\ell(K,X) = \infty \quad \textit{for all } X > 0 \quad \textit{and} \quad \lim_{X \searrow 0} \partial_X F_t^\ell(K,X) = \infty \quad \textit{for all } K > 0. \tag{6}$$

Condition (6) ensures that both production factors are employed at equilibrium.

2.3 Climate model

Climate damages and risk
Climate damages in (4) are determined by global temperature anomaly T_t via the damage function

$$D_t^\ell := 1 - \exp(-\gamma_t^\ell T_t). \tag{7}$$

The exponential form (7) is widely used in the literature (cf. Golosov et al. (2014) and Gerlagh and Liski (2018)) and implies marginal damages $\gamma_t^\ell \cdot Y_t^\ell$. The process $(\gamma_t^\ell)_{t\geq 0}$ mirrors the exogenous state process $(s_t)_{t\geq 0}$ and is generated by a map $\gamma^\ell : \mathbb{S} \to \mathbb{R}$,

$$\gamma_t^\ell := \gamma^\ell(s_t). \tag{8}$$

The previous structure is suitable for our purpose of incorporating endogenous, region-specific climate risk into our model.

Global emissions and temperature
Following Dietz and Venmans (2019) and Rezai and van der Ploeg (2021), we assume a linear relation between temperature and cumulative emissions E_t relative to $t = 0$, i.e.,

$$T_t = T_{-1} + \zeta \cdot E_t \tag{9}$$

where $\zeta > 0$ denotes temperature sensitivity. To render the model dynamics asymptotically stationary, we slightly deviate from the model in Rezai and van der Ploeg (2021) by supposing that cumulative emissions decay at a small rate $\delta_E \in (0,1)$ such that

$$E_t = (1-\delta_E) \cdot E_{t-1} + \overline{X}_t \tag{10}$$

where $\overline{X}_t = \sum_{\ell \in \mathbb{L}} X_t^\ell$ denotes global emissions in period t. Combining (9) and (10) one obtains the temperature dynamics in the following recursive form

$$T_t = \delta_E \cdot T_{-1} + (1-\delta_E) \cdot T_{t-1} + \zeta \cdot \overline{X}_t \quad \text{for all } t = 0,1,2,\ldots \tag{11}$$

For $\delta_E = 0$, this specification is fully consistent with Rezai and van der Ploeg (2021).

2.4 Consumption sector

Representative consumer
The consumption sector in region $\ell \in \mathbb{L}$ consists of a single representative household who consumes C_t^ℓ and forms $K_t^{\ell,s}$ units of new capital in each period $t = 0,1,2,\ldots$ for the next period $t+1$. Initial capital $K_{-1}^{\ell,s}$ formed prior to $t = 0$ is taken as given in the decision. The consumer is entitled to receive all profits from the domestic production sector and any transfers from the regional government.

Consumer preferences
The households' preferences over non-negative consumption processes $\left(C_t^\ell\right)_{t\geq 0}$ are represented by the following time-additive expected utility function

$$U\left((C_t^\ell)_{t\geq 0}\right) = \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t u(C_t^\ell)\right] \quad \text{where} \quad u(C) = \begin{cases} \frac{C^{1-\sigma}}{1-\sigma} & \text{for } \sigma > 0, \sigma \neq 1 \\ \log(C) & \text{for } \sigma = 1. \end{cases} \tag{12}$$

The discount factor satisfies $0 < \beta < 1$. The specification (12) is widely used in economic models of climate change and known to be consistent with balanced growth in the absence of climate damages (cf. King, Plosser, and Rebelo (1988)). The form of preferences is key for the separability between efficiency and optimality exploited in Hillebrand and Hillebrand (2019) and also used below in the derivation of optimal climate policies for the complete markets case.

2.5 Fundamentals and risk structure

The economy

The economy introduced in this section can be summarized by its regional and stochastic structure, the parameters of production, climate model, damages, and preferences. Formally, the fundamentals of the economy are

$$\mathcal{E} = \left\langle \mathbb{L}, \mathbb{S}, M, \left((F_t^\ell)_{t\geq 0}, \theta^\ell, \gamma^\ell\right)_{\ell\in\mathbb{L}}, \delta_K, c_x, \delta_E, \zeta, \beta, \sigma \right\rangle \tag{13}$$

In addition, the initial state $s_0 = \bar{s}_0 \in \mathbb{S}$ and the initial capital distribution $(K_{-1}^{s,\ell})_{\ell\in\mathbb{L}}$ as well as initial initial temperature T_{-1} are given. Initial cumulative emissions relative to $t = 0$ satisfy $E_{-1} = 0$.

Fundamental and endogenous risks

Combining (4) and (7) permits to decompose output produced in region ℓ at time t into three factors:

$$Y_t^\ell = \underbrace{Z_t^\ell}_{I} \cdot \underbrace{(1 - D_t^\ell)}_{II} \cdot \underbrace{F_t^\ell(K_t^\ell, X_t^\ell)}_{III} = \underbrace{\exp\left(\theta_t^\ell\right)}_{I} \cdot \underbrace{\exp\left(-\gamma_t^\ell \cdot T_t\right)}_{II} \cdot \underbrace{F_t^\ell(K_t^\ell, X_t^\ell)}_{III}. \tag{14}$$

Factor I represents exogenous business cycle risk, which is independent of policy choices but can be potentially (partially) insured via international financial markets to the extent that this risk is aggregate. Factor II captures endogenous climate risk determined by global temperature (9) which is shaped by the joint mitigation efforts of all regions. Depending on the correlation structure of the functions in (8), this risk may also be partially insured against. Factor III represents exogenous deterministic growth forces determining the sequence $(F_t^\ell)_{t\geq 0}$ such as region-specific population and productivity growth as well as endogenous growth driven by capital accumulation.

The exponential form of total factor productivity (5) and climate damages (7) permits to combine factors I and II in (14) to obtain net TFP in period t as

$$Q_t^\ell := \exp\left(\theta_t^\ell - \gamma_t^\ell \cdot T_t\right). \tag{15}$$

Regional output (4) can then be denoted more compactly as $Y_t^\ell = Q_t^\ell F_t(K_t^\ell, X_t^\ell)$.

Scope for cooperation, trade, and risk sharing

A main theoretical question of this paper is how countries can share the risks posed by factors I and II based on available market structures and political arrangements. It stands to reason that the scope for risk-sharing depends on the existence of assets whose pay-offs can be made contingent on the exogenous state s_t. As a result, potential gains from risk-sharing are shaped by the correlation patterns (within and cross-country) borne out by dependencies of θ^ℓ and γ^ℓ on s_t. Moreover, the severity of climate risk is scaled by global temperature T_t which in turn depends on mitigation efforts in each country. Thus, our model captures a direct connection between climate policy and risk sharing. The gains from cooperation for a specific region $\ell \in \mathbb{L}$ will be shaped by its susceptibility to climate damages D_t^ℓ determined by the levels of γ_t^ℓ, but also by its reliance on fossil fuels X_t^ℓ and the substituteability with clean factors represented by capital K_t^ℓ. In addition, there are further potential trade gains due to regional heterogeneity of the technologies F_t^ℓ due to region-specific demographics and technological developments such as labor- and energy augmenting technological change. In addition, there is scope for permanent as well as transitory improvements via trade due to specialization and factor reallocation, respectively. Thus, our model is flexible enough to study multiple aspects of climate policy and its interaction with risk-sharing and trade on international markets.

3 Decentralized equilibrium

This section studies the decentralized equilibrium of the economy where consumers and producers interact on markets taking available production technologies and resource constraints as well as prices and climate policies as given. To understand the gains from trade and risk sharing, the analysis distinguishes three market scenarios. First, the case of autarky where regions trade neither capital nor in financial market. Second, the case with complete financial markets where regions trade Arrow-securities permitting to ensure against risk. Third, the case with complete financial markets and international capital trade where regions can directly transfer capital to other regions. In each case, we establish the structure and form of equilibrium for an arbitrary climate policy. Optimal climate policies under non-cooperation and full-cooperation and the resulting properties of equilibrium will be studied in Sections 4 and 5. As a result, the theoretical comparison in the presents section quantifies the gains from trade and risk-sharing, while the comparison of non-cooperative and cooperative climate policy under the third market scenario permits to study the additional gain of coordinating international climate policy.

3.1 Climate policy

Each region $\ell \in \mathbb{L}$ chooses a process of state-contingent carbon taxes $(\tau_t^\ell)_{t\geq 0}$ where τ_t^ℓ is the tax per unit of emissions in period t paid by the production sector. All tax revenue in period t is fully returned as a lump sum transfer $\tau_t^\ell \cdot X_t^\ell$ to the domestic consumer.[2] The process $(\tau_t^\ell)_{t\geq 0}$ may consist of given exogenous random variables but can also be generated by a time-invariant rule that depends on endogenous and exogenous variables.

[2]We abstract from cross-regional transfers for the following reasons. Firstly, under autarky, cross-border good flows are prohibited, making transfers across regions inconsistent with the underlying structural trade restriction. Secondly, under cooperation, transfers would be used by the planner to share risks explicitly using transfers, replicating the complete markets allocation even in the absence of financially developed markets whereas this paper focuses on the risk-sharing potential of carbon taxation only, which would be blurred by perfect risk-sharing via transfers. Lastly, the political set-up of politically autonomous regions studied here would require commitment devices to avoid regions defecting on the solution under cooperation. On behalf of the lack of evidence supporting the political feasibility of such state-contingent international transfers, we therefore exclude such transfer schemes.

3.2 Autarky

Market structure

Under autarky regions do not exchange commodities or capital and do not trade assets on international financial markets. In each period $t = 0,1,2,\ldots$, there exists a local commodity market and a local capital market in each region $\ell \in \mathbb{L}$. Denote by r_t^ℓ the rental price of capital and by $R_t^\ell := r_t^\ell + 1 - \delta_K$ the gross capital return in region ℓ at time t. The consumption good is the numeraire in each region such that prices in region ℓ are denominated in units of local output. Demanded and supplied amounts of capital are identified by superscripts s and d.

Producer behavior

Given the technology F_t^ℓ and net TFP Q_t^ℓ determined by (15), the production sector in period t determines profits Π_t^ℓ by solving the following maximization problem taking the capital price r_t^ℓ and regional tax τ_t^ℓ as given:

$$\Pi_t^\ell = \max_{K^\ell, X^\ell \geq 0} \left\{ Q_t^\ell \cdot F_t^\ell(K^\ell, X^\ell) - r_t^\ell \cdot K^\ell - (c_x + \tau_t^\ell) \cdot X^\ell \right\}. \tag{16}$$

Profits in (16) are transferred to consumers in region ℓ. Under Assumption 1, profit maximizing factor demand $(K_t^{\ell,d}, X_t^{\ell,d})$ solves the standard first order conditions

$$Q_t^\ell \cdot \partial_K F_t^\ell(K_t^{\ell,d}, X_t^\ell) = r_t^\ell \quad \text{and} \quad Q_t^\ell \cdot \partial_X F_t^\ell(K_t^{\ell,d}, X_t^\ell) = \tau_t^\ell + c_x. \tag{17}$$

Consumer behavior

The representative consumer in region ℓ receives factor income from supplying capital $K_{t-1}^{\ell,s}$ formed in the previous period $t-1$ and collects profits Π_t^ℓ from the final sector as well as the transfers $\tau_t^\ell \cdot X_t^\ell$ from the local government. We interpret $K_t^{\ell,s}$ as physical assets and, therefore, need to have $K_t^{\ell,s} \geq 0$ in all periods. Consumption and newly formed capital must be chosen from a budget set defined by

$$K_t^{\ell,s} \leq \Pi_t^\ell + R_t^\ell \cdot K_{t-1}^{\ell,s} + \tau_t^\ell \cdot X_t^\ell - C_t^\ell \quad \text{for each } t = 0,1,2,\ldots \tag{18}$$

The household's formal decision problem then reads:

$$\max_{(C_t^\ell, K_t^{\ell,s})_{t\geq 0}} \left\{ U\left((C_t^\ell)_{t\geq 0}\right) \middle| (18),\ C_t^\ell \geq 0 \text{ for all } t = 0,1,2,\ldots \right\}. \tag{19}$$

Standard arguments imply that any solution $(C_t^\ell, K_t^{\ell,s})_{t\geq 0}$ to the decision problem (19) is interior, i.e., $C_t^\ell, K_t^{\ell,s} > 0$ and satisfies (18) with equality and the Euler equation

$$u'(C_t^\ell) = \beta \cdot \mathbb{E}_t \left[u'(C_{t+1}^\ell) \cdot R_{t+1}^\ell \right] \tag{20}$$

for all $t = 0,1,2,\ldots$, as well as the transversality condition

$$\lim_{t\to\infty} \beta^t \cdot \mathbb{E}\left[u'(C_{t+1}^\ell) \cdot K_t^{\ell,s} \right] = 0 \tag{21}$$

Market clearing
The equilibrium concept reconciles market clearing with optimal behavior of households and producers for a given climate policy. The market clearing condition for the capital market is

$$K_t^{\ell,d} = K_{t-1}^{\ell,s} \quad \text{for } t = 0, 1, 2, \ldots \tag{22}$$

A direct implication of (22) is that capital input in period t is pre-determined by capital formation in period $t-1$. We therefore denote equilibrium capital for region ℓ formed in period t for $t+1$ by

$$K_t^{\ell} := K_t^{\ell,s}. \tag{23}$$

Then, equilibrium capital returns and factor inputs solve the conditions

$$Q_t^{\ell} \partial_K F_t^{\ell}(K_{t-1}^{\ell}, X_t^{\ell}) = r_t^{\ell} \quad \text{and} \quad Q_t^{\ell} \partial_X F_t^{\ell}(K_{t-1}^{\ell}, X_t^{\ell}) = \tau_t^{\ell} + c_x \tag{24}$$

Using the definition of profits (16) and (23) in the consumer's budget equation (18) one obtains the aggregate resource constraint determining the evolution of regional capital

$$K_t^{\ell} = Q_t^{\ell} F_t(K_{t-1}^{\ell}, X_t^{\ell}) + (1 - \delta_K) \cdot K_{t-1}^{\ell} - c_x \cdot X_t^{\ell} - C_t^{\ell}. \tag{25}$$

Definition of equilibrium
Following definition of equilibrium under autarky is now straightforward.

Definition 1
A decentralized equilibrium of $\mathcal{E}$ under autarky consists of adapted processes of climate policy $\big((\tau_t^{\ell})_{t\geq 0}\big)_{\ell\in\mathbb{L}}$, an allocation $A^* = \big((K_t^{\ell *}, X_t^{\ell *}, C_t^{\ell *})_{t\geq 0}\big)_{\ell\in\mathbb{L}}$, regional capital prices $P^* = \big((r_t^{\ell *})_{t\geq 0}\big)_{\ell\in\mathbb{L}}$, and temperature $T^* = (T_t^*)_{t\geq 0}$ such that for all $t \geq 0$ and each $\ell \in \mathbb{L}$:

(i) The producer's optimality conditions (24) *are satisfied.*

(ii) The consumer's optimality condition (20) *and resource constraint* (25) *hold.*

(iii) Emissions and temperature evolve as in (11) *determining net TFP by* (15).

3.3 Complete financial markets

Market structure
The arrangement with complete financial markets refers to the situation where regions trade state-contingent claims permitting to ensure against the exogenous state in the next period. Formally, in each period t and history $s^t \in \mathbb{S}_t$, there exists a complete set of Arrow securities traded at prices $q_{t,t+1}(s^t, s)$ for each $s \in \mathbb{S}$. The Arrow security pertaining to state $s \in \mathbb{S}$ delivers one-unit of the consumption good in $t+1$ if and only if the state s materializes, i.e., $s_{t+1} = s$.
While trading of assets necessarily induces real payment flows between countries, we continue to assume that capital can only be formed at the domestic level implying a regional

capital price r_t^ℓ in each period t as before. However, since domestic capital investment in period t now competes with financial investment in Arrow securities, the gross capital return $R_{t+1}^\ell = r_{t+1}^\ell + 1 - \delta_K$ must satisfy the no-arbitrage condition

$$\sum_{s\in\mathbb{S}} q_{t,t+1}(s^t,s)\cdot R_{t+1}^\ell(s^t,s) = 1 \tag{26}$$

for all $t = 0,1,2,\ldots$ and all $s^t \in \mathbb{S}_t$. Economically, condition (26) equates the value of the portfolio of Arrow securities replicating the domestic capital asset to the real price of capital investment in period t which is unity. Thus, the introduction of international financial markets induces a synchronization mechanism for regional capital returns.

The previous asset structure gives rise to an adapted process $(q_t)_{t\geq 0}$ of so-called Arrow-Debreu (AD) prices (stochastic discount factors) defined recursively as $q_0 := 1$ and

$$q_t(s^t) := q_{t-1}(s^{t-1})\cdot q_{t-1,t}(s^{t-1},s_t) \quad \text{for all } t = 1,2,3,\ldots \text{ and } s^t = (s^{t-1},s_t)\in\mathbb{S}_t. \tag{27}$$

The AD-price $q_t(s^t)$ expresses the value of a unit of output/consumption in period t under history $s^t \in \mathbb{S}_t$ in units of consumption in $t = 0$. For purposes of a compact notation, define the probability adjusted AD-price for each $t = 0,1,2,\ldots$ and $s_t \in \mathbb{S}_t$ as

$$q_t^p(s^t) := q_t(s^t)/\mu_t(s^t). \tag{28}$$

Combining (2) and (28) permits to express discounted sums of adapted stochastic processes $(\xi_t)_{t\geq 0}$ compactly as the unconditional expectation

$$\sum_{t=0}^{\infty}\sum_{s^t\in\mathbb{S}_t} \xi_t(s^t)\cdot q_t(s^t) = \mathbb{E}\left[\sum_{t=0}^{\infty} q_t^p\cdot\xi_t\right] = \sum_{t=0}^{\infty}\mathbb{E}\left[q_t^p\cdot\xi_t\right]. \tag{29}$$

Producer behavior

The production sector in region ℓ takes adapted processes of net-TFP $(Q_t^\ell)_{t\geq 0}$ defined as in (15), domestic capital returns $(r_t^\ell)_{t\geq 0}$, taxes $(\tau_t^\ell)_{t\geq 0}$ and AD-prices $(q_t)_{t\geq 0}$ as given and chooses an adapted stochastic process of inputs $(K_t^\ell, X_t^\ell)_{t\geq 0}$ to maximize total discounted profits

$$\Pi^\ell = \max_{(K_t^\ell,X_t^\ell)_{t\geq 0}} \left\{ \mathbb{E}\left[\sum_{t=0}^{\infty} q_t^p\cdot\left(Q_t^\ell\cdot F_t^\ell(K_t^\ell,X_t^\ell) - r_t^\ell\cdot K_t^\ell - (\tau_t^\ell + c_x)\cdot X_t^\ell\right)\right] \middle| K_t^\ell, X_t^\ell \geq 0 \right\} \tag{30}$$

Profits Π^ℓ determined by (30) are transferred as lifetime profit income to the consumer in region ℓ. Profit maximizing factor demand $(K_t^{\ell,d}, X_t^{\ell,d})$ solves again the first order conditions for all $t = 0,1,2,\ldots$:

$$Q_t^\ell \partial_K F_t^\ell(K_t^{\ell,d}, X_t^\ell) = r_t^\ell \quad \text{and} \quad Q_t^\ell \partial_X F_t^\ell(K_t^{\ell,d}, X_t^\ell) = \tau_t^\ell + c_x. \tag{31}$$

Consumer behavior

The representative consumer in region ℓ receives profit income (30) and the transfer $\tau_t^\ell\cdot X_t^\ell$ from the government in each period $t = 0,1,2,\ldots$. In addition, he owns initial capital $K_{-1}^{\ell,s}$ in $t=0$ formed during the previous period.[3] Any consumption decision $(C_t^\ell)_{t\geq 0}$ must satisfy the lifetime budget constraint

$$\mathbb{E}\left[\sum_{t=0}^{\infty} q_t^p C_t^\ell\right] \leq W^\ell := \Pi^\ell + \mathbb{E}\left[\sum_{t=0}^{\infty} q_t^p \tau_t^\ell \cdot X_t^\ell\right] + R_0^\ell \cdot K_{-1}^{\ell,s}. \tag{32}$$

where W^ℓ denotes lifetime wealth. A detailed derivation of (32) can be found in Appendix A.1. The consumer's decision problem determining optimal consumption reads:

$$\max_{(C_t^\ell)_{t\geq 0}} \left\{ U\left((C_t^\ell)_{t\geq 0}\right) \middle| (32) \text{ holds, } C_t^\ell, \geq 0 \text{ for all } t=0,1,2,\ldots \right\}. \tag{33}$$

Solutions to (33) are characterized by the following lemma.

Lemma 1

Suppose lifetime wealth defined in (32) *satisfies* $W^\ell > 0$. *Then, the following holds:*

(i) Any solution to (33) *satisfies* (32) *with equality and the optimality condition*

$$\beta^t \cdot \frac{u'(C_t^\ell)}{u'(C_0^\ell)} = q_t^p \quad \textit{for all } t=0,1,2,\ldots \tag{34a}$$

(ii) The solution to (33) is unique and computes explicitly as

$$C_t^\ell = \frac{(\beta^t/q_t^p)^{\frac{1}{\sigma}}}{\sum_{t=0}^{\infty} \mathbb{E}\left[q_t^p \cdot (\beta^t/q_t^p)^{\frac{1}{\sigma}}\right]} \cdot W^\ell \quad \textit{for all } t=0,1,2,\ldots \tag{34b}$$

Thus, households consume a time- and state-dependent share of their lifetime wealth in each period which is consistent with the classical lifetime-income hypothesis. Combining optimality condition (34a) with the definition (27) of AD-prices permits to state the no-arbitrage condition (26) in the following form for all $\ell \in \mathbb{L}$:

$$u'(C_t^\ell) = \beta \cdot \mathbb{E}_t\left[u'(C_{t+1}^\ell) \cdot R_{t+1}^\ell\right] \quad \text{for all } t=0,1,2,\ldots \tag{35}$$

Similar to (20), (35) is an Euler equation associated with the domestic capital return.

Market clearing

The market clearing condition (22) and the notation for regional capital (23) in region $\ell \in \mathbb{L}$ continues to hold for all $t=0,1,2,\ldots$. However, since goods are now mobile across countries, one obtains the following market clearing condition for the global commodity market in each period $t=0,1,2,\ldots$:

$$\sum_{\ell\in\mathbb{L}} K_t^\ell = \sum_{\ell\in\mathbb{L}} \left(Q_t^\ell F_t(K_{t-1}^\ell, X_t^\ell) + (1-\delta_K)\cdot K_{t-1}^\ell - c_x \cdot X_t^\ell - C_t^\ell\right). \tag{36}$$

Definition of equilibrium

Following definition under complete markets reconciles market clearing with optimal behavior of households and producers for a given climate policy.

[3] We think of this value as financial capital adjusted by the pay-offs of any initially held Arrow securities in $t=0$. Hence, $K_{-1}^{\ell,s} < 0$ is not excluded, but $\bar{K}_{-1} := \sum_{\ell\in\mathbb{L}} K_{-1}^{\ell,s} > 0$.

Definition 2
A decentralized equilibrium of $\mathscr{E}$ under complete financial markets consists of climate policies $\big((\tau_t^\ell)_{t\geq 0}\big)_{\ell\in\mathbb{L}}$, an allocation $A^* = \big((K_t^{\ell *}, X_t^{\ell *}, C_t^{\ell *})_{t\geq 0}\big)_{\ell\in\mathbb{L}}$, prices $P^* = \big(q_t^*, (r_t^{\ell *})_{\ell\in\mathbb{L}}\big)_{t\geq 0}$, and global temperature $T^* = (T_t^*)_{t\geq 0}$ such that for all $t = 0,1,2,\ldots$ and all $\ell \in \mathbb{L}$:

(i) The producers' optimality conditions (24) *hold.*

(ii) The consumers' optimality conditions (34a) *and* (35) *and the market clearing condition* (36) *for the global commodity market hold.*

(iii) Emissions and temperature evolve as in (11) *determining net TFP by* (15).

3.4 Complete financial markets and capital mobility

Market structure
We now extend the previous market scenario by permitting, in addition, free flow of capital across countries. As a result, there is now a uniform global capital price r_t in each period t. Let $\overline{K}_{t-1} > 0$ denote the pre-determined global capital stock in period t formed at time $t-1$. Then, the market clearing condition for the global capital market reads

$$\sum_{\ell\in\mathbb{L}} K_t^\ell = \overline{K}_{t-1} \quad \text{for } t = 0,1,2,\ldots \tag{37}$$

where $\bar{K}_{-1} = \sum_{\ell\in\mathbb{L}} K_{-1}^{\ell,s} > 0$ is given. The main implication of (37) is that capital inputs to production (4) in period t are no longer predetermined by the regional savings decisions in $t-1$ as in (22). Thus, the optimality conditions (24) now take the form

$$Q_t^\ell \partial_K F_t^\ell(K_t^\ell, X_t^\ell) = r_t \quad \text{and} \quad Q_t^\ell \partial_X F_t^\ell(K_t^\ell, X_t^\ell) = \tau_t^\ell + c_x \tag{38}$$

The evolution of aggregate capital now takes the form

$$\overline{K}_t = \sum_{\ell\in\mathbb{L}} Q_t^\ell F_t(K_t^\ell, X_t^\ell) + (1-\delta_K)\cdot \overline{K}_{t-1} - c_x \sum_{\ell\in\mathbb{L}} X_t^\ell - \sum_{\ell\in\mathbb{L}} C_t^\ell \quad \text{for } t = 0,1,2,\ldots \tag{39}$$

Definition of equilibrium
A modification of Definition 2 to include (37), (38), and (39) and a uniform global capital price $(r_t^*)_{t\geq 0}$ is straightforward, and we omit the formal details here.

3.5 Efficiency properties of equilibrium

We can now study and compare properties of equilibrium under the previous market structures. Specifically, we want to understand the efficiency of risk sharing and factor allocations and the stochastic properties of equilibrium consumption.

Efficiency of risk sharing
A first important implication of Lemma 1 (ii) is that the consumption distribution under complete financial markets is time- and state-independent, as stated in the next result.

Lemma 2

If financial markets are complete, equilibrium consumption of region $\ell \in \mathbb{L}$ is a constant share of global consumption $\overline{C}_t$ determined by its relative lifetime wealth (32)*, i.e.*

$$C_t^\ell = c^\ell \cdot \overline{C}_t \quad \textit{for all } t = 0,1,2,\ldots \textit{ where } \quad c^\ell = W^\ell / \sum_{h \in \mathbb{L}} W^h. \tag{40}$$

For each region $\ell \in \mathbb{L}$, define the one-period stochastic discount factor (SDF) as

$$M_{t,t+1}^\ell := \beta u'(C_{t+1}^\ell)/u'(C_t^\ell) = \beta \left(C_{t+1}^\ell / C_t^\ell \right)^{-\sigma} \qquad \text{for } t = 0,1,2,\ldots \tag{41}$$

The SDF serves to price risky pay-offs in $t+1$ such as the capital return R_{t+1}^ℓ in the Euler equation (20). In general, the SDF may be region-dependent. A direct implication of Lemma 2, however, which follows directly from (40) and (41) is the following

Lemma 3

If financial markets are complete, the regional SDFs (41) *align, i.e., for all $t = 0,1,2,\ldots$:*

$$M_{t,t+1}^\ell = M_{t,t+1} := \beta u'(\bar{C}_{t+1})/u'(\bar{C}_t) = \beta \left(\bar{C}_{t+1}/\bar{C}_t \right)^{-\sigma} \qquad \textit{for all } \ell \in \mathbb{L}. \tag{42}$$

Lemma 3 reproduces the well-known result that under complete markets, the pricing of risk is uniquely defined. As a result, regions in our setup agree on the pricing of all future climate and fundamental risks leading to an efficient allocation of risk across countries. By contrast, the autarky scenario generically implies $M_{t,t+1}^\ell \neq M_{t,t+1}^h$ for $\ell \neq h$, i.e. regions disagree on the discounting of future risk, despite identical risk preferences (12) and correct beliefs about fundamentals. This will have important implications for the form of optimal climate policy studied in the next section.

Efficiency of capital allocations

The absence of international capital markets implies that returns r_t^ℓ and, by (17), marginal products of capital will typically and permanently differ across countries. This feature implies generic inefficiency of the global capital allocation which is fully removed with free capital mobility. To formalize this notion of capital-efficiency, consider an arbitrary period t and history $s^t \in \mathbb{S}_t$. Let temperature T_{t-1}, aggregate capital $\overline{K}_{t-1} > 0$, and an emissions profile $(X_t^\ell)_{\ell \in \mathbb{L}}$ be given determining net TFP's Q_t^ℓ for each $\ell \in \mathbb{L}$ by (15). We call the allocation $(K_t^\ell)_{\ell \in \mathbb{L}}$ *capital-efficient*, if it maximizes global output in period t for the given variables, i.e., it solves the maximization problem

$$\max_{(K^\ell)_{\ell \in \mathbb{L}}} \left\{ \sum_{\ell \in \mathbb{L}} Q_t^\ell F_t^\ell (K^\ell, X_t^\ell) \middle| \sum_{\ell \in \mathbb{L}} K^\ell \leq \overline{K}_{t-1}, K^\ell \geq 0 \text{ for all } \ell \in \mathbb{L} \right\}. \tag{43}$$

Efficiency of factor allocations

An even stronger requirement is that of *production efficiency*. To formalize this concept, fix an arbitrary period t and history $s^t \in \mathbb{S}_t$. Let temperature T_{t-1}, aggregate capital $\overline{K}_{t-1}$, and aggregate emissions $\overline{X}_t$ be given determining net-TFP Q_t^ℓ for each $\ell \in \mathbb{L}$ by

(15). We call the factor allocation $(K_t^\ell, X_t^\ell)_{\ell\in\mathbb{L}}$ *production-efficient*, if it maximizes global production in period t, i.e., is a solution to

$$\max_{(K^\ell,X^\ell)_{\ell\in\mathbb{L}}} \left\{ \sum_{\ell\in\mathbb{L}} Q_t^\ell F_t^\ell(K^\ell, X^\ell) \,\middle|\, \sum_{\ell\in\mathbb{L}} K^\ell \le \overline{K}_{t-1}, \sum_{\ell\in\mathbb{L}} X^\ell \le \overline{X}_t, K^\ell, X^\ell \ge 0 \text{ for all } \ell \in \mathbb{L} \right\}. \tag{44}$$

The following result shows that the equilibrium factor allocation under capital mobility is always capital-efficient and production efficient under uniform carbon taxation.

Lemma 4
If capital is internationally mobile, the equilibrium factor allocation $(K_t^{\ell*}, X_t^{\ell*})_{\ell\in\mathbb{L}}$ in period t is capital-efficient and production-efficient if and only if $\tau_t^\ell = \tau_t$ for all $\ell \in \mathbb{L}$.

The proof of Lemma 4 follows immediately by observing from (38) that marginal products of capital always align under capital mobility implying capital efficiency. If, in addition, taxes are uniform, marginal products of fossil fuels also align implying production efficiency. Note that the latter holds in particular with zero taxation. Below we will see that full production efficiency is only restored if regions cooperate implying a uniform global carbon tax. We also see from the second assertion of Lemma 4 that one-sided deviations of carbon pricing may help internalize the externality but will also lead to efficiency losses in the global production process due to carbon leakage, etc.

Stochastic properties of consumption
In the autarky case the stochastic properties of consumption can be read off directly from the local market clearing condition (25):

$$C_t^\ell = Q_t^\ell F_t^\ell(K_{t-1}^\ell, X_t^\ell) - c_x X_t^\ell - (K_t^\ell - (1-\delta_K)\cdot K_{t-1}^\ell). \tag{45}$$

Thus, regional consumption is fully exposed to local climate and fundamental risk embodied by Q_t^ℓ. In the absence of trading opportunities, this risk can only be mitigated by adjusting emissions X_t^ℓ or investment $K_t^\ell - (1-\delta_K)\cdot K_{t-1}^\ell$.
By contrast, a direct consequence of Lemma 2 and (36) is that regional consumption under complete financial markets can be written as

$$C_t^\ell = c^\ell \cdot \left(\sum_{h\in\mathbb{L}} Q_t^h F_t^h(K_{t-1}^h, X_t^h) - c_x \cdot \overline{X}_t - (\overline{K}_t - (1-\delta_K)\cdot \overline{K}_{t-1}) \right). \tag{46}$$

Thus, regional consumption in region ℓ is determined as a constant share of *global production* net of global extraction costs and investment and, therefore, only affected by aggregate risk and global variables. Intuitively, this is a direct consequence of the risk-sharing opportunities under complete markets.
In summary, under complete markets regional consumption risk mirrors *global production risk* while under autarky it mirrors *local production risk*. If we permit international capital mobility, capital inputs to production in (46) can even respond to the shock s_t, i.e., can be adjusted in period t. As a result, aggregate production in (46) becomes capital-efficient. If, in addition, all regions coordinate on a uniform global carbon tax, as they

will along the cooperative scenario studied below, then aggregate production in (46) will be fully efficient. Thus, relative to the autarky scenario, there are several efficiency gains from introducing additional markets. However, whether these gains are also Pareto-improving and benefit each region is an open question. Our simulation results for the two-region case illustrate that this may not be the case.

4 Optimal Climate Policy under Non-Cooperation

In this section we study the question how much regions may gain from international risk sharing and capital trade when climate policy remains uncoordinated. To this end, we set up a non-cooperative game where each region ℓ sets its climate tax policy $\tau^\ell = (\tau_t^\ell)_{t\geq 0}$ to maximize domestic welfare, taking as given the decisions of other regions. This regionally optimal tax policy can be derived in two steps. The first step involves a regional planning problem determining a regionally optimal allocation taking emissions from other regions as well as global prices on international markets as given. The second step determines regional carbon taxes such that the regionally optimal allocation obtains as a decentralized equilibrium.

4.1 Non-cooperative solution concept

Notation

In a non-cooperative equilibrium, the decisions of all regions $\ell \in \mathbb{L}$ must be mutually compatible in the sense that actions of all other players are correctly anticipated. For this purpose, denote the emissions generated by all regions other than region $\ell \in \mathbb{L}$ by

$$\overline{X}_t^{-\ell} := \sum_{h \in \mathbb{L}/\{\ell\}} X_t^h \quad \text{for } t = 0,1,2,\dots \tag{47}$$

Using (47), we will express the evolution of global temperature (11) from the perspective of region $\ell \in \mathbb{L}$ as

$$T_t = \delta_E \cdot T_{-1} + (1-\delta_E)\cdot T_{t-1} + \zeta \cdot \left(X_t^\ell + \overline{X}_t^{-\ell}\right) \quad \text{for all } t = 0,1,2,\dots \tag{48}$$

Finally, it will be convenient to write net-TFP (15) as a function $Q^\ell : \mathbb{R}_+ \times \mathbb{S} \to \mathbb{R}$,

$$Q^\ell(T_t, s_t) := \exp\left(\theta^\ell(s_t) - \gamma^\ell(s_t)\cdot T_t\right). \tag{49}$$

Local cost of carbon

In anticipation of the results of this section, use the regional SDFs from (41) to define the local cost of carbon (LCC) in region $\ell \in \mathbb{L}$ as the adapted stochastic process $(\hat{\tau}_t^\ell)_{t\geq 0}$ defined recursively for each period $t = 0,1,2,\dots$ as

$$\hat{\tau}_t^\ell = \zeta\gamma_t^\ell Y_t^\ell + \beta\cdot(1-\delta_E)\cdot\mathbb{E}_t\left[M_{t,t+1}^\ell \cdot \hat{\tau}_{t+1}^\ell\right]. \tag{50}$$

Solving (50) forward and defining the n-period SDF $M^{\ell}_{t,t+n} := M^{\ell}_{t,t+1} \cdots M^{\ell}_{t+n-1,t+n} = \beta^n (C^{\ell}_{t+n}/C^{\ell}_t)^{-\sigma}$ one can write the LCC as

$$\hat{\tau}^{\ell}_t = \zeta \sum_{n=0}^{\infty} (1-\delta_E)^n \cdot \mathbb{E}_t \left[M^{\ell}_{t,t+n} \cdot \gamma^{\ell}_{t+n} \cdot Y^{\ell}_{t+n} \right]. \tag{51}$$

Economically, the LCC captures the expected total discounted local marginal climate damages from a unit emitted in period t. Crucially, this quantity depends on the discounting of future damages by means of the SDF (41).

4.2 Autarky

Regional planning problems

Under autarky the planning problem for region $\ell \in \mathbb{L}$ is constrained by the same regional resource constraint (25) as in the decentralized equilibrium which we restate here for convenience:

$$K^{\ell}_t \le Q^{\ell}_t F^{\ell}_t (K^{\ell}_{t-1}, X^{\ell}_t) + (1-\delta_K) K^{\ell}_{t-1} - c_x X^{\ell}_t - C^{\ell}_t \quad \text{for all } t = 0,1,2,\ldots \tag{52}$$

Suppose the planner takes into account the impact of local emissions on temperature (48) and regional net-TFP (49), taking emissions (47) of all other regions as given. Formally, the regional planning problem for region $\ell \in \mathbb{L}$ can be stated as

$$\max_{(C^{\ell}_t, K^{\ell}_t, X^{\ell}_t, T_t)_{t\ge 0}} \left\{ U((C^{\ell}_t)_{t\ge 0}) \middle| (48), (49), (52),\ C^{\ell}_t, X^{\ell}_t, K^{\ell}_{t+1} \ge 0 \text{ for each } t = 0,1,2,\ldots \right\} \tag{53}$$

The following lemma characterizes the solution to this problem.

Lemma 5

Let emissions $(\overline{X}^{-\ell}_t)_{t\ge 0}$ *be given. A solution to the decision problem* (53) *of player* $\ell \in \mathbb{L}$ *is an adapted stochastic process* $(C^{\ell}_t, X^{\ell}_t, K^{\ell}_t, T_t)_{t\ge 0}$ *which satisfies* (52) *with equality, the intertemporal optimality condition*

$$1 = \mathbb{E}_t \left[\beta \cdot \left(C^{\ell}_{t+1}/C^{\ell}_t \right)^{-\sigma} \cdot \left(Q^{\ell}_{t+1} \cdot \partial_K F^{\ell}_{t+1}(K^{\ell}_t, X^{\ell}_{t+1}) + 1 - \delta_K \right) \right], \tag{54}$$

consistent with (48) *and* (49) *as well as the intratemporal optimality condition*

$$Q^{\ell}_t \partial_X F^{\ell}_t (K^{\ell}_{t-1}, X^{\ell}_t) = \hat{\tau}^{\ell}_t + c_x. \tag{55}$$

with $\hat{\tau}^{\ell}_t$ *defined as in* (50) *for all* $t = 0,1,2,\ldots$.

Specifically, the regional planner equates the marginal product of fossil fuels (net of extraction costs) to local climate costs (50), i.e. the local damages of regional emissions are fully internalized.

Non-cooperative equilibrium

A Nash equilibrium under autarky makes the decisions of all regions compatible in the sense that each player $\ell \in \mathbb{L}$ correctly anticipates emissions of all other regions. In particular, the decisions all players imply the same global temperature process. Formally, we can define the non-cooperative equilibrium as follows.

Definition 3
A Nash-equilibrium of $\mathscr{E}$ under autarky is an allocation

$$A^{\text{ne}} = ((C_t^{\ell,\text{ne}}, X_t^{\ell,\text{ne}}, K_t^{\ell,\text{ne}})_{\ell\in\mathbb{L}})_{t\geq 0}$$

and a temperature process $T^{\text{ne}} = (T_t^{\text{ne}})_{t\geq 0}$ such that $(C_t^{\ell,ne}, K_t^{\ell,ne}, X_t^{\ell,ne}, T_t^{\text{ne}})_{t\geq 0}$ solves the planning problem (53) *for each $\ell \in \mathbb{L}$ given emissions $(\overline{X}_t^{-\ell,\text{ne}})_{t\geq 0}$ of all other regions.*

It is worth noting that despite the absence of market interactions of regions, the regional decision problems (53) are still connected via the externality and the impact of regional emissions on all other regions.

4.3 Complete financial markets

Regional planning problem
With complete markets, the regional planner can now also trade assets in international asset markets at the given prices. While this behavior is similar to that of the consumer in Section 3.3, the planner directly chooses inputs to the production technology (4) and, as in the previous scenario, takes into account the impact of local emissions on temperature dynamics (48) and regional net-TFP (49), taking emissions (47) of all other regions as given. Using the same formal arguments (cf. Section A.1) as for the consumer problem (33), the constraints facing the planner in region $\ell \in \mathbb{L}$ can be stated as the single lifetime budget constraint

$$\sum_{t=0}^{\infty} \mathbb{E}\left[q_t^p \left(Q_t^\ell \cdot F_t^\ell(K_{t-1}^\ell, X_t^\ell) + (1-\delta_K)\cdot K_{t-1}^\ell - c_x \cdot X_t^\ell - C_t^\ell - K_t^\ell\right)\right] \geq 0. \tag{56}$$

with net TFP Q_t^ℓ given again by (49) for all $\ell \in \mathbb{L}$. Thus, in addition to the emissions process $(\overline{X}_t^{-\ell})_{t\geq 0}$ of other regions in the temperature dynamics (48), the planner also takes prices $(q_t)_{t\geq 0}$ on international financial markets as given. Formally, the regional planning problem under complete markets takes the following form.

$$\max_{(C_t^\ell, K_t^\ell, X_t^\ell, T_t)_{t\geq 0}} \left\{ U((C_t^\ell)_{t\geq 0}) \middle| (49), (48), (56), C_t^\ell, X_t^\ell, K_t^\ell \geq 0 \text{ for } t = 0,1,2,\ldots \right\} \tag{57}$$

The solution to this problem can then be characterized as follows:

Lemma 6
Let emissions $(\overline{X}_t^{-\ell})_{t\geq 0}$ and prices $(q_t)_{t\geq 0}$ be given. A solution to the decision problem (57) *of player $\ell \in \mathbb{L}$ is an adapted stochastic process $(C_t^\ell, X_t^\ell, K_t^\ell, T_t)_{t\geq 0}$ which satisfies* (56) *with equality, the intertemporal optimality conditions*

$$1 = \mathbb{E}_t\left[\beta \cdot \left(C_{t+1}^\ell / C_t^\ell\right)^{-\sigma} \cdot \left(Q_{t+1}^\ell \cdot \partial_K F_{t+1}^\ell(K_t^\ell, X_{t+1}^\ell) + 1 - \delta_K\right)\right] \tag{58a}$$

$$q_t^p = \beta^t \cdot u'(C_t^\ell)/u'(C_0^\ell) = \beta^t \cdot (C_t^\ell / C_0^\ell)^{-\sigma}, \tag{58b}$$

consistent with (48) *and* (49) *as well as the intratemporal optimality condition*

$$Q_t^\ell \partial_X F_t^\ell(K_t^\ell, X_t^\ell) = \hat{\tau}_t^\ell + c_x \tag{58c}$$

with $\hat{\tau}_t^\ell$ *defined as in* (50) *for all* $t = 0, 1, 2, \ldots$.

Market-maker
In the regional planning problem (57), player $\ell \in \mathbb{L}$ takes not only emissions of other regions (47) but also the prices on international markets as given. To describe the choice of these variables as part of the non-cooperative solution concept, we follow the approach in Hillebrand (2025) by introducing an additional player $\ell = 0$ that will be referred to as a *market-maker*. The market-maker chooses state-contingent prices $(q_t)_{t\geq 0}$ to render the non-cooperative equilibrium compatible with the market clearing condition (36). Formally, suppose the market maker sets q_t in period t and history $s^t \in \mathbb{S}_t$ to maximize the value of excess demand, i.e., as the solution to the decision problem

$$\max_{q_t} \left\{ q_t \cdot \sum_{\ell \in \mathbb{L}} \left(Q_t^\ell F_t^\ell(K_{t-1}^\ell, X_t^\ell) + (1-\delta) \cdot K_{t-1}^\ell - c_x \cdot X_t^\ell - C_t^\ell - K_t^\ell \right) \middle| q_t \geq 0 \right\} \tag{59}$$

Intuitively, the market makes sets prices prohibitively low in the case of excess supply and prohibitively high in case of excess demand. Thus, the only case where (59) admits a non-trivial and finite solution is when the respective market clears. In this case, the market maker becomes indifferent between different prices and is therefore willing to support equilibrium prices defined below.

Non-cooperative equilibrium
Combining the previous results, we are now in a position to formalize the non-cooperative equilibrium (Nash equilibrium) under complete markets.

Definition 4
A Nash-equilibrium of $\mathscr{E}$ *under complete financial markets is an allocation*

$$A^{\mathrm{ne}} = ((C_t^{\ell,\mathrm{ne}}, X_t^{\ell,\mathrm{ne}}, K_t^{\ell,\mathrm{ne}})_{\ell \in \mathbb{L}})_{t \geq 0},$$

global temperature $T^{\mathrm{ne}} = (T_t^{\mathrm{ne}})_{t\geq 0}$ *and prices* $P^{\mathrm{ne}} := (q_t^{\mathrm{ne}})_{t \geq 0}$ *such that:*

(i) For each $\ell \in \mathbb{L}$, *the process* $(C_t^{\ell,ne}, K_t^{\ell,ne}, X_t^{\ell,ne}, T_t^{\mathrm{ne}})_{t\geq 0}$ *solves the planning problem* (57) *given prices* P^{ne} *and emissions* $(\overline{X}_t^{\mathrm{ne}-\ell})_{t\geq 0}$ *of other regions.*

(ii) For each $t = 0, 1, 2, \ldots$, *prices* $q_t^{\mathrm{ne}} > 0$ *solve the market maker's decision problem* (59) *given* A^{ne} *and* T^{ne}.

Note that (58b) implies again a constant consumption distribution as in Lemma 2.

4.4 Complete financial markets and capital mobility

Regional planning problem

It is straightforward to extend the non-cooperative solution concept to the third market scenario with complete financial markets and capital trade. In this case, the planner in region $\ell \in \mathbb{L}$ takes not only the commodity prices $(q_t)_{t\geq 0}$ but also global capital returns $(r_t)_{t\geq 0}$ as given and we assume that these satisfy the no-arbitrage condition (58a). The lifetime budget constraint (56) now reads

$$\sum_{t=0}^{\infty} \mathbb{E}\left[q_t^p \left(Q_t^\ell \cdot F_t^\ell(K_t^\ell, X_t^\ell) - r_t \cdot K_t^\ell - c_x \cdot X_t^\ell - C_t^\ell\right)\right] + R_0^\ell \cdot K_{-1}^{\ell,s} \geq 0. \tag{60}$$

The optimality conditions from Lemma 6 remain unchanged, except that (58a) is now redundant and there is now an additional intratemporal optimality condition

$$Q_t^\ell \partial_K F_t^\ell(K_t^\ell, X_t^\ell) = r_t \tag{61}$$

which must hold for all regions $\ell \in \mathbb{L}$ and all periods $t = 0, 1, 2, \ldots$

Market maker

The market maker sets prices q_t and r_t in period t to enforce market clearing conditions (39) and (37). Specifically, the capital price is determined as the solution to the problem

$$\max_{r_t} \left\{ r_t \left(\sum_{\ell \in \mathbb{L}} K_t^\ell - \overline{K}_{t-1} \right) \middle| 0 \leq r_t \leq r_t^{\max} \right\} \tag{62}$$

Modifying the decision problem (59) to represent (39) is straightforward.

Non-cooperative equilibrium

The previous Definition 4 of a non-cooperative equilibrium can now easily modified to accommodate the previous changes and we omit the formal details here.

4.5 Optimal carbon taxation under non-cooperation

The properties of non-cooperative equilibrium established in the previous subsections raise the question how climate policy must be chosen such that the non-cooperative solution is decentralized, i.e., coincides with the decentralized equilibrium solution studied in Section 3. The following main result of this section shows that this is the case, precisely when each region $\ell \in \mathbb{L}$ chooses its tax policy $(\tau_t^\ell)_{t\geq 0}$ based on the local cost of carbon (50).

Theorem 1

Suppose each region $\ell \in \mathbb{L}$ chooses the tax process $(\tau_t^\ell)_{t\geq 0}$ based on the local cost of carbon (50)*, i.e., for all $t = 0, 1, 2, \ldots$, taxes satisfy the recursive condition*

$$\tau_t^\ell = \zeta \gamma_t^\ell Y_t^\ell + \beta \cdot (1 - \delta_E) \cdot \mathbb{E}_t \left[M_{t,t+1}^\ell \cdot \hat{\tau}_{t+1}^\ell \right] \tag{63}$$

where $M_{t,t+1}^\ell$ is defined as in (41)*. Then the non-cooperative solution is decentralized, i.e., $A^{\mathrm{ne}} = A^*$ and $T^{\mathrm{ne}} = T^*$.*

Specifically, carbon taxes under non-cooperation internalize only local damages, taking emissions of other regions as given. Note that the stochastic discount factor $M^{\ell}_{t,t+1}$ in (63) depends on the market structure. Specifically, if financial markets are complete, it follows directly from Lemma 3 that all regions use the same SDF defined by aggregate consumption. Theorem 1 therefore shows that perfect risk-sharing via complete financial markets ensures that all regions agree on how future damages are discounted, but markets do not determine which of these damages are internalized.

5 Optimal Climate Policy under Cooperation

Having established the role of the market structure in the absence of cooperation, we now turn to the additional gain that regions can obtain from cooperation. For this reason, and also to obtain analytical results we study this question exclusively in the most developed market scenario discussed before with complete financial markets and international capital mobility. Under full cooperation, all regions agree on a uniform carbon tax $\tau^{\text{opt}} = (\tau^{\text{opt}}_t)_{t\geq 0}$. This optimal tax policy is determined in two steps. In the first step, we derive the globally optimal allocation as the solution to a global planning problem. In the second step, the optimal tax is determined such that this optimal allocation obtains as a decentralized equilibrium.

5.1 The global planning problem

Consider a global planner who maximizes lifetime utility of a world representative consumer receiving global consumption $\bar{C}_t$ in each period t. Based on this objective, the planner only chooses global consumption but not is distribution across regions. Formally, the planner chooses an optimal aggregate allocation

$$\bar{A} = ((X^{\ell}_t, K^{\ell}_t)_{\ell\in\mathbb{L}}, \overline{C}_t, \overline{K}_t)_{t\geq 0}. \tag{64}$$

where $\overline{K}_t$ as before denotes aggregate capital formation in period t. The planner also takes into account the impact of emissions on global temperature (11) and climate damages via (15). The allocation $\bar{A}$ is further restricted by the global resource constraint

$$\overline{K}_t \leq \sum_{\ell\in\mathbb{L}} \left(Q^{\ell}_t F^{\ell}_t (K^{\ell}_t, X^{\ell}_t) + (1-\delta_K)\cdot K^{\ell}_t - c_x \cdot X^{\ell}_t \right) - \overline{C}_t \quad \text{for } t = 0,1,2,\ldots \tag{65}$$

and the capital constraint

$$\sum_{\ell\in\mathbb{L}} K^{\ell}_t \leq \overline{K}_{t-1} \quad \text{for } t = 0,1,2,\ldots \tag{66}$$

where $\overline{K}_{-1} = \sum_{\ell\in\mathbb{L}} K_{-1}t^{\ell,s} > 0$ is given. Formally, the global planning problem reads

$$\max_{\bar{A},(T_t)_{t\geq 0}} \left\{ U\left((\overline{C}_t)_{t\geq 0} \right) \Big| (11),(15),(65),(66), \overline{C}_t, \overline{K}_t, X^{\ell}_t, K^{\ell}_t \geq 0 \,\forall \ell \in \mathbb{L}, t = 0,1,2,\ldots \right\} \tag{67}$$

A solution to (67) defines a Pareto-optimal (aggregate) allocation denoted by

$$\bar{A}^{\text{opt}} = ((X_t^{\ell,\text{opt}}, K_t^{\ell,\text{opt}})_{\ell\in\mathbb{L}}, \overline{C}_t^{\text{opt}}, \overline{K}_t^{\text{opt}})_{t\geq 0}.$$

and an induced optimal temperature process $T^{\text{opt}} = (T_t^{\text{opt}})_{t\geq 0}$ defined by (11). The next result characterizes this solution formally.

Lemma 7
A solution to problem (67) *is an aggregate allocation* $\bar{A} = ((X_t^\ell, K_t^\ell)_{\ell\in\mathbb{L}}, \overline{C}_t, \overline{K}_t)_{t\geq 0}$ *and a global temperature process* $(T_t)_{t\geq 0}$ *which satisfies the following for all* $t = 0, 1, 2, \ldots$*:*

(i) The global resource constraints (65) *and* (66) *hold with equality.*

(ii) Capital and emissions satisfy the intratemporal optimality conditions

$$Q_t^\ell \partial_K F_t^\ell(K_t^\ell, X_t^\ell) = Q_t^1 \partial_K F_t^1(K_t^1, X_t^1) \tag{68a}$$

$$Q_t^\ell \partial_X F_t^\ell(K_t^\ell, X_t^\ell) = c_x + \hat{\tau}_t \tag{68b}$$

for all $\ell \in \mathbb{L}$ *where the process* $(\hat{\tau}_t)_{t\geq 0}$ *is defined recursively as*

$$\hat{\tau}_t = \zeta \sum_{\ell\in\mathbb{L}} \gamma_t^\ell Q_t^\ell F_t^\ell \left(K_t^\ell, X_t^\ell\right) + (1-\delta_E)\cdot \mathbb{E}_t \left[\beta \cdot \left(\overline{C}_{t+1}/\overline{C}_t\right)^{-\sigma} \cdot \hat{\tau}_{t+1}\right]. \tag{68c}$$

(iii) The intertemporal optimality condition (Euler equation) holds:

$$1 = \mathbb{E}_t \left[\beta \cdot \left(\overline{C}_{t+1}/\overline{C}_t\right)^{-\sigma} \cdot \left(Q_{t+1}^1 \partial_K F_{t+1}^1 \left(K_{t+1}^1, X_{t+1}^1\right) + 1 - \delta_K\right)\right]. \tag{68d}$$

(iv) Temperature evolves according to (11) *with net-TFP defined as in* (49)*.*

5.2 Optimal carbon taxation under full cooperation

The next question to be explored is how the optimal allocation can be decentralized, i.e., which climate policies implement the solution $\bar{A}^{\text{opt}}$ and T^{opt} as a decentralized equilibrium outcome. The following main result provides a complete characterization of such globally optimal climate policies. The proof follows directly by comparing the optimality conditions (68) from Lemma 7 to the conditions in Definition 2 in conjunction with Lemma 2.

Theorem 2
For the case with complete financial markets and capital mobility, suppose all regions $\ell \in \mathbb{L}$ *choose identical carbon tax policies based on the rule*

$$\tau_t = \zeta \sum_{\ell\in\mathbb{L}} \gamma_t^\ell Q_t^\ell F_t^\ell \left(K_t^\ell, X_t^\ell\right) + (1-\delta_E)\cdot \mathbb{E}_t \left[\beta \cdot \left(\overline{C}_{t+1}/\overline{C}_t\right)^{-\sigma} \cdot \tau_{t+1}\right] \tag{69}$$

for all $t = 0, 1, 2, \ldots$*. Then, the induced aggregate equilibrium allocation*

$$\bar{A}^* = \left((X_t^{\ell *}, K_t^{\ell *})_{\ell\in\mathbb{L}}, \sum_{\ell\in\mathbb{L}} C_t^{\ell *}, \sum_{\ell\in\mathbb{L}} K_{t+1}^{\ell *}\right)_{t\geq 0}$$

is Pareto-optimal, i.e., is a solution to the global planning problem (67)*.*

Comparing the optimal tax formula (69) with the non-cooperative solution (63) from Theorem 1, we observe that the latter internalizes only domestic marginal damages while the former takes into account the global damages corresponding to the sum of regional damages. This is a straightforward extension of the main finding in Hillebrand (2025) to the present stochastic setup.

6 Quantitative Results

This section illustrates and quantifies the theoretical results from the previous sections by comparing four scenarios: autarky, complete financial markets, and complete markets with mobile capital all under non-cooperation and complete markets with mobile capital under full cooperation. All scenarios consider the case with two regions and a common parameter set calibrated to match selected empirical targets. We first describe the model specification and calibration strategy then present the results.

6.1 Specification

Production technology

Following Hassler, Krusell, and Olovsson (2021) and Hillebrand (2025), we assume that the production function (4) in period t takes the CES-form

$$F_t^\ell(K,X) = \left[\kappa \cdot \left((h_t^\ell \cdot N_t^\ell)^{1-\alpha} \cdot K^\alpha\right)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\kappa)\cdot\left(e_t^\ell \cdot X\right)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}}, \quad \alpha,\kappa \in (0,1),\ \varepsilon > 0. \tag{70}$$

Here, N_t^ℓ denotes regional population size, h_t^ℓ labor efficiency, and e_t^ℓ energy efficiency. The population sequence $(N_t^\ell)_{t\geq 0}$ evolves exogenously while both efficiency parameters grow at constant exogenous rates implying that

$$h_{t+1}^\ell = (1+g_h)\cdot h_t^\ell \quad \text{and} \quad e_{t+1}^\ell = (1+g_e)\cdot e_t^\ell \quad \text{for all } t = 0,1,2,\ldots \tag{71}$$

We will impose the restrictions $g_h > g_e$ and $\varepsilon > 1$ to ensure that aggregate equilibrium emissions satisfy $\lim_{t\to\infty} \bar{X}_t = 0$. Then, global emissions will be uniformly bounded by $\bar{X}^{\max}$ and temperature evolving as in (11) satisfies $T_t \leq T^{\max} := T_{-1} + \zeta \cdot \bar{X}^{\max}/\delta_E$ for all t permitting to define a compact state space as explained in Appendix B.

Time and exogenous states

One model period corresponds to one decade in real time. Periods are identified by the last year. Hence, the initial model period corresponding to the decade from 2011 until 2020 is referred to as year 2020. We restrict ourselves to the simplest possible case with only two states ($S = 2$). The transition matrix for the state process $(s_t)_{t\geq 0}$ on $\mathbb{S} = \{1,2\}$ is

$$M = \begin{bmatrix} 0.4 & 0.6 \\ 0.6 & 0.4 \end{bmatrix} \tag{72}$$

giving equal weight to either of the states $s \in \mathbb{S}$ in the invariant distribution, with an average duration of 2.5 periods (25 years) to either state.

Regional structure
We consider the case with two regions ($L = 2$). Region $\ell = 1$ is constructed by aggregating all members of the OECD and other high income countries according to the UN income classification. All remaining countries then form region $\ell = 2$. Based on our calibration targets for regional GDP (cf. Table 6 in Appendix B), both regions have similar economic weight in period $t = 0$, but region 2 will be more negatively affected by the adverse state of the world. Thus, we will refer to countries in $\ell = 1$ as 'resilient' and to countries in region $\ell = 2$ as 'vulnerable'.

6.2 Parameter choices

Parameter classification
The calibration procedure largely follows Hillebrand (2025) but is extended to capture the stochastic nature of the model. We distinguishes two classes of parameters: (i) predetermined parameters for which we mostly rely on values common in the literature on integrated assessment models; (ii) calibrated parameters which are chosen to match explicit empirical targets such as regional GDP, emissions, or population projections.

Predetermined parameters
Table 1 lists our predetermined parameter values. The elasticities α and κ in (70) are

Table 1: Structural economic parameters in baseline scenario

Description	Notation	Value	Description	Notation	Value
Energy share	$1-\kappa$	0.05	Capital elasticity	α	0.3158
El. of substitution	ε	1.5	Depreciation rate	δ_K	0.5
Labor eff. growth	g_h	0.1046	Energy eff. growth	g_e	0.0511
Extraction costs	$c_x \cdot 10^4$	0.7903			
Discount factor	β	0.8597	Risk aversion	σ	1

based on Hassler et al. (2021) and consistent with empirical capital and labor income shares and a cost share $1-\kappa = 0.05$ of fossil energy relative to GDP. An elasticity of substitution $\varepsilon = 1.5$ is in line with the estimate in Papageorgiou et al. (2017) who report a (long-run) elasticity significantly exceeding unity. The depreciation rate of capital δ_K corresponds to an annual rate of $\approx 7-8\%$ which is in the range of values typically used in the business cycle literature. Since global fossil fuel emissions are driven by coal-based emissions, we choose c_x to match extraction costs of 43 USD per physical ton of coal used in Golosov et al. (2014). Given the carbon content of 0.5441 tons of carbon per ton of coal, this translates into an extraction cost of approximately 79 USD per ton of carbon, corresponding to the parameter value $c_x = 0.43 \cdot 10^{-4}/0.5441 \approx 0.7903 \cdot 10^{-4}$. Finally, the growth rates in (71) imply annual changes in labor and energy efficiency of about 1% and 0.5%, respectively, which are also in line with the previous literature.

As for consumer parameters, our choice $\sigma = 1$ corresponding to logarithmic utility takes a middle-ground on the relative strength of intertemporal substitution and income effects. A discount factor $\beta = 0.985^{10}$ corresponds to an annual discount rate of 1.5%. Both choices are identical to the values in Golosov et al. (2014).

Stochastic shocks

To quantify the magnitudes and co-movements of the exogenous processes $(\gamma_t^\ell, \theta_t^\ell)_{t\geq 0}$ determining climate and production risk, we need to specify the functions $\theta^\ell : \mathbb{S} \to \mathbb{R}$ and $\gamma^\ell : \mathbb{S} \to \mathbb{R}$. Given the assumption of a two-state Markov process and the broad range of estimates on cross-country and within-country correlations for these processes, the values in Table 2 are chosen to imply $\mathbb{E}[\theta^1] = \mathbb{E}[\theta^2] = 0.05$, and $\mathbb{V}[\theta^1] < \mathbb{V}[\theta^2]$ as well as $\rho(\theta^1, \theta^2) = 1$.[4] As a result, region $\ell = 2$ faces larger TFP variation and thus amplified exposure to the synchronized global business cycle.[5] Similarly, the climate damage parameters γ^ℓ are within the range of projections in Burke et al. (2015) and Bilal and Känzig (2024), matching a global 12.5% GDP-loss for a 1°C global temperature increase (see Appendix B.7 for details). Our choices imply $\mathbb{E}[\gamma^1] < \mathbb{E}[\gamma^2]$, and $\mathbb{V}[\gamma^1] < \mathbb{V}[\gamma^2]$, i.e. region $\ell = 2$ faces higher damage risk, both in terms of expected levels and in volatility. In terms of intra-regional correlation, our values imply $\rho(\gamma^\ell, \theta^\ell) = 1$ for each $\ell \in \mathbb{L}$, i.e., total factor productivity is negatively correlated with climate risks.[6]

Table 2: TFP parameters and implied country-specific moments

		State $s = 0$		State $s = 1$		Mean		Std. Dev.*	
Description	Notation	$\ell = 1$	$\ell = 2$	$\ell = 1$	$\ell = 2$	$\ell = 1$	$\ell = 2$	$\ell = 1$	$\ell = 2$
Productivity	θ^ℓ	.0400	.0250	.0600	.0750	.0500	.0500	.0100	.0250
Climate damages	γ^ℓ	.0281	.0504	.0186	.0209	.0233	.0357	.0048	.0148

*All values scaled up by factor 10^2 for readability.

Climate model

We follow Rezai and van der Ploeg (2021) by setting temperature sensitivity in (9) to $\zeta = 0.002$, corresponding to a 2°C increase per 1000 GtC. The depreciation rate of cumulative carbon in (10) is set to $\delta_E = 0.01$ which is small enough to be consistent with

[4]All moments are computed with respect to the invariant distribution of M.

[5]This choice is consistent with the positive correlation estimates found in the literature on international business cycles, which strongly suggest positive co-movement of international productivity across industrialized economies ((Backus, Kehoe, and Kydland 1992), (Ambler, Cardia, and Zimmermann 2004)). However, there is also evidence that global business cycle synchronization has increasingly taken place within the group of industrialized economies over the last century (Bordo and Helbling 2011), while global business cycles have become more independent (Kose, Otrok, and Prasad 2012).

[6]There is limited evidence on the extent to which total factor productivity variation due to climate change (such as agricultural productivity losses, cf. Liang et al. (2017), Ortiz-Bobea et al. (2021)) correlates with other sources of total factor productivity variation (such as R&D, allocation efficiency, etc.). Exceptions are Letta and Tol (2019) and Song et al. (2023), who establish the pattern used here.

zero depreciation in Rezai and van der Ploeg (2021) and in the upper half of the usual range for the remaining share of an emission impulse after 1,000 years.[7] Initial global temperatures in year 2020 is set to $T_{-1} = 1.2$ in line with empirical observation.

Description	Notation	Value	Description	Notation	Value
Temperature sensitivity	ζ	0.002	Carbon depreciation	δ_E	0.01
Initial temperature	T_{-1}	1.2			

Table 3: Climate module parameters

Calibrated parameters
Based on the specification (70) and (71), we pick initial values for regional labor and energy efficiencies h_0^ℓ and e_0^ℓ to match empirical observations for real GDP and emissions in the initial modeling period $t = 0$. In addition, we use wealth data to obtain the distribution η_K^ℓ, $\ell = 1,2$ of initial global capital $\overline{K}_{-1}^s$. The parameter values implied by this calibration procedure are listed in Table 4. The specific calibration targets and additional details on how we match them can be found in Section B.7 in Appendix B.

Description	Notation	Region 1	Region 2
Initial labor efficiency	$h_0^\ell \cdot 10^4$	6.7383	2.1376
Initial energy efficiency	$e_0^\ell \cdot 10^5$	1.7044	4.4108
Initial share of capital	η_K^ℓ	.7350	.2649

Table 4: Initial values for efficiency and capital distribution.

It is worth noting that the values in Table 4 suggest that region 1 has specialization advantages in the use of clean production factors reflected by higher labor efficiency relative to energy efficiency, while region 2 has scope for specialization in dirty production due to a relatively higher level of energy efficiency.

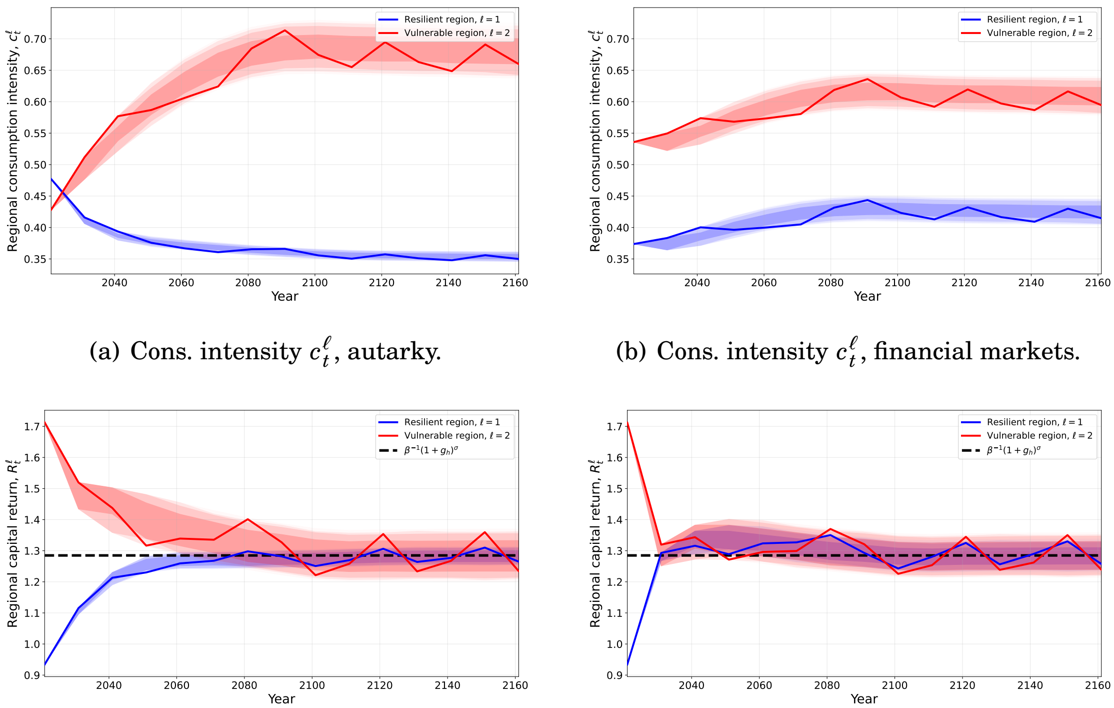
6.3 Results

Using the parameter set developed in the previous section, we study the four scenarios in pairwise conjunction, which allows us to isolate the effect of (i) *risk-sharing*, moving from autarky to complete financial markets; (ii) *capital mobility*, comparing complete financial markets with and without mobile capital; (iii) *cooperation*, moving from regionally to globally optimal climate policy under the most complete market structure.

[7]The IPCC Sixth Assessment report quantifies the remainder of an emission impulse to fall in the range of 15-40% over 1,000 years. This range covers the value of $(1-0.01)^{100} = 0.3660$ used here.

Risk-sharing effect

Figure 1[8] illustrates how complete financial markets affect the consumption intensities c_t^ℓ as well as the capital returns for both regions. A first striking observation is that consumption levels for the resilient region $\ell = 1$ are initially lower under complete financial markets than under autarky, but substantially higher in the long-run, while the opposite is true for the vulnerable region $\ell = 2$. Secondly, consumption of the resilient region ($\ell = 1$) is substantially less volatile under autarky than under complete markets, while the converse is true for the vulnerable region ($\ell = 2$). Thirdly, as can be seen from the solid lines, consumption is now perfectly synchronized across regions.



(a) Cons. intensity c_t^ℓ, autarky.

(b) Cons. intensity c_t^ℓ, financial markets.

(c) Capital returns R_t^ℓ, autarky.

(d) Capital returns R_t^ℓ, financial markets.

Figure 1: Risk-sharing effects (non-cooperation).

International risk-sharing is thus a permanent source of additional consumption for the resilient region, whereas the vulnerable region permanently transfers part of consumption to the resilient region in return for the insurance it provides against risk.[9] The bottom row of figure 1 further illustrates that due to the common stochastic discount

[8] All figures were generated by repeatedly simulating the model for different realizations of the shock-process $(s_t)_{t\geq 0}$, starting from an identical initial state $s_0 = \bar{s}_0$. The graphs each show a single simulation (solid lines) and percentile bands from 3,000 independent simulated time series. Dark shading represents the 10−90% quantile range, medium shading the 5−95% range, and light shading the 1−99% range, capturing relative frequencies across all realizations.

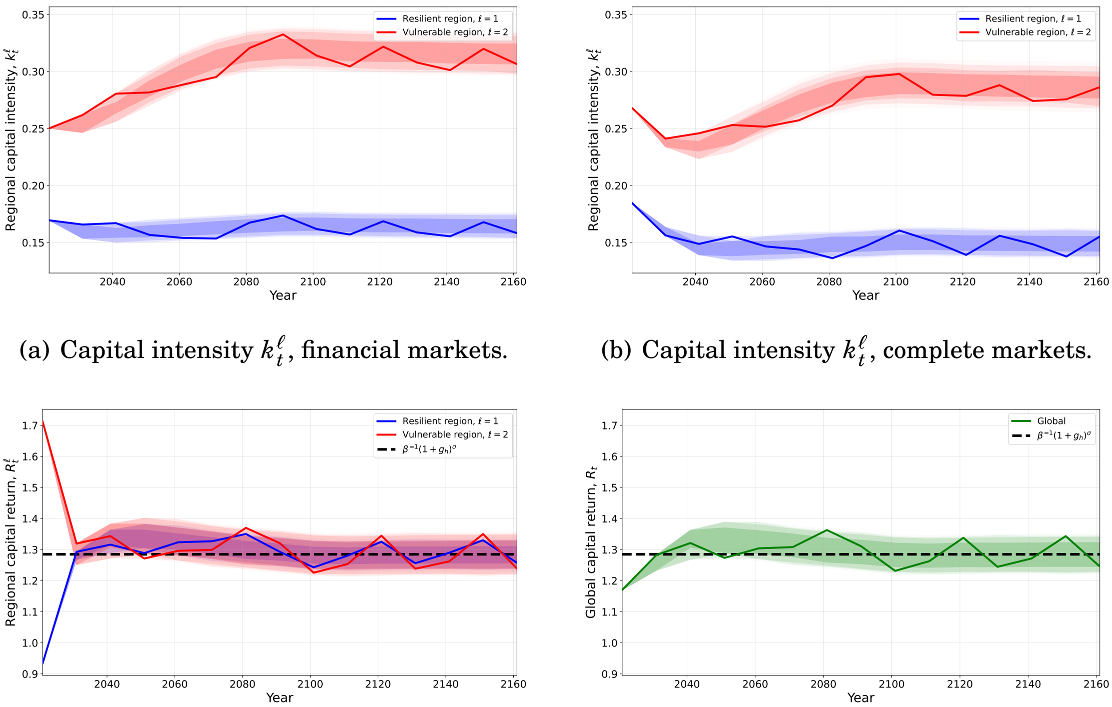
[9] Emission volatilities also shift across regions and become more volatile in the vulnerable region than in the resilient region, though less markedly than consumption.

factor implied by complete financial markets, capital returns must equate in expected terms, which is not required under autarky.[10]
For ease of reference, we state the previous observations as follows:

Numerical Result 1 (Risk-sharing effects)
Introducing complete financial markets has the following effects on consumption:

1. *Mean consumption of the resilient (vulnerable) region is initially lower (higher) but higher (lower) in the long term relative to autarky*
2. *Consumption volatility increases (decreases) in the resilient (vulnerable) region.*
3. *Consumption and expected capital returns synchronize across regions.*

Capital-mobility effect
Figure 2 illustrates how opening capital markets (under complete financial markets) affects capital intensities k_t^ℓ as well as the capital returns for both regions.



(a) Capital intensity k_t^ℓ, financial markets. (b) Capital intensity k_t^ℓ, complete markets.

(c) Capital returns R_t^ℓ, financial markets. (d) Capital returns R_t^ℓ, complete markets.

Figure 2: Capital-mobility effects (non-cooperation).

The bottom row in Figure 2 confirms that capital returns in both regions are perfectly synchronized under capital mobility. In the absence of capital mobility, capital accumulation in the the vulnerable region increases initially which can be attributed to high population growth in these countries. Introducing capital mobility reverses this pattern

[10]Capital returns under autarky also converge to the expected mean of the inverted stochastic discount factor, which is essentially determined by the long-run growth rate of the economy g_h and consumers' preference parameters, i.e. the measure $\beta^{-1}(1+g_h)^\sigma$.

and leads to initial dis-investment in both regions. Intuitively, this is due to the gains from capital-efficiency (cf. Lemma 4) implying that less capital accumulation is required to accommodate the opportunities of international productivity conditions. Intuitively, these efficiency gains abandon the need for large capital buffers leading to lower capital intensities in both regions.

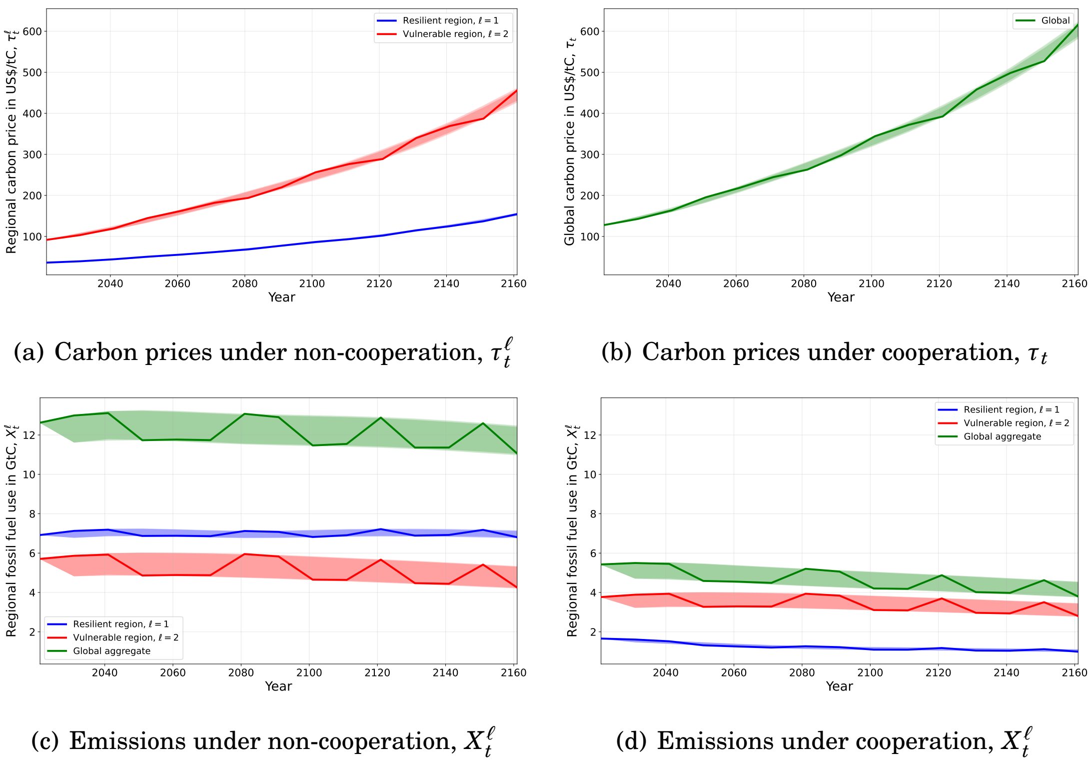
We summarize the effects of capital mobility as follows:

Numerical Result 2 (Capital-mobility effects)
International capital mobility has the following effects:

1. *Long-run capital intensities are lower in both regions.*
2. *Capital returns are perfectly synchronized across regions.*

Cooperation effects

Next consider the effects of cooperation within the complete markets case when regions switch from regionally to globally optimal carbon taxes. Figure 3 depicts these carbon prices and also the induced regional and global emissions.



(a) Carbon prices under non-cooperation, τ_t^ℓ

(b) Carbon prices under cooperation, τ_t

(c) Emissions under non-cooperation, X_t^ℓ

(d) Emissions under cooperation, X_t^ℓ

Figure 3: Impact of cooperation on regional emissions and carbon prices.

As one would expect from the formulae (63) and (69), carbon prices which internalize global climate damages are significantly higher than regionally optimal taxes which internalize only local damages. As a result, emissions under cooperation are not only substantially lower, they also shift from the resilient to the vulnerable region. Intuitively, this is due to taxes under non-cooperation being much higher in the vulnerable region which internalizes its much higher damages while the resilient region does not have sufficient incentive to tax carbon. This results in carbon-leakage from the vulnerable to the resilient region. With taxes under cooperation being harmonized, this effect is reversed. Summarizing, we have

Numerical Result 3 (Cooperation effects)
Under complete markets, cooperation has the following effects:

1. *Carbon prices are substantially higher in both regions relative to non-cooperation.*
2. *Aggregate emissions are substantially lower and shifted to the vulnerable region.*

6.4 Welfare analysis

A final key objective of this paper is to quantify the regional welfare gains and losses from risk-sharing, market openness, and international cooperation in carbon taxation. Table 5 lists the welfare gains in consumption equivalents quantified as follows: the isolated effects arise from pairwise comparisons, i.e. when relating consumption profiles across (i) autarky and complete financial markets (first row), (ii) complete financial markets with and without capital trade (second row), and (iii) cooperative and non-cooperative complete markets (third row). The combined effects compare the consumption profiles of autarky vs. complete financial markets with capital trade under non-cooperation (openness) and under cooperation (openness & cooperation). For all scenarios, regional welfare is measured by lifetime utility in (12) and expressed in consumption equivalents.[11]

Table 5: Welfare gains (consumption equiv., in %)

	Resilient region	Vulnerable region
Isolated effects		
Financial markets	4.47	-1.25
Capital trade	-1.69	2.56
Cooperation	-0.08	0.28
Combined effects		
Openness	2.70	1.29
Openness & cooperation	2.62	1.57

Gains from risk-sharing
Complete markets do not necessarily raise welfare in all regions. In particular, the vulnerable region is worse-off under complete financial markets than under autarky, despite

[11]The listed results are qualitatively robust to variations in the consumer's parameters, the elasticity of substitution (heeding $\varepsilon > 1$) and alternative calibrations of regional damages. This also includes the relative size of the effects, in particular the effects of cooperation.

lower consumption variation. This result can be attributed to the diminished permanent consumption share in global consumption: while risk-sharing in the complete financial markets set-up reduces volatility over all horizons, the relative share of global consumption accruing to the vulnerable region is reduced in the long-run. This is a direct implication of the implied synchronization of capital returns and the consumption share determination via lifetime incomes: since capital returns must equate in expectations under complete markets, the vulnerable region's capital gets effectively devalued which reduces the regional share in lifetime incomes. Put differently, if there is no direct international capital investment, a region exposed to higher risk will have to cut back on its capital accumulation to generate an attractive capital return satisfying (26). Figure 4 illustrates that while the share in global consumption is initially higher under complete markets, it gets permanently reduced when compared to the autarky scenario. This permanent effect dominates both the initial effect and the risk-sharing effects in terms of overall regional welfare.

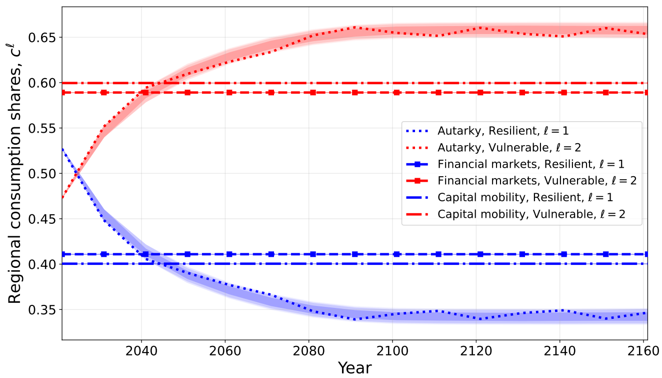


Figure 4: Consumption shares, c^ℓ.

Gains from capital trade

When capital markets are open, the vulnerable region is better off than under complete financial markets only, while the resilient region loses. This swapping of welfare gains is due to a reversal of the devaluation effect: now that the vulnerable region can employ its capital stock in the resilient region, it benefits from lower exposure to the fundamental risks there. This overcomes the redistribution effects of financial markets by increasing the vulnerable region's consumption share again. The efficiency gain in the international allocation of capital thus predominantly helps vulnerable regions, whose capital accumulation is not as negatively affected by production risks under capital-efficient markets as under autarky or financial markets only.

Gains from openness

The gains of openness arise from the combined effects of perfect risk-sharing and efficient capital markets, which are realized when exchanging the autarky scenario with the scenario of complete financial markets and capital trade. We find that the net effect of this combination is unambiguously positive for both regions, with the gains for the resilient region twice as big as for the vulnerable region. Closer inspection reveals that the gains of region 1 are mainly due to financial market openness while region 2 benefits much more from capital trade. Intuitively, financial markets enforce equalization of (ex-ante) capital returns due to the no-arbitrage condition (26). Only in the case of capital trade will the international harmonization of capital returns be accompanied by an increased influx of foreign capital investment which also leads to higher welfare in the vulnerable region.

Gains from cooperation
A remarkable observation from Table 5 is that the additional welfare gains from cooperation are quite modest, even for the vulnerable regions, and in fact negative for the resilient region 1. As can be seen from the schedule of carbon prices and thus emissions under cooperation, the resilient region faces drastic cutbacks in its emissions. The resilient region is the main offender under non-cooperation due to two forces: firstly, it produces at relatively lower energy efficiency; secondly, it is less susceptible to climate damages. The resilient region therefore faces much larger carbon prices when production is efficient and carbon prices are harmonized. Thus, in the absence of compensating transfers, cooperation will not result in a Pareto-improvement, which in part may explain the reluctance of developed countries to adopt globally coordinated climate policies. Finally, we note that the size of cooperation gains is at least one order of magnitude below the potential gains of openness. We interpret this result as partially driven by the two-region set-up, where optimal climate policy prescribes a substantial amount of internalization. As illustrated by the carbon price schedules in figure 3, the vulnerable region engineers a relatively high carbon price even under non-cooperation, bringing the non-cooperative allocation closer to the allocation under full cooperation.

7 Conclusion

Our paper provides a theoretical evaluation of the role of financial markets and international trade in addressing the climate externality. The main theoretical results derive closed form expressions for optimal carbon taxation under different degrees of cooperation and demonstrate how trade and risk-sharing opportunities shape the structure of these policies. Our numerical results quantify the impact of trade and risk-sharing and evaluate the welfare effects for different countries. We show that there are potentially large welfare gains of combined interventions, such as market openness in combination with harmonization of carbon prices, while isolated interventions tend to have more ambiguous effects. Closer inspection reveals that financial market openness is much more beneficial for the resilient region while the vulnerable regions benefits much more from direct capital investments. Relative to these effects, international cooperation in carbon taxation has only modest additional welfare effects, which are even negative for the resilient region.

In future research, we plan to extend these results along various dimensions. First, on the theoretical side we seek to extend the model by bringing in additional sources of risk, including tipping points such as in Lemoine and Traeger (2016), and disaster risks, which play a key role in Hambel and van der Ploeg (2025) and others. Additional trade frictions such as borrowing constraints and financial market incompleteness will allow us to study additional obstacles to reaching a globally coordinated climate policy. On the the computational side, we aim to further explore the potential gains of cooperation under a more disaggregated specification of the model, involving a larger number of regions. To this end, we are exploring the potential of more elaborate numerical methods including adaptive sparse grids developed by Brumm and Scheidegger (2017) and machine learning methods as used by Kübler, Scheidegger, and Surbek (2025) to handle the additional computational burden due to a much larger state space under these modifications.

A Proofs

A.1 Lifetime budget constraint with complete financial markets

In each period $t = 0,1,2,\dots$ and history $s^t = (s^{t-1}, s_t) \in \mathbb{S}_t$ the consumer receives factor income from supplying capital $K^{\ell,s}_{t-1}$ formed in $t-1$ and collects domestic profits Π^ℓ_t as well as the transfer $\tau^\ell_t(s^t)\cdot X^\ell_t(s^t)$ from the government and chooses consumption $C^\ell_t(s^t)$ and capital formation $q_t(s^t)$. In addition, the consumer invests in a portfolio $(A^\ell_{t+1}(s^t,s))_{s\in\mathbb{S}}$ of one-period Arrow securities priced at $(q_{t,t+1}(s^t,s))_{s\in\mathbb{S}}$ and receives the pay-off on the previous portfolio $A^\ell_t(s^{t-1},s_t)$. The period-budget constraint reads:

$$C^\ell_t(s^t) + K^{\ell,s}_t(s^t) + \sum_{s\in\mathbb{S}} q_{t,t+1}(s^t,s)\cdot A^\ell_{t+1}(s^t,s) \le \Pi^\ell_t(s^t) + \tau^\ell_t(s^t)\cdot X^\ell_t(s^t) + A^\ell_t(s^{t-1},s_t) + R^\ell_t(s^t)\cdot K^{\ell,s}_{t-1}(s^{t-1}) \tag{73}$$

with $K^{\ell,s}_{-1}$ and $A^\ell_0 = 0$ given.[12] For $t = 0,1,2,\dots$ and $s^t \in \mathbb{S}_t$, define financial wealth

$$W^\ell_t(s^t) := K^{\ell,s}_t(s^t) + \sum_{s\in\mathbb{S}} q_{t,t+1}(s^t,s)\cdot A^\ell_{t+1}(s^t,s) \tag{74}$$

Multiplying (73) by $q_t(s^t)$ and summing over all $s^t \in \mathbb{S}_t$ gives after rearranging terms

$$\sum_{s^t\in\mathbb{S}_t} q_t(s^t)\cdot W^\ell_t(s^t) \le \sum_{s^t\in\mathbb{S}_t} q_t(s^t)\cdot\Big(\Pi^\ell_t(s^t) + \tau^\ell_t(s^t)\cdot X^\ell_t(s^t) - C^\ell_t(s^t)\Big) + \sum_{s^t\in\mathbb{S}_t} q_t(s^t)\Big(A^\ell_t(s^{t-1},s_t) + R^\ell_t(s^t)\cdot K^{\ell,s}_{t-1}(s^{t-1})\Big). \tag{75}$$

Use the definition (27) of AD-prices to write

$$\sum_{s^t\in\mathbb{S}_t} q_t(s^t)\cdot A^\ell_t(s^{t-1},s_t) = \sum_{s^{t-1}\in\mathbb{S}_{t-1}} q_{t-1}(s^{t-1}) \sum_{s_t\in\mathbb{S}} q_{t-1,t}(s^{t-1},s_t)\cdot A^\ell_t(s^{t-1},s_t)$$

[12]The assumption of zero asset holdings before $t = 0$ is w.l.o.g. for consumer behavior if we interpret $K^{\ell,s}_{-1}$ as the net initial capital position.

and observe from the no-arbitrage condition (26) that

$$\sum_{s^t \in \mathbb{S}_t} q_t(s^t) \cdot R_t^\ell(s^t) \cdot K_{t-1}^{\ell,s}(s^{t-1}) = \sum_{s^{t-1} \in \mathbb{S}_{t-1}} q_{t-1}(s^{t-1}) \cdot K_{t-1}^{\ell,s}(s^{t-1}) \sum_{s_t \in \mathbb{S}} q_{t-1,t}(s^{t-1}, s_t) \cdot R_t^\ell(s^t)$$
$$= \sum_{s^{t-1} \in \mathbb{S}_{t-1}} q_{t-1}(s^{t-1}) \cdot K_{t-1}^{\ell,s}(s^{t-1}).$$

Using both properties and (74) in (75) one can use the probability-adjusted prices (28) and the notation from (29) to obtain

$$\mathbb{E}[q_t^p \cdot W_t^\ell] \leq \mathbb{E}\left[q_t^p \cdot \left(\Pi_t^\ell + \tau_t^\ell \cdot X_t^\ell - C_t^\ell\right)\right] + \mathbb{E}[q_{t-1}^p \cdot W_{t-1}^\ell]. \tag{76}$$

Setting $\mathbb{E}[q_{t-1}^p \cdot W_{t-1}^\ell] = R_0^\ell \cdot K_{-1}^{\ell,s}$ for $t = 0$ one shows by induction that (76) implies

$$\mathbb{E}[q_t^p \cdot W_t^\ell] \leq \sum_{n=0}^{t} \mathbb{E}\left[q_n^p \cdot \left(\Pi_n^\ell + \tau_n^\ell \cdot X_n^\ell - C_n^\ell\right)\right] + R_0^\ell \cdot K_{-1}^{\ell,s}. \tag{77}$$

Imposing the No-Ponzi Game condition $\lim_{t\to\infty} \mathbb{E}[q_t^p \cdot W_t^\ell] \geq 0$ condition (77) implies

$$0 \leq \sum_{n=0}^{\infty} \mathbb{E}\left[q_n^p \cdot \left(\Pi_n^\ell + \tau_n^\ell \cdot X_n^\ell - C_n^\ell\right)\right] + R_0^\ell \cdot K_{-1}^{\ell,s}. \tag{78}$$

which can be rearranged to obtain the lifetime-budget constraint (32). ■

A.2 Proof of Lemma 1

(i) Defining W^ℓ as in (32), the Lagrangian associated with problem (33) reads

$$\mathscr{L}(((C_t^\ell(s^t))_{s^t \in \mathbb{S}_t})_{t \geq 0}, \lambda) := \sum_{t=0}^{\infty} \sum_{s^t \in \mathbb{S}_t} \beta^t \mu_t(s^t) \frac{(C_t^\ell(s^t))^{1-\sigma}}{1-\sigma} + \lambda \cdot \left(W^\ell - \sum_{t=0}^{\infty} \sum_{s^t \in \mathbb{S}_t} q_t(s^t) C_t^\ell(s^t)\right).$$

For each $t = 0, 1, 2, \ldots$ and all $s^t \in \mathbb{S}_t$, the first order conditions read

$$\frac{\partial \mathscr{L}(-)}{\partial C_t^\ell(s^t)} = \beta^t \mu_t(s^t) (C_t^\ell(s^t))^{-\sigma} - \lambda \cdot q_t(s^t) \overset{!}{=} 0. \tag{79}$$

Solving (79) for $t = 0$ gives $\lambda = (C_0^\ell)^{-\sigma} > 0$ and using this result back in (79) along with (28) proves (34a). Since $\lambda > 0$, the Kuhn-Tucker constraint implies that (32) is binding.
(ii) Solving (34a) for C_0^ℓ gives for all $t = 0, 1, 2, \ldots$ and all $s^t \in \mathbb{S}_t$

$$C_t^\ell(s^t) = \left(\beta^t / q_t^p(s^t)\right)^{\frac{1}{\sigma}} \cdot C_0^\ell. \tag{80}$$

Substituting (80) into the binding budget constraint (32) and solving for C_0^ℓ gives

$$C_0^\ell = \frac{W^\ell}{\sum_{t=0}^{\infty} \mathbb{E}[q_t^p \cdot (\beta^t / q_t^p)^{\frac{1}{\sigma}}]} \tag{81}$$

Substituting (81) back into (80) gives the form (34b). ■

A.3 Proof of Lemma 2

Summing (34b) over all $\ell \in \mathbb{L}$ gives:

$$\overline{C}_t = \frac{(\beta^t/q_t^p)^{\frac{1}{\sigma}}}{\sum_{t=0}^{\infty} \mathbb{E}\left[q_t^p \cdot (\beta^t/q_t^p)^{\frac{1}{\sigma}}\right]} \cdot \sum_{\ell \in \mathbb{L}} W^\ell \quad \text{for all } t = 0,1,2,\dots \tag{82}$$

Dividing (34b) by (82) gives the claim. ■

A.4 Proof of Lemma 5

The Lagrangian associated with the decision problem (53) of region $\ell \in \mathbb{L}$ takes the form

$$\begin{aligned}
&\mathscr{L}(((C_t^\ell(s^t), X_t^\ell(s^t), K_t^\ell(s^t), T_t(s^t))_{s^t \in \mathbb{S}_t})_{t\geq 0}, ((\lambda_{K,t}(s^t), \lambda_{T,t}(s^t))_{s^t\in\mathbb{S}_t})_{t\geq 0}) := \sum_{t=0}^{\infty} \sum_{s^t \in \mathbb{S}_t} \beta^t \mu_t(s^t) u(C_t^\ell(s^t)) \\
&+ \sum_{t=0}^{\infty} \sum_{s^t \in \mathbb{S}_t} \lambda_{K,t}(s^t) \cdot \Big(Q^\ell(T_t(s^t), s_t) \cdot F_t^\ell(K_{t-1}^\ell(s^t), X_t^\ell(s^t)) + (1-\delta_K) \cdot K_{t-1}^\ell(s^{t-1}) - c_x \cdot X_t^\ell(s^t) - C_t^\ell(s^t) \\
&- K_t^\ell(s^t)\Big) + \sum_{t=0}^{\infty} \sum_{s^t \in \mathbb{S}_t} \lambda_{T,t}(s^t) \cdot \Big(T_t(s^t) - \delta_E \cdot T_{-1} - (1-\delta_E) \cdot T_{t-1}(s^{t-1}) - \zeta \cdot \Big(X_t^\ell(s^t) + \overline{X}_t^{-\ell}(s^t)\Big)\Big).
\end{aligned}$$

For each $t = 0,1,2,\dots$ and all $s^t \in \mathbb{S}_t$ the first order conditions take the form:

$$\frac{\partial \mathscr{L}(-)}{\partial C_t^\ell(s^t)} = \beta^t \mu_t(s^t) u'(C_t^\ell(s^t)) - \lambda_{K,t}(s^t) \stackrel{!}{=} 0 \tag{83a}$$

$$\frac{\partial \mathscr{L}(-)}{\partial K_t^\ell(s^t)} = -\lambda_{K,t}(s^t) + \sum_{s\in\mathbb{S}} \lambda_{K,t+1}(s^t,s)\Big(Q^\ell(T_{t+1}(s^t,s),s) \cdot \partial_K F_{t+1}^\ell(K_t^\ell(s^t), X_{t+1}^\ell(s^t,s)) + 1 - \delta_K\Big) \stackrel{!}{=} 0 \tag{83b}$$

$$\frac{\partial \mathscr{L}(-)}{\partial X_t^\ell(s^t)} = \lambda_{K,t}(s^t) \cdot \Big(Q^\ell(T_t(s^t), s_t) \cdot \partial_X F_t^\ell(K_{t-1}^\ell(s^t), X_t^\ell(s^t)) - c_x\Big) - \lambda_{T,t}(s^t) \cdot \zeta \stackrel{!}{=} 0 \tag{83c}$$

$$\frac{\partial \mathscr{L}(-)}{\partial T_t(s^t)} = -\lambda_{K,t}(s^t) \cdot \gamma^\ell(s_t) \cdot Q^\ell(T_t(s^t), s_t) \cdot F_t^\ell(K_{t-1}^\ell(s^t), X_t^\ell(s^t)) + \lambda_{T,t}(s^t) - (1-\delta_E) \sum_{s\in\mathbb{S}} \lambda_{T,t+1}(s^t,s) \stackrel{!}{=} 0 \tag{83d}$$

Solving (83a) gives

$$\lambda_{K,t}(s^t) = \beta^t \mu_t(s^t) u'(C_t^\ell(s^t)). \tag{84}$$

Using (84) in (83b) in conjunction with (3) proves (54). Defining $\hat{\tau}_t^\ell := \zeta \cdot \lambda_{T,t}/\lambda_{K,t}$ and rearranging (83d) using (84) in conjunction with (3) gives the local cost of carbon (50). Using $\hat{\tau}_t^\ell$ in (83c) and rearranging gives (55). ■

A.5 Proof of Lemma 6

The derivation is mostly analogous to the proof of Lemma 5 and employs a standard Lagrangean argument. The Lagrangian associated with the decision problem (57) of region $\ell \in \mathbb{L}$ takes the form

$$\mathscr{L}(((C_t^\ell(s^t), X_t^\ell(s^t), K_t^\ell(s^t), T_t(s^t))_{s^t \in \mathbb{S}_t})_{t\geq 0}, \lambda, ((\lambda_{T,t}(s^t))_{s^t \in \mathbb{S}_t})_{t\geq 0}) := \sum_{t=0}^{\infty} \sum_{s^t \in \mathbb{S}_t} \beta^t \mu_t(s^t) u(C_t^\ell(s^t))$$

$$+ \lambda \sum_{t=0}^{\infty} \sum_{s^t \in \mathbb{S}_t} q_t(s^t) \cdot \Big(Q^\ell(T_t(s^t), s_t) \cdot F_t^\ell(K_{t-1}^\ell(s^{t-1}), X_t^\ell(s^t)) + (1-\delta_K) \cdot K_{t-1}^\ell(s^{t-1}) - c_x \cdot X_t^\ell(s^t)$$

$$- C_t^\ell(s^t) - K_t^\ell(s^t) \Big) + \sum_{t=0}^{\infty} \sum_{s^t \in \mathbb{S}_t} \lambda_{T,t}(s^t) \cdot \Big(T_t(s^t) - \delta_E \cdot T_{-1} - (1-\delta_E) \cdot T_{t-1}(s^{t-1}) - \zeta \cdot \Big(X_t^\ell(s^t) + \overline{X}_t^{-\ell}(s^t) \Big) \Big).$$

For each $t = 0, 1, 2, \ldots$ and all $s^t \in \mathbb{S}_t$ the first order conditions take the form:

$$\frac{\partial \mathscr{L}(-)}{\partial C_t^\ell(s^t)} = \beta^t \mu_t(s^t) u'(C_t^\ell(s^t)) - \lambda \cdot q_t(s^t) \stackrel{!}{=} 0 \tag{85a}$$

$$\frac{\partial \mathscr{L}(-)}{\partial K_t^\ell(s^t)} = -\lambda \cdot \Big(q_t(s^t) + \sum_{s \in \mathbb{S}} q_{t+1}(s^t, s) \Big(Q^\ell(T_{t+1}(s^t, s), s) \cdot \partial_K F_{t+1}^\ell(K_t^\ell(s^t), X_{t+1}^\ell(s^t, s)) + 1 - \delta_K \Big) \Big) \stackrel{!}{=} 0 \tag{85b}$$

$$\frac{\partial \mathscr{L}(-)}{\partial X_t^\ell(s^t)} = \lambda \cdot q_t(s^t) \cdot \Big(Q^\ell(T_t, s_t) \cdot \partial_X F_t^\ell(K_{t-1}^\ell(s^{t-1}), X_t^\ell(s^t)) - c_x \Big) - \lambda_{T,t}(s^t) \cdot \zeta \stackrel{!}{=} 0 \tag{85c}$$

$$\frac{\partial \mathscr{L}(-)}{\partial T_t(s^t)} = -\lambda \cdot q_t(s^t) \cdot \gamma^\ell(s_t) \cdot Q^\ell(T_t, s_t) \cdot F_t^\ell(K_{t-1}^\ell(s^{t-1}), X_t^\ell(s^t)) + \lambda_{T,t}(s^t)$$
$$- (1-\delta_E) \sum_{s \in \mathbb{S}} \lambda_{T,t+1}(s^t, s) \stackrel{!}{=} 0. \tag{85d}$$

Rearranging (85a) gives

$$\lambda = \beta^t \mu_t(s^t) u'(C_t^\ell(s^t)) / q_t(s^t). \tag{86}$$

For $t = 0$, this expression gives $\lambda = u'(C_0^\ell)$ which can be used in (86) to obtain (58b). Moreover, since $\lambda > 0$, (56) is binding by the Kuhn-Tucker Theorem. Further, using (58b) in conjunction with (3) in (85b) and rearranging terms gives (58a). Finally, defining $\hat{\tau}_t^\ell = \zeta \cdot \frac{\lambda_{T,t}(s^t)}{\lambda \cdot q_t}$, one can rearrange (85d) to obtain the local cost of carbon (50). Using $\hat{\tau}_t^\ell$ in (85c) and rearranging gives (58c). ■

A.6 Proof of Lemma 7

The formal arguments are again similar to the previous proofs. The Lagrangian function associated with the global planning problem (67) is

$$\mathscr{L}((((K_t^\ell(s^t), X_t^\ell(s^t))_{\ell\in\mathbb{L}}, \bar{K}_t(s^t), \bar{C}_t(s^t), T_t(s^t))_{s^t\in\mathbb{S}_t})_{t\geq 0}, , ((\lambda_{K,t}(s^t), \lambda_{\bar{K},t}(s^t), \lambda_{T,t}(s^t))_{s^t\in\mathbb{S}_t})_{t\geq 0})$$

$$:= \sum_{t=0}^{\infty}\sum_{s^t\in\mathbb{S}_t} \beta^t \mu_t(s^t) u(\bar{C}_t(s^t)) + \sum_{t=0}^{\infty}\sum_{s^t\in\mathbb{S}_t} \lambda_{\bar{K},t}(s^t)\left(\bar{K}_{t-1}(s^{t-1}) - \sum_{\ell\in\mathbb{L}} K_t^\ell(s^t)\right)$$

$$+ \sum_{t=0}^{\infty}\sum_{s^t\in\mathbb{S}_t} \lambda_{K,t}(s^t)\cdot\Big(\sum_{\ell\in\mathbb{L}}\Big(Q^\ell(T_t(s^t), s_t)\cdot F_t^\ell(K_t^\ell(s^t), X_t^\ell(s^t)) + (1-\delta_K)\cdot K_t^\ell(s^t) - c_x\cdot X_t^\ell(s^t)\Big)$$

$$- \bar{K}_t(s^t) - \bar{C}_t(s^t)\Big) + \sum_{t=0}^{\infty}\sum_{s^t\in\mathbb{S}_t} \lambda_{T,t}(s^t)\cdot\Big(T_t(s^t) - \delta_E\cdot T_{-1} - (1-\delta_E)\cdot T_{t-1}(s^{t-1}) - \zeta\cdot\sum_{\ell\in\mathbb{L}} X_t^\ell(s^t)\Big).$$

For each $t = 0, 1, 2, \ldots$ and all $s^t \in \mathbb{S}_t$ the first order conditions take the form:

$$\frac{\partial\mathscr{L}(-)}{\partial K_t^\ell(s^t)} = -\lambda_{\bar{K},t}(s^t) + \lambda_{K,t}(s^t)\cdot Q^\ell(T_t(s^t), s_t)\cdot\partial_K F_t^\ell(K_t^\ell(s^t), X_t^\ell(s^t)) + 1 - \delta_K \stackrel{!}{=} 0 \tag{87a}$$

$$\frac{\partial\mathscr{L}(-)}{\partial X_t^\ell(s^t)} = \lambda_{K,t}(s^t)\cdot\Big(Q^\ell(T_t(s^t), s_t)\cdot\partial_X F_t^\ell(K_t^\ell(s^t), X_t^\ell(s^t)) - c_x\Big) - \zeta\cdot\lambda_{T,t}(s^t) \stackrel{!}{=} 0 \tag{87b}$$

$$\frac{\partial\mathscr{L}(-)}{\partial \bar{K}_t(s^t)} = \sum_{s\in\mathbb{S}} \lambda_{\bar{K},t}(s^t, s) - \lambda_{K,t}(s^t) \stackrel{!}{=} 0 \tag{87c}$$

$$\frac{\partial\mathscr{L}(-)}{\partial \bar{C}_t(s^t)} = \beta^t \mu_t(s^t) u'(\bar{C}_t(s^t)) - \lambda_{K,t}(s^t) \stackrel{!}{=} 0 \tag{87d}$$

$$\frac{\partial\mathscr{L}(-)}{\partial T_t(s^t)} = -\sum_{\ell\in\mathbb{L}} \gamma^\ell(s_t)\cdot Q^\ell(T_t, s_t)\cdot F_t^\ell(K_t^\ell(s^t), X_t^\ell(s^t)) + \lambda_{T,t}(s^t) - (1-\delta_E)\sum_{s\in\mathbb{S}} \lambda_{T,t+1}(s^t, s) \stackrel{!}{=} 0. \tag{87e}$$

Rearranging (87d) gives

$$\lambda_{K,t}(s^t) = \beta^t \mu_t(s^t) u'(\bar{C}_t(s^t)) > 0. \tag{88}$$

From $\lambda_{K,t}(s^t)$ we infer that (65) holds with equality by the Kuhn-Tucker Theorem. Rearranging (87a) gives

$$\lambda_{\bar{K},t}(s^t) = \lambda_{K,t}(s^t)\cdot\Big(Q^\ell(T_t(s^t), s_t)\cdot\partial_K F_t^\ell(K_t^\ell(s^t), X_t^\ell(s^t)) + 1 - \delta_K\Big) \tag{89}$$

Dividing by $\lambda_{K,t}(s^t)$ and noting that the l.h.s. is independent of ℓ, this establishes (68a).
For each t, define $\tau_t = \zeta\cdot\frac{\lambda_{T,t}(s^t)}{\lambda_{K,t}(s^t)}$. Using it in 87b and rearranging establishes (68b).
Using (88) and (89) and exploiting (68a) in (87c) and rearranging proves (68d).
Finally, using $\hat{\tau}_t$ and (88) in (87e) and rearranging gives (68c). ■

B Computation

This section describes the numerical algorithm used in our simulations to compute equilibrium for the three scenarios of autarky under non-cooperation, complete markets under non-cooperation, and complete markets under full cooperation. For each of the three scenarios, we first transform the equilibrium conditions into a stationary form and then employ functional methods to determine equilibrium variables by (sequences of) functions defined on a compact state space. The form of the latter depends on the respective scenario. Computations in the complete markets case make extensive use of the aggregation properties that the model exhibits under this market structure.

B.1 Notation and stationary transformation

Since the growth rates g_h and g_e are identical across regions, we can write regional labor and energy efficiency as $h_t^\ell = h_t \cdot h_0^\ell$ and $e_t^\ell = e_t \cdot e_0^\ell$ where

$$h_t := (1+g_h)^t \quad \text{and} \quad e_t := (1+g_e)^t \quad \text{for } t = 0,1,2,\ldots \tag{90}$$

are referred to as aggregate labor and energy efficiency, respectively. Our restriction $g_h > g_e$ then implies $\lim_{t\to\infty} e_t/h_t = 0$. As a consequence of this and our restriction $\varepsilon > 1$, we will assume and verify in our simulations that global emissions $(\overline{X}_t)_{t\geq 0}$ and temperature $(T_t)_{t\geq 0}$ take values in compact intervals $[0, \overline{X}_{\max}]$ and $[T_{-1}, T_{\max}]$ where $T_{\max} := T_{-1} + \zeta \cdot \overline{X}_{\max}/\delta_E$. Therefore, these variables are non-trending. For trending equilibrium variables, we define the stationary transformation

$$c_t^\ell := C_t^\ell/h_t, \quad k_t^\ell := K_t^\ell/h_t, \quad \bar{\tau}_t^\ell := \tau_t^\ell/h_t. \tag{91}$$

Further, defining the linear-homogeneous function $F : \mathbb{R}_+^3 \to \mathbb{R}$

$$F(K, L_e, X_e) := \left[\kappa \cdot \left(L_e^{1-\alpha} \cdot K^\alpha\right)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\kappa) \cdot X_e^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}} \tag{92}$$

permits to write the production function (70) as

$$F_t^\ell(K, X) = F(K, h_t^\ell \cdot N_t^\ell, e_t^\ell \cdot X) = F(K, h_t \cdot h_0^\ell \cdot N_t^\ell, e_t \cdot e_0^\ell \cdot X). \tag{93}$$

Note from (93) and linear homogeneity of F that the partial derivatives satisfy

$$\partial_K F_t^\ell(K, X) = \partial_K F(K/h_t, h_0^\ell \cdot N_t^\ell, e_0^\ell \cdot e_t/h_t \cdot X) \tag{94a}$$

$$\partial_X F_t^\ell(K, X) = \partial_{X_e} F(K/h_t, h_0^\ell \cdot N_t^\ell, e_0^\ell \cdot e_t/h_t \cdot X) \cdot e_0^\ell \cdot e_t. \tag{94b}$$

In all scenarios, initial temperature T_{-1} and the capital distribution $(K_{-1}^\ell)_{\ell\in\mathbb{L}}$ are given.

B.2 Autarky under non-cooperation

Based on Definition 1, equilibrium in this first scenario is an adapted stochastic process $((C_t^\ell, K_t^\ell, X_t^\ell, \tau_t^\ell)_{\ell\in\mathbb{L}}, T_t)_{t\geq 0}$ which satisfies the following for all $t = 0,1,2,\ldots$ and $\ell \in \mathbb{L}$:

$$\tau_t^\ell + c_x = Q^\ell(T_t, s_t)\cdot \partial_X F_t^\ell(K_{t-1}^\ell, X_t^\ell) \tag{95a}$$

$$(C_t^\ell)^{-\sigma} = \mathbb{E}_t\left[\beta\cdot (C_{t+1}^\ell)^{-\sigma}\cdot\left(Q^\ell(T_{t+1}, s_{t+1})\cdot\partial_K F_{t+1}^\ell(K_t^\ell, X_{t+1}^\ell) + 1 - \delta_K\right)\right] \tag{95b}$$

$$\tau_t^\ell = \zeta\cdot\gamma^\ell(s_t)\cdot Q^\ell(T_t, s_t)\cdot F_t^\ell(K_{t-1}^\ell, X_t^\ell) + \mathbb{E}_t\left[\beta\cdot\left(C_{t+1}^\ell / C_t^\ell\right)^{-\sigma}\cdot\tau_{t+1}^\ell\right] \tag{95c}$$

$$K_t^\ell = Q^\ell(T_t, s_t)\cdot F(K_{t-1}^\ell, h_0^\ell\cdot h_t\cdot N_t^\ell, e_t\cdot e_0^\ell\cdot X_t^\ell) + (1-\delta_K)\cdot K_{t-1}^\ell - c_x\cdot X_t^\ell - C_t^\ell \tag{95d}$$

$$T_t = \delta_E\cdot T_{-1} + (1-\delta_E)\cdot T_{t-1} + \zeta\cdot\sum_{\ell\in\mathbb{L}} X_t^\ell. \tag{95e}$$

Using (91) and (94) permits to transform (95) into the equivalent stationary form

$$\bar\tau_t^\ell + c_x/h_t = Q^\ell(T_t, s_t)\cdot\partial_{X_e} F(k_{t-1}^\ell/(1+g_h), h_0^\ell\cdot N_t^\ell, e_0^\ell\cdot e_t/h_t\cdot X_t^\ell)\cdot e_0^\ell\cdot e_t/h_t \tag{96a}$$

$$\begin{aligned}(c_t^\ell)^{-\sigma} = \mathbb{E}_t\Big[\beta\cdot(1+g_h)^{-\sigma}\cdot(c_{t+1}^\ell)^{-\sigma}\Big(1-\delta_K \\ + Q^\ell(T_{t+1}, s_{t+1})\cdot\partial_K F(k_t^\ell/(1+g_h), h_0^\ell\cdot N_{t+1}^\ell, e_0^\ell\cdot e_{t+1}/h_{t+1}\cdot X_{t+1}^\ell)\Big)\Big]\end{aligned} \tag{96b}$$

$$\begin{aligned}\bar\tau_t^\ell = \zeta\cdot\gamma^\ell(s_t)\cdot Q^\ell(T_t, s_t)\cdot F(k_{t-1}^\ell/(1+g_h), h_0^\ell\cdot N_t^\ell, e_0^\ell\cdot e_t/h_t\cdot X_t^\ell) \\ + \mathbb{E}_t\left[\beta\cdot(1+g_h)^{1-\sigma}\cdot\left(c_{t+1}^\ell/c_t^\ell\right)^{-\sigma}\cdot\bar\tau_{t+1}^\ell\right]\end{aligned} \tag{96c}$$

$$\begin{aligned}k_t^\ell = Q^\ell(T_t, s_t)\cdot F(k_{t-1}^\ell/(1+g_h), h_0^\ell\cdot N_t^\ell, e_0^\ell\cdot e_t/h_t\cdot X_t^\ell) \\ + (1-\delta_K)/(1+g_h)\cdot k_{t-1}^\ell - c_x/h_t\cdot X_t^\ell - c_t^\ell\end{aligned} \tag{96d}$$

$$T_t = \delta_E\cdot T_{-1} + (1-\delta_E)\cdot T_{t-1} + \zeta\cdot\sum_{\ell\in\mathbb{L}} X_t^\ell. \tag{96e}$$

The stationary equilibrium process $((c_t^\ell, k_t^\ell, X_t^\ell, \bar\tau_t^\ell)_{\ell\in\mathbb{L}}, T_t)_{t\geq 0}$ solves the system (96). Now define the endogenous state space $\Xi := \prod_{\ell\in\mathbb{L}}[k_{\min}^\ell, k_{\max}^\ell]\times[T_{-1}, T_{\max}]$ and for each $t = 0,1,2,\ldots$ the endogenous state $\xi_t := ((k_t^\ell)_{\ell\in\mathbb{L}}, T_t)\in\Xi$. A recursive equilibrium consists of a (deterministic) sequence of *policy functions* $((P_{c,t}^\ell, P_{X,t}^\ell, P_{\bar\tau,t}^\ell)_{\ell\in\mathbb{L}})_{t\geq 0}$ each mapping $\Xi\times\mathbb{S}$ into $\mathbb{R}_+$ and generating the stationary equilibrium process of control variables $((c_t^\ell, X_t^\ell, \tau_t^\ell)_{\ell\in\mathbb{L}})_{t\geq 0}$ for all $t = 0,1,2,\ldots$ and $\ell\in\mathbb{L}$ as

$$c_t^\ell = P_{c,t}^\ell(\xi_{t-1}, s_t),\quad X_t^\ell = P_{X,t}^\ell(\xi_{t-1}, s_t),\quad \bar\tau_t^\ell = P_{\bar\tau,t}^\ell(\xi_{t-1}, s_t). \tag{97}$$

These policy functions induce a *transition function* $G_t = ((G_{k,t}^\ell)_{\ell\in\mathbb{L}}, G_{T,t}) : \Xi\times\mathbb{S}\to\mathbb{R}_+^L\times\mathbb{R}_+$ determining the evolution of endogenous states as $\xi_t = G_t(\xi_{t-1}, s_t)$ for all $t = 0,1,2,\ldots$. The form of these transition functions follows directly from (96d) and (96e) as

$$T_t = G_{T,t}(\xi_{t-1}, s_t) := \delta_E\cdot T_{-1} + (1-\delta_E)\cdot T_{t-1} + \zeta\cdot\sum_{\ell\in\mathbb{L}} P_{X,t}^\ell(\xi_{t-1}, s_t) \tag{98a}$$

$$\begin{aligned}k_t^\ell = G_{k,t}^\ell(\xi_{t-1}, s_t) := Q^\ell(G_{T,t}(\xi_{t-1}, s_t), s_t)\cdot F(k_{t-1}^\ell/(1+g_h), h_0^\ell\cdot N_t^\ell, e_0^\ell\cdot e_t/h_t\cdot P_{X,t}^\ell(\xi_{t-1}, s_t)) \\ + (1-\delta_K)/(1+g_h)\cdot k_{t-1}^\ell - c_x/h_t\cdot P_{X,t}^\ell(\xi_{t-1}, s_t) - P_{c,t}^\ell(\xi_{t-1}, s_t).\end{aligned} \tag{98b}$$

Thus, G_t follows directly from the policy functions $P_t = (P^\ell_{c,t}, P^\ell_{X,t}, P^\ell_{\bar{\tau},t})_{\ell\in\mathbb{L}}$. Clearly, for the equilibrium to be well-defined, the numbers $(k^\ell_{\min}, k^\ell_{\max})_{\ell\in\mathbb{L}}$, and $T^{\max}$ defining the endogenous state space must be chosen such that each G_t maps into Ξ.

Note from (96a) that for each $\ell \in \mathbb{L}$ functions $P^\ell_{X,t}$ and $P^\ell_{\bar{\tau},t}$ are related by the condition

$$P^\ell_{\bar{\tau},t}(\xi,s) + c_x/h_t = Q^\ell(T',s)\cdot\partial_{X_e}F(k^\ell/(1+g_h), h^\ell_0\cdot N^\ell_t, e^\ell_0\cdot e_t/h_t\cdot P^\ell_{X,t}(\xi,s))\cdot e^\ell_0\cdot e_t/h_t \quad (99)$$

for all $\xi = ((k^\ell)_{\ell\in\mathbb{L}}, T) \in \Xi$ and $s \in \mathbb{S}$ where $T' = G_{T,t}(\xi,s)$. Since the transition function $G_{T,t}$ in (98a) also depends only on the list $(P^\ell_{X,t})_{\ell\in\mathbb{L}}$, equation (99) establishes a one-to-one relation between $(P^\ell_{X,t})_{\ell\in\mathbb{L}}$ and $(P^\ell_{\bar{\tau},t})_{\ell\in\mathbb{L}}$.

It follows from equilibrium conditions (96b) and (96c) that the sequence of policy functions $(P_t)_{t\geq 0}$ solves the functional equation

$$\begin{aligned}(P^\ell_{c,t}(\xi,s))^{-\sigma} = \sum_{s_+\in\mathbb{S}} M(s,s_+)\cdot\Big[\beta\cdot(1+g_h)^{-\sigma}\cdot(P^\ell_{c,t+1}(\xi_+,s_+))^{-\sigma}\Big(1-\delta_K + Q^\ell(G_{T,t+1}(\xi_+,s_+),s_+)\\ \cdot\partial_K F(k^\ell_+/(1+g_h), h^\ell_0\cdot N^\ell_{t+1}, e^\ell_0\cdot e_{t+1}/h_{t+1}\cdot P^\ell_{X,t+1}(\xi_+,s_+)\Big)\Big]\end{aligned} \quad (100a)$$

$$\begin{aligned}P^\ell_{\bar{\tau},t}(\xi,s) =& \zeta\cdot\gamma^\ell(s)\cdot Q^\ell(G_{T,t}(\xi,s),s)\cdot F(k^\ell/(1+g_h), h^\ell_0\cdot N^\ell_t, e^\ell_0\cdot e_t/h_t\cdot P^\ell_{X,t}(\xi,s))\\ &+ \sum_{s_+\in\mathbb{S}} M(s,s_+)\cdot\Big[\beta\cdot(1+g_h)^{1-\sigma}\cdot\Big(P^\ell_{c,t+1}(\xi_+,s_+)/P^\ell_{c,t}(\xi,s)\Big)^{-\sigma}\cdot P^\ell_{\bar{\tau},t}(\xi_+,s_+)\Big]\end{aligned} \quad (100b)$$

for all $\xi = ((k^\ell)_{\ell\in\mathbb{L}}, T) \in \Xi$ and all $s \in \mathbb{S}$ where $\xi_+ = ((k^\ell_+)_{\ell\in\mathbb{L}}, T_+) = G_t(\xi,s)$. Recall from (98) that G_t depends on the policy functions P_t and G_{t+1} on the functions P_{t+1}. Mathematically, (100) defines an operator which maps policies $P_{t+1} = (P^\ell_{c,t+1}, P^\ell_{X,t+1}, P^\ell_{\bar{\tau},t+1})_{\ell\in\mathbb{L}}$ for period $t+1$ into policies $P_t = (P^\ell_{c,t}, P^\ell_{X,t}, P^\ell_{\bar{\tau},t})_{\ell\in\mathbb{L}}$ for period t. In our computations, we apply this operator as follows: Choose a (preferably large) terminal period $t_{\max}$ and a number of burn-in periods $t_{\text{burn-in}}$. For $t = t_{\max} + t_{\text{burn-in}}$, choose initial guesses for the policies $P_t = (P^\ell_{c,t}, P^\ell_{X,t}, P^\ell_{\bar{\tau},t})_{\ell\in\mathbb{L}}$. Then, we can iterate (100) backwards as follows: For each simulation period $t = 0,1,2,\ldots,t_{\max}+t_{\text{burn-in}}-1$, let the policy functions P_{t+1} and associated transition functions G_{t+1} be given. Fix current states $\xi = ((k^\ell)_{\ell\in\mathbb{L}}, T) \in \Xi$ and $s \in \mathbb{S}$. Then, we can combine (99) and (100) to determine the current values $c^\ell_t = P^\ell_{c,t}(\xi,s)$, $X^\ell_t = P^\ell_{X,t}(\xi,s)$, and $\bar{\tau}^\ell_t = P^\ell_{\bar{\tau},t}(\xi,s)$ for each $\ell \in \mathbb{L}$. Since ξ and s were arbitrary, this permits to determine the functions P_t and the induced transitions G_t point-wise for any current state.

The previous procedure yields a finite sequence of policy and transitions functions P_t and G_t for each $t = 0,1,2,\ldots,t_{\max}+t_{\text{burn-in}}$. The functions P_t, G_t for $t > t_{\max}$ are then discarded to eliminate possible dependence on the initial guess for $t = t_{\max}+t_{\text{burn-in}}$. Our numerical results show that setting $t_{\text{burn-in}} = 20$ completely eliminates this dependence. A realization of the stationary equilibrium process $((c^\ell_t, k^\ell_t, X^\ell_t, \bar{\tau}^\ell_t)_{\ell\in\mathbb{L}}, T_t)_{t=0}^{t_{\max}}$ can then be computed by drawing a realization of the exogenous states $(s_t)_{t=0}^{t_{\max}}$ and computing the endogenous variables in a forward-recursive fashion based on the previously determined policy and transition functions.

B.3 Complete financial markets under non-cooperation

In the case with complete financial markets, the endogenous state variable ξ_t and the state space Ξ are defined as in the previous autarky scenario. Relative to the previous scenario, there are two major deviations in the equilibrium restrictions. First, a direct implication of Lemma 2 is that it suffices to consider stationary aggregate consumption $\bar{c}_t = \overline{C}_t/h_t$ and compute the stationary equilibrium process $(\bar{c}_t, (k_t^\ell, X_t^\ell, \bar{\tau}_t^\ell)_{\ell\in\mathbb{L}}, T_t)_{t\geq 0}$. The consumption distribution $(c^\ell)_{\ell\in\mathbb{L}}$ can be computed ex-post based on the consumption shares defined in (40) as described in Section B.6 below. Thus, the policy functions determining regional consumption are now replaced by the single aggregate policy function $P_{\bar{c},t} : \Xi \times \mathbb{S} \to \mathbb{R}_+$ and the Euler equations (96b) are now replaced by the condition

$$\begin{aligned} \bar{c}_t^{-\sigma} = & \mathbb{E}_t \Big[\beta \cdot (1+g_h)^{-\sigma} \cdot \bar{c}_{t+1}^{-\sigma} \Big(1 - \delta_K \\ & + Q^\ell(T_{t+1}, s_{t+1}) \cdot \partial_K F(k_t^\ell/(1+g_h), h_0^\ell \cdot N_{t+1}^\ell, e_0^\ell \cdot e_{t+1}/h_{t+1} \cdot X_{t+1}^\ell) \Big) \Big] \end{aligned} \tag{101}$$

Second, due to the commodity exchange via trade on financial markets, the regional resource constraints (96d) need no longer hold and must be replaced by the single aggregate constraint derived from (36)

$$\sum_{\ell\in\mathbb{L}} k_t^\ell = \sum_{\ell\in\mathbb{L}} \Big(Q_t^\ell F_t(k_{t-1}^\ell/(1+g_h), X_t^\ell) + (1-\delta_K)/(1+g_h) \cdot k_{t-1}^\ell - c_x \cdot X_t^\ell \Big) - \overline{C}_t. \tag{102}$$

With these modifications, the remaining computations and methods are the same as in the previous scenario, with some obvious notational modifications.

B.4 Complete markets under non-cooperation

As in the previous scenario, we also focus on aggregate consumption $\bar{c}_t = \overline{C}_t/h_t$. A second major simplification due to capital mobility is that it now suffices to consider aggregate capital formation $\bar{K}_t$ in each period t. Defining $\bar{k}_t := \overline{K}_t/h_t$, this simplifies the endogenous state variable to $\xi_t := (\overline{K}_t, T_t)$ taking values in $\Xi := [\bar{k}_{\min}, \bar{k}_{\max}] \times [T_{-1}, T_{\max}]$.
Second, we can separate the factor allocation problem in period t from the dynamic evolution of aggregate variables. To formalize this idea, consider an arbitrary period t and let the endogenous and exogenous states $\xi_{t-1} = (\bar{k}_{t-1}, T_{t-1}) \in \Xi$ and $s_t \in \mathbb{S}$ as well as exogenous variables be given. Fix an arbitrary (stationary) tax profile $(\bar{\tau}_t^\ell)_{\ell\in\mathbb{L}}$. Then, the factor allocation problem in period t is to determine the disaggregated allocation $(k_t^\ell, X_t^\ell)_{\ell\in\mathbb{L}}$ along with gross capital return R_t and temperature T_t as the solution to

$$R_t - (1-\delta_K) = Q^\ell(T_t, s_t) \partial_K F(k_t^\ell, h_0^\ell \cdot N_t^\ell, e_0^\ell \cdot e_t/h_t \cdot X_t^\ell) \tag{103a}$$

$$h_t \cdot \bar{\tau}_t^\ell + c_x = Q^\ell(T_t, s_t) \partial_{X_e} F(k_t^\ell, h_0^\ell \cdot N_t^\ell, e_0^\ell \cdot e_t/h_t \cdot X_t^\ell) \cdot e_0^\ell \cdot e_t \tag{103b}$$

$$\sum_{\ell\in\mathbb{L}} k_t^\ell = \bar{k}_{t-1}/(1+g_h) \tag{103c}$$

$$T_t = \delta_E \cdot T_{-1} + (1-\delta_E) \cdot T_{t-1} + \zeta \cdot \sum_{\ell\in\mathbb{L}} X_t^\ell. \tag{103d}$$

The solution to this problem is a list $((k_t^{\ell*}, X_t^{\ell*})_{\ell\in\mathbb{L}}, R_t^*, T_t^*)$ which can conveniently be determined by the algorithm developed in Hillebrand and Hillebrand (2023) and applied to a similar problem in Hillebrand (2025). This defines functions $\Phi_{kX,t}: \mathbb{R}_+^L \times \Xi \times \mathbb{S} \to \mathbb{R}_+^{2L}$, $\Phi_{R,t}: \mathbb{R}_+^L \times \Xi \times \mathbb{S} \to \mathbb{R}_{++}$, and $\Phi_{T,t}: \mathbb{R}_+^L \times \Xi \times \mathbb{S} \to \mathbb{R}_+$ determining the previous solution as

$$(k_t^{\ell*}, X_t^{\ell*})_{\ell\in\mathbb{L}} = \Phi_{kX,t}((\bar{\tau}_t^\ell)_{\ell\in\mathbb{L}}, \xi_{t-1}, s_t) \tag{104a}$$

$$R_t^* = \Phi_{R,t}((\bar{\tau}_t^\ell)_{\ell\in\mathbb{L}}, \xi_{t-1}, s_t) \tag{104b}$$

$$T_t^* = \Phi_{T,t}((\bar{\tau}_t^\ell)_{\ell\in\mathbb{L}}, \xi_{t-1}, s_t). \tag{104c}$$

Equipped with these preparations, we can now characterize equilibrium as an adapted process $((k_t^\ell, X_t^\ell, \bar{\tau}_t^\ell)_{\ell\in\mathbb{L}}, \bar{k}_t, \bar{c}_t, T_t)_{t\geq 0}$ which satisfies for all $t = 0,1,2,\ldots$ and $\ell \in \mathbb{L}$:

$$(\bar{c}_t)^{-\sigma} = \mathbb{E}_t\left[\beta\cdot(1+g_h)^{-\sigma}\cdot(\bar{c}_{t+1})^{-\sigma}\cdot\Phi_{R,t+1}((\bar{\tau}_{t+1}^\ell)_{\ell\in\mathbb{L}}, \bar{k}_t, T_t, s_{t+1})\right] \tag{105a}$$

$$\begin{aligned}\bar{\tau}_t^\ell =& \zeta\cdot\gamma^\ell(s_t)\cdot Q^\ell(T_t,s_t)\cdot F(k_t^\ell, h_0^\ell\cdot N_t^\ell, e_0^\ell\cdot e_t/h_t\cdot X_t^\ell)\\ &+\mathbb{E}_t\left[\beta\cdot(1+g_h)^{1-\sigma}\cdot(\bar{c}_{t+1}/\bar{c}_t)^{-\sigma}\cdot\bar{\tau}_{t+1}^\ell\right]\end{aligned} \tag{105b}$$

$$\begin{aligned}\bar{k}_t =& \sum_{\ell\in\mathbb{L}} Q^\ell(T_t,s_t)\cdot F(k_t^{\ell*}, h_0^\ell\cdot N_t^\ell, e_0^\ell\cdot e_t/h_t\cdot X_t^{\ell*}) + (1-\delta_K)/(1+g_h)\bar{k}_{t-1}\\ &- c_x/h_t\cdot\sum_{\ell\in\mathbb{L}} X_t^\ell - \bar{c}_t\end{aligned} \tag{105c}$$

where T_t and $(k_t^\ell, X_t^\ell)_{\ell\in\mathbb{L}}$ are determined by (104a) and (104c).
Similar to the first scenario, equations (105) define an operator mapping policy functions $P_{t+1} = (P_{\bar{c},t+1}, (P_{X,t+1}^\ell, P_{\bar{\tau},t+1}^\ell)_{\ell\in\mathbb{L}})$ to $P_t = (P_{\bar{c},t}, (P_{X,t}^\ell, P_{\bar{\tau},t}^\ell)_{\ell\in\mathbb{L}})$ for each t. The policy functions P_t define transition functions $G_t = (G_{\bar{k},t}, G_{T,t})$ by (105c) and (104c).
In our computations, we apply the previous operator as follows: In each simulation period $t = 0,1,2,\ldots,t_{\max}+t_{\text{burn-in}}$, let policies P_{t+1} be given. Fix current states $\xi = (\bar{k}, T)$ and $s \in \mathbb{S}$ and determine $\bar{c}_t = P_{\bar{c},t}(\xi,s)$, $X_t^\ell = P_{X,t}^\ell(\xi,s)$, and $\bar{\tau}_t^\ell = P_{\bar{\tau},t}^\ell(\xi,s)$, $\ell\in\mathbb{L}$ as follows:

1. Start with an initial guess $(\hat{\tau}_t^\ell)_{\ell\in\mathbb{L}}$ for $(\bar{\tau}_t^\ell)_{\ell\in\mathbb{L}}$
2. Compute the factor allocation $(\hat{k}_t^\ell, \hat{X}_t^\ell)_{\ell\in\mathbb{L}}$ and temperature $\hat{T}_t$ based on (104)
3. Determine $\hat{\bar{c}}_t$ and $\hat{\bar{k}}_t$ by solving (105a,c) using $P_{\bar{c},t+1}$, $(P_{\bar{\tau},t+1}^\ell)_{\ell\in\mathbb{L}}$, and $\Phi_{R,t+1}$.
4. Update the tax profile to $(\tilde{\tau}_t^\ell)_{\ell\in\mathbb{L}}$ by solving (105b) using $P_{\bar{c},t+1}$ and $(P_{\bar{\tau},t+1}^\ell)_{\ell\in\mathbb{L}}$.
5. Iterate until the tax values converge to the solution $(\bar{\tau}_t^\ell)_{\ell\in\mathbb{L}}$.

The remaining computations and methods are the same as in the previous scenario, with the obvious notational modifications.

B.5 Complete markets under full cooperation

The last scenario is almost identical to the previous one. The main difference is that taxes are now uniform and the functions defined in (104) depend on the global tax $\bar{\tau}_t := \tau_t/h_t$. As a result, the recursive system generating the stationary equilibrium now takes the form

$$
\begin{aligned}
(\bar{c}_t)^{-\sigma} =& \mathbb{E}_t \left[\beta \cdot (1+g_h)^{-\sigma} \cdot (\bar{c}_{t+1})^{-\sigma} \cdot \Phi_{R,t+1}(\bar{\tau}_{t+1}, \bar{k}_t, T_t, s_{t+1})\right] && \text{(106a)}\\
\bar{\tau}_t =& \zeta \cdot \sum_{\ell \in \mathbb{L}} \gamma^\ell(s_t) \cdot Q^\ell(T_t, s_t) \cdot F(k_t^\ell, h_0^\ell \cdot N_t^\ell, e_0^\ell \cdot e_t/h_t \cdot X_t^\ell) \\
& + \mathbb{E}_t \left[\beta \cdot (1+g_h)^{1-\sigma} \cdot (\bar{c}_{t+1}/\bar{c}_t)^{-\sigma} \cdot \bar{\tau}_{t+1}\right] && \text{(106b)}\\
\bar{k}_t =& \sum_{\ell \in \mathbb{L}} Q^\ell(T_t, s_t) \cdot F(k_t^{\ell *}, h_0^\ell \cdot N_t^\ell, e_0^\ell \cdot e_t/h_t \cdot X_t^{\ell *}) + (1-\delta_K)/(1+g_h)\bar{k}_{t-1} \\
& - c_x/h_t \cdot \sum_{\ell \in \mathbb{L}} X_t^\ell - \bar{c}_t && \text{(106c)}
\end{aligned}
$$

The recursive computation of policy functions $P_t = (P_{\bar{c},t}, (P_{X,t}^\ell)_{\ell \in \mathbb{L}}, P_{\bar{\tau},t})$ and transition functions $G_t = (G_{\bar{k},t}, G_{T,t})$ for $t = 0, 1, 2, \ldots, t_{\max} + t_{\text{burn-in}}$ starting with some initial guess P_t for $t = t_{\max} + t_{\text{burn-in}}$ is now straightforward permitting to compute equilibrium as in the previous two scenarios.

B.6 Further computational details

To represent functions defined on the state space $\Xi \times \mathbb{S}$ numerically, we use Chebyshev polynomials and a finite grid $\Xi^{\text{grid}} \subset \Xi$ defined by Chebyshev roots. The grid of capital states consists of n_k points and takes the form $\mathbb{K}^{\text{grid}} = \{k_1, ..., k_{n_k}\} \subset \mathbb{R}_{++}$. It is isomorphic to the n_k Chebyshev roots in $[-1, 1]$. The grid of temperature states consists of n_T points and takes the form $\mathbb{T}^{\text{grid}} = \{T_1, ..., T_{n_T}\} \subset \mathbb{R}_{++}$. It is isomorphic to the n_T Chebyshev roots in $[-1, 1]$. The state space grid under autarky and complete financial markets is $\Xi^{\text{grid}} = \prod_{\ell \in \mathbb{L}} \mathbb{K}^{\text{grid}} \times \mathbb{T}^{\text{grid}}$ and under complete markets with capital trade it is $\Xi^{\text{grid}} = \mathbb{K}^{\text{grid}} \times \mathbb{T}^{\text{grid}}$. Since policy functions display a high degree of linearity in T, we chooses $n_T = 5$ and $n_k = 75$ in our default simulations. These choices produce Euler-errors of at most 0.02% along the simulated equilibrium path in all three scenarios.

To compute the consumption shares c^ℓ in scenarios 2 and 3, we fix a terminal period $t_{\max}$ and use the transition functions G_t to recursively compute the state variables $\xi_t(s^t)$ for all $t = 0, 1, 2, \ldots, t_{\max}$ and all possible histories $s^t \in \mathbb{S}_t$. We also infer the probability $\mu_t(s^t)$ of each history. All endogenous equilibrium variables in period t can then be obtained from the policy functions P_t and can be used to define further variables in the definition of W^ℓ, $\ell \in \mathbb{L}$. We then compute the implied consumption shares from (40) and verify numerically that further increasing $t_{\max}$ does not alter these values.

B.7 Calibration details

Population data of the World Population Prospects 2024 from the United Nations (2025) were aggregated to obtain the population sequences $(N_t^\ell)_{t\geq 0}$ in (70). To calibrate initial regional efficiency levels $(h_0^\ell, e_0^\ell)_{\ell\in\mathbb{L}}$ and the initial distribution of capital $(\eta_K^\ell)_{\ell\in\mathbb{L}}$ we use national statistics of GDP and wealth from World Bank (2025) and regional emissions data from Global Carbon Project (2025). Annual variables are aggregated to obtain values per decade consistent with our time structure. As for the initial capital distribution, we use the `comprehensive wealth` and `produced capital` statistics from the wealth accounts from World Bank (2025). This implies the calibration targets listed in table 6. We

Table 6: Calibration targets (aggregates for years 2011-2020)

Variable	Units	Region 1	Region 2	Data source
$Y_0^{\ell,\text{target}}$	Trn. U.S.$	566.9	574.4	World Bank
$K_0^{\ell,\text{target}}$	Trn. U.S.$	611.5	376.8	World Bank
$X_0^{\ell,\text{target}}$	GtC	36.43	57.58	Carbon project

then combine the production technologies (14) and optimality conditions (17) respectively (31) to determine h_0^ℓ and e_0^ℓ for each $\ell \in \mathbb{L}$ such that the calibration targets in Table 6 are matched under zero taxation in $t = 0$. Further details of this approach can be found in Hillebrand (2025).

The regional damage functions $\gamma^\ell(\cdot)$ are specified as follows. We set

$$\gamma^\ell(s) = \psi^\ell(s)\bar{\gamma}^\ell, \qquad \bar{\gamma}^\ell := \omega^\ell\,\bar{\gamma}, \tag{107}$$

where $\psi^\ell : \mathbb{S} \to \mathbb{R}_+$ captures region-specific state-dependence in climate damages, ω^ℓ are pattern-scaling constants satisfying $\sum_{\ell\in\mathbb{L}} \omega^\ell = 1$, and $\bar{\gamma}$ is our calibration target for the global expected damage rate. The function ψ is normalized so that its expectation under the stationary distribution μ^* equals unity, $\mathbb{E}_{\mu^*}[\psi^\ell(s_t)] = 1$ for all $\ell \in \mathbb{L}$, ensuring that $\bar{\gamma}^\ell$ equals region ℓ's expected damage rate under μ^*. This normalization fully pins down the functions $\psi^\ell, \ell \in \mathbb{L}$ for $S = 2$ once values $\psi^\ell(1) \in (0,1)$ are given according to:

$$\psi^\ell(0) = \frac{1-\mu^*(1)\psi^\ell(1)}{1-\mu^*(1)}, \quad \ell \in \mathbb{L}$$

The values in table 2 follow for $\bar{\gamma} = 0.125$, $\omega^0 = 0.4$, and $\psi^1(1) = 0.8$, $\psi^2(1) = 0.6$.

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