

# Win as a Team or Fail as Individuals: Cooperation and Non-Cooperation in the Climate Tax Game\*

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## Abstract

This paper studies the strategic interaction of arbitrarily many heterogeneous regions in a macroeconomic growth model of climate change. Regions differ with respect to production technologies, productivity and factor endowments, stocks of fossil fuels, and climate damages. They trade on frictionless international markets for capital and fossil fuels and choose climate policies under different scenarios of cooperation and non-cooperation. I derive closed form solutions of optimal policies for the non-cooperative equilibrium where regions internalize only domestic climate damages and cases with partial cooperation where regions form coalitions and choose policies to maximize welfare of their coalition. Efficient carbon taxation obtains as the special case with full cooperation corresponding to a grand coalition that internalizes global climate damages. I study how transfers can incentivize regions to cooperate and determine a class of optimal transfer schemes under which all regions are better-off under full cooperation relative to the non-cooperative outcome. Numerical simulations based on calibrated parameter values illustrate and quantify the theoretical results for different coalition scenarios.

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# 1 Introduction

Climate change is a global threat requiring a coordinated effort of all nations to significantly and permanently reduce their emissions from burning fossil fuels. Several climate summits accompanied by intense negotiations held over the past years and even decades suggest that there is wide agreement on this necessity. Yet, a political solution that all countries have committed to has not been reached. A major obstacle to implementing climate policies at the global level are that nations or regions differ substantially along many dimensions such as their state of economic development, reliance on fossil fuels, and the climate damages they are projected to suffer. Therefore, the incentives for implementing climate policies vary considerably across regions. Past climate agreements have also seen the formation of coalitions being an integral part of negotiations. Hence, it is important to understand how the formation of coalitions determines the outcome of the political process and which policies remain feasible.

A theoretical analysis of optimal climate policies and their successful implementation must therefore be based on a framework which incorporates three key features. First, decisions on climate policies are taken by politically autonomous regions acting in their own self-interest rather than for the common good. Second, these regions differ substantially along key economic and other dimensions and, therefore, have different incentives for choosing and implementing a particular climate policy. Third, countries may not be willing to fully cooperate at the global level but instead form coalitions of regions with common political interests.

The present paper studies the existence and form of optimal climate policies in a model with heterogeneous regions that incorporates all of the previous features. The analysis draws on the multi-region framework and results developed in earlier work Hillebrand & Hillebrand (2019, 2023). In these papers, the focus was on optimal climate policies under full cooperation. The present paper extends this approach to a general non-cooperative setup in which the fully cooperative scenario emerges as a special case.

Within this setup, the paper addresses the following specific questions. First, which climate policies emerge in a purely non-cooperative setting and how do they differ from the fully cooperative solution? Second, which policies emerge with partial cooperation and the formation of coalitions? Third, how can regions be incentivized to cooperate by means of side payments and how can such transfer policies be characterized?

Answering these and a number of related questions is the general contribution of this paper. Specifically, I derive closed form solutions of optimal climate policies for the fully non-cooperative case and the fully cooperative case and for scenarios with partial cooperation where regions form coalitions. All these results take a very simple and intuitive form. Finally, I provide a complete characterization of transfer schemes which redistribute the gains from cooperation such that each region has an incentive to cooperate.

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This defines a range of admissible transfers that forms the basis for successful climate negotiations.

The paper contributes to a large and growing literature studying the climate problem from an economic perspective. Modern representatives of this field use dynamic general equilibrium theory which is the standard approach in macroeconomics.<sup>1</sup> The paper closest to mine is Hambel, Kraft & Schwartz (2021), henceforth HKS who also derive optimal climate policies corresponding to abatement efforts in a fully non-cooperative setup. Using the implicit definition of the social cost of carbon from Nordhaus (2014), HKS also obtain a measure of the implied regional emissions taxes. In this paper, I use a different concept of the social cost of carbon based on explicitly defined planning problem similar to Golosov et al. (2014) and Hillebrand & Hillebrand (2019). A main difference to HKS and others is that I allow for regions to trade on frictionless international markets for capital and fossil fuels. This assumption ensures existence of a uniform discount factor applied by all regions to discount future marginal climate damages. This is the key ingredient to my results permitting to derive closed form solutions of optimal carbon taxes that have a simple and intuitive economic interpretation.

A question closely connected to the problem climate change is whether economic growth can be sustained in the presence of finite stocks of fossil fuels. This scarcity problem studied, e.g., by Hassler, Krusell & Olovsson (2021) is also incorporated in the present paper by including explicit resource constraints and various forms of exogenous factor-augmenting technological change in the model. This permits to study the full interactions between climate change and resource scarcity and also how the distribution of fossil resources among countries affects their incentives to implement climate policies.

The paper also contributes to the game theoretic literature on climate change advanced by Harstad (2016, 2012) and Battaglini & Harstad (2016). These papers usually focus on game theoretic aspects and, therefore, employ highly stylized models of both the macroeconomy and the climate system. As a consequence, the cost of climate change and damages are specified directly in a somewhat ad-hoc fashion rather than being derived as an endogenous outcome of the interaction between the economic production sector and the climate system. A related paper in this branch is Bourany (2024) who uses a static production economy with heterogeneous regions to study the optimal design of climate agreements. Relative to these papers, I maintain the full-fledged growth framework of Hillebrand & Hillebrand (2019) featuring an explicit description of the production process including capital formation and the climate system. Despite this more detailed specification, I retain the virtue of being able to derive analytical results including closed form solutions of optimal climate policies under different levels of cooperation among regions.

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<sup>1</sup>Examples are Golosov et al. (2014), Hassler & Krusell (2012), Gerlagh & Liski (2018), or Rezai & van der Ploeg (2021).

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A final strand of research studies scenarios of cooperation and non-cooperation based on the RICE model developed in Nordhaus & Yang (1996). Setting aside the conceptual problems facing the RICE model and the derivation of its solution (cf. Denning & Emmerling (2017) or Hillebrand & Hillebrand (2019)), all these studies are confined to purely numerical results and analytical expressions can not be derived.<sup>2</sup> In addition, the RICE-framework severely restricts or even excludes trade among countries.

The paper is organized as follows. Section 2 introduces the model. Section 3 derives the decentralized equilibrium under arbitrary climate policies. Sections 4 and 5 study the non-cooperative solution and the case with partial cooperation under formation of coalitions. Section 6 derives the globally efficient solution and studies the incentives to cooperate. Section 7 presents results from a numerical simulation study. Section 8 concludes. Mathematical proofs and computational details are placed in the appendix.

## 2 The Model

### 2.1 World economy

The world economy is divided into  $L \geq 1$  politically autonomous regions, indexed by  $\ell \in \mathbb{L} := \{1, \dots, L\}$ . Time evolves in discrete periods  $t \in \{0, 1, 2, \dots\}$ . All variables determined prior to the initial period  $t = 0$  are treated as given parameters. Regional dependence of a variable is denoted by a superscript  $\ell$  and summation of this variable over all regions by a bar superscript. For example,  $X_t^\ell$  will denote fossil fuel consumption of region  $\ell$  in period  $t$  and  $\bar{X}_t := \sum_{\ell \in \mathbb{L}} X_t^\ell$  global emissions in period  $t$ .

The major building blocks of the model are the production sector, the climate model, and the consumption sector which are introduced in the following subsections.

### 2.2 Production sector

#### *Final output*

In each region  $\ell \in \mathbb{L}$  a single representative firm produces a homogeneous final output commodity  $Y_t^\ell$  using capital  $K_t^\ell$  and fossil fuels  $X_t^\ell$  as inputs in period  $t$ . The production technology is of the general form

$$Y_t^\ell = (1 - D_t^\ell) F_t^\ell(K_t^\ell, X_t^\ell). \quad (1)$$

Here,  $D_t^\ell \in [0, 1]$  denotes endogenous climate damage which is further specified below. Capital input  $K_t^\ell$  is rented in the international capital market at price  $r_t$ . Input factor

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<sup>2</sup>Models in this category include Bosetto et al. (2003), Eyckmans & Tulkens (2003), Eyckmans & Finus (2003), or Finus et al. (2014).

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$X_t^\ell$  subsumes all kinds of fossil fuels (coal, oil, etc.) and is purchased in the global resource market at price  $v_t$ . Time-dependence of the production function  $F_t^\ell$  captures both regional population growth as well exogenous technological progress.

*Restrictions on technology*

I impose the following standard restrictions on the production function  $F_t^\ell$  in (1). The left-side Inada condition (2) ensures that each factor will be employed at equilibrium.

**Assumption 1**

The function  $F_t^\ell : \mathbb{R}_+^2 \rightarrow \mathbb{R}_+$  is strictly increasing, strictly concave, and continuously differentiable on  $\mathbb{R}_{++}^2$ . The partial derivatives satisfy the boundary condition<sup>3</sup>

$$\lim_{K \searrow 0} \partial_K F_t^\ell(K, X) = \infty \text{ for all } X > 0 \quad \text{and} \quad \lim_{X \searrow 0} \partial_X F_t^\ell(K, X) = \infty \text{ for all } K > 0. \quad (2)$$

*Extraction of fossil fuels*

Region  $\ell \in \mathbb{L}$  possesses an initial stock of fossil fuels  $R_0^\ell \geq 0$  which can be extracted at constant unit costs  $c_x \geq 0$ . Extraction of fossil fuels takes place in a resource sector operated by a single firm which chooses an extraction sequence  $(X_t^{\ell,s})_{t \geq 0}$  with  $X_t^{\ell,s} \geq 0$  denoting the extraction of fossil fuels in period  $t$ . Extracted resources  $X_t^{\ell,s}$  are supplied to the global resource market in period  $t$ . Feasible extraction plans satisfy

$$\sum_{t=0}^{\infty} X_t^{\ell,s} \leq R_0^\ell. \quad (3)$$

## 2.3 Climate model

*Emissions*

Emissions of CO<sub>2</sub> are generated by burning fossil fuels in production. Measuring fossil fuel inputs  $X_t^\ell$  in (1) directly in units of carbon, global emission in period  $t$  are

$$\bar{X}_t := \sum_{\ell \in \mathbb{L}} X_t^\ell. \quad (4)$$

Emissions prior to  $t = 0$  are given and I assume that  $\bar{X}_{-t} = 0$  for  $t > 0$  sufficiently large reflecting the fact that emissions before the industrial age were uniformly zero.

*Climate state*

Climate damages in period  $t$  are determined by atmospheric carbon concentration  $S_t$  relative to the pre-industrial level that depends on past aggregate emissions, i.e.,<sup>4</sup>

$$S_t = \sum_{n=0}^{\infty} \delta_n \bar{X}_{t-n}. \quad (5)$$

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<sup>3</sup>Denote by  $\partial_K F(K, X) := \frac{\partial F(K, X)}{\partial K}$  and  $\partial_X F(K, X) := \frac{\partial F(K, X)}{\partial X}$  the partial derivatives of  $F : \mathbb{R}_+^2 \rightarrow \mathbb{R}$ .

<sup>4</sup>Rezai & van der Ploeg (2021) model temperature as a linear function of cumulative emissions. In such cases,  $S_t$  could equivalently be interpreted as global temperature.

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The non-negative sequence  $(\delta_n)_{n \geq 0}$  in (5) determines the evolution and persistence of emissions in the atmosphere. Specification (5) encompasses various climate models in the literature including Golosov et al. (2014), Gerlagh & Liski (2018), or Rezai & van der Ploeg (2021). The latter will be used in the numerical study of Section 7.

#### *Climate damages*

Climate damages in region  $\ell \in \mathbb{L}$  at time  $t$  depend exclusively on carbon concentration  $S_t$  given by (5) and are determined by the damage function  $D^\ell : \mathbb{R}_+ \rightarrow [0, 1]$ ,

$$D_t^\ell = D^\ell(S_t) := 1 - \exp\{-\gamma^\ell S_t\}, \quad \gamma^\ell > 0. \quad (6)$$

Regional differences in climate damages are captured by the region-specific parameter  $\gamma^\ell$ ,  $\ell \in \mathbb{L}$ . The exponential form (6) is also widely used in the literature, cf. again Golosov et al. (2014) or Gerlagh & Liski (2018). Golosov et al. (2014) show that this specification approximates well the damage function of the DICE-model (cf. Nordhaus (2014)) in the empirically relevant range. The main mathematical advantage is that the marginal loss in output (1) due to an increase in  $S_t$  can be written as  $\gamma^\ell \cdot Y_t^\ell$ .

## 2.4 Consumption sector

#### *Representative consumer*

The consumption sector in region  $\ell \in \mathbb{L}$  consists of a single representative household who supplies capital  $K_t^{\ell,s}$  to the global capital market in each period  $t$ . Initial capital  $K_0^{\ell,s}$  in period  $t = 0$  is taken as given in the decision. In addition, the consumer is entitled to receive all profits from domestic firms and transfers from the government.

#### *Consumer preferences*

The household's preferences over non-negative consumption sequences  $(C_t^\ell)_{t \geq 0}$  are represented by a standard time-additive utility function

$$U((C_t^\ell)_{t \geq 0}) = \sum_{t=0}^{\infty} \beta^t u(C_t^\ell) \quad \text{where} \quad u(C) = \begin{cases} \frac{C^{1-\sigma}}{1-\sigma} & \text{for } \sigma > 0, \sigma \neq 1 \\ \log(C) & \text{for } \sigma = 1. \end{cases} \quad (7)$$

The discount factor satisfies  $0 < \beta < 1$ . The specification (7) 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 & Rebelo (1988)). The form of preferences is key for the separability between efficiency and optimality exploited in Hillebrand & Hillebrand (2019) and also used below in the derivation of optimal climate policies.

## 2.5 Summary of the economy

The economy  $\mathcal{E}$  introduced in this section can be summarized by its regional structure, production parameters, climate model, damage parameters, and consumer parameters.

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Formally,

$$\mathcal{E} = \left\langle \mathbb{L}, \left( (F_t^\ell)_{t \geq 0} \right)_{\ell \in \mathbb{L}}, c_x, (\delta_n)_{n \geq 0}, (\gamma^\ell)_{\ell \in \mathbb{L}}, \beta, \sigma \right\rangle. \quad (8)$$

In addition, the initial distribution of capital  $(K_0^{\ell,s})_{\ell \in \mathbb{L}}$  and initial stocks of fossil fuels  $(R_0^\ell)_{\ell \in \mathbb{L}}$  are given as well as aggregate emissions  $(\bar{X}_{-t})_{t > 0}$  prior to  $t = 0$ . I will impose the conditions  $\sum_{\ell \in \mathbb{L}} R_0^\ell > 0$  and  $\sum_{\ell \in \mathbb{L}} K_0^{\ell,s} > 0$  requiring that initial global stocks of capital and fossil fuels are strictly positive.

### 3 Decentralized Equilibrium

The decentralized equilibrium reconciles optimal behavior of consumers and producers in each region with market clearing on international markets. It is determined for given climate policies chosen independently by each region which are specified first.

#### 3.1 Climate policy

##### *Climate tax*

Each region  $\ell \in \mathbb{L}$  levies a carbon tax  $\tau_t^\ell$  on regional emissions in period  $t$  paid by the final sector. The tax sequence  $(\tau_t^\ell)_{t \geq 0}$  is the first building block of a climate policy. This sequence may consist of given exogenous numbers or can be generated by a time-invariant rule that depends on endogenous variables.

##### *Transfers*

Tax revenue is fully returned to consumers as lump sum transfers. The distribution of transfers across regions depends on whether regions cooperate or not. In the absence of cooperation, each region simply rebates its tax revenue to domestic consumers implying that consumers in each region receive a transfer in period  $t$  equal to

$$T_t^\ell = \tau_t^\ell X_t^\ell \quad \text{for each } \ell \in \mathbb{L}. \quad (9)$$

In the cooperative case, regions pool their tax revenue and agree on a transfer policy  $\theta : \mathbb{L} \rightarrow \mathbb{R}, \ell \mapsto \theta^\ell$  satisfying  $\sum_{\ell \in \mathbb{L}} \theta^\ell = 1$  which determines the transfer share  $\theta^\ell$  received by region  $\ell$ . Transfers received by consumers in region  $\ell$  at time  $t$  then follow as

$$T_t^\ell = \theta^\ell \sum_{k \in \mathbb{L}} \tau_t^k X_t^k \quad \text{for each } \ell \in \mathbb{L}. \quad (10)$$

The assumption of time-invariant transfer shares imposes no restriction since consumer behavior depends exclusively on lifetime transfers defined below. Any time-dependent distribution of transfers is therefore equivalent to a time-invariant transfer policy that would lead to the same consumption behavior.

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## 3.2 Producer behavior

### *Final sectors*

The representative firm in the final sector chooses non-negative factor inputs in period  $t$  to maximize its period-profit, taking climate damages  $D_t^\ell$  and prices  $r_t$  for capital and  $v_t$  for fossil fuels as given. The latter is increased by the tax  $\tau_t^\ell$  on emissions. The formal problem determining profits  $\Pi_t^\ell$  in the final sector in period  $t$  reads:

$$\Pi_t^\ell = \max_{K^\ell, X^\ell \geq 0} \left\{ (1 - D_t^\ell) F_t^\ell(K^\ell, X^\ell) - r_t K^\ell - (v_t + \tau_t^\ell) X^\ell \right\}. \quad (11)$$

Profit maximizing factor demand  $(K_t^\ell, X_t^\ell)$  solves the standard first order conditions

$$(1 - D_t^\ell) \partial_K F_t^\ell(K_t^\ell, X_t^\ell) = r_t \quad (12a)$$

$$(1 - D_t^\ell) \partial_X F_t^\ell(K_t^\ell, X_t^\ell) = v_t + \tau_t^\ell. \quad (12b)$$

Profits determined by (11) are fully transferred to consumers in region  $\ell$ .

### *Resource sector*

Unlike the final sector, the resource sector in region  $\ell \in \mathbb{L}$  solves an intertemporal decision problem involving the entire stream of future profits. To discount these payments to period  $t = 0$ , define the time  $t$ -discount factor (Arrow-Debreu price)

$$q_t := \prod_{n=1}^t r_n^{-1} \text{ for each } t = 0, 1, 2, \dots \text{ where } q_0 = 1. \quad (13)$$

The resource firm's discounted profit stream in  $t = 0$  generated by an optimal extraction sequence is then determined as

$$\Pi_x^\ell := \max_{(X_t^{\ell,s})_{t \geq 0}} \left\{ \sum_{t=0}^{\infty} q_t (v_t - c_x) X_t^{\ell,s} \mid (3) \text{ holds, } X_t^{\ell,s} \geq 0 \text{ for all } t \geq 0 \right\}. \quad (14)$$

Applying standard arguments (cf. Hillebrand & Hillebrand (2019)), the existence of an optimal extraction sequence requires the Hotelling rule

$$v_t - c_x = r_t (v_{t-1} - c_x) \quad \text{for all } t = 1, 2, 3, \dots \quad (15)$$

If (15) holds, maximum profits (11) are given by

$$\Pi_x^\ell = (v_0 - c_x) R_0^\ell. \quad (16)$$

## 3.3 Consumer behavior

In each period  $t$ , the representative consumer in region  $\ell$  receives factor income from supplying capital  $K_t^{\ell,s}$  formed in the previous period  $t - 1$ . In addition, the consumer



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collects profits  $\Pi_t^\ell$  from the final sector and  $\Pi_{x,t}^\ell = (v_t - c_x)X_t^{\ell,s}$  from the domestic resource sector as well as transfers  $T_t^\ell$  from the government. Consumption  $C_t^\ell$  and newly formed capital  $K_{t+1}^{\ell,s}$  satisfy the period budget constraint

$$K_{t+1}^{\ell,s} = \Pi_t^\ell + r_t K_t^{\ell,s} + (v_t - c_x)X_t^{\ell,s} + T_t^\ell - C_t^\ell. \quad (17)$$

I will interpret  $K_{t+1}^{\ell,s}$  as the consumer's net asset position and, therefore, do not exclude negative values. To exclude Ponzi-schemes, however, I impose the usual restriction  $\lim_{t \rightarrow \infty} q_t K_{t+1}^{\ell,s} \geq 0$ . Using this and (16) and defining lifetime transfer income  $T^\ell := \sum_{t=0}^{\infty} q_t T_t^\ell$  and the discounted stream of final profits  $\Pi^\ell := \sum_{t=0}^{\infty} q_t \Pi_t^\ell$  one can solve (17) forward to obtain the lifetime budget constraint

$$\sum_{t=0}^{\infty} q_t C_t^\ell \leq \Pi^\ell + r_0 K_0^{\ell,s} + (v_0 - c_x)R_0^\ell + T^\ell. \quad (18)$$

The consumer chooses consumption  $(C_t^\ell)_{t \geq 0}$  subject to (18) to maximize lifetime utility  $U$  defined in (7). Optimal behavior requires equality of (18) and the Euler equation

$$C_{t+1}^\ell = C_t^\ell (\beta r_{t+1})^{\frac{1}{\sigma}} \quad \text{for all } t = 0, 1, 2, \dots \quad (19)$$

### 3.4 Market clearing and equilibrium

#### *Market clearing*

Capital and fossil fuels are traded on frictionless international markets in each period. The market clearing conditions for period  $t$  read:

$$\sum_{\ell \in \mathbb{L}} K_t^\ell \stackrel{!}{=} \sum_{\ell \in \mathbb{L}} K_t^{\ell,s} \quad \text{and} \quad \sum_{\ell \in \mathbb{L}} X_t^\ell \stackrel{!}{=} \sum_{\ell \in \mathbb{L}} X_t^{\ell,s}. \quad (20)$$

Since the Hotelling rule (15) makes resource firms indifferent between the timing of extraction, the equilibrium extraction sequence  $(X_t^{\ell,s})_{t \geq 0}$  will, in general, be indeterminate. Due to (17), the same will be true of regional capital supply  $(K_{t+1}^{\ell,s})_{t \geq 0}$ . However, regional consumption of fossil fuels  $(X_t^\ell)_{t \geq 0}$  is uniquely determined at equilibrium and satisfies the world resource constraint

$$\sum_{t=0}^{\infty} \sum_{\ell \in \mathbb{L}} X_t^\ell = \sum_{t=0}^{\infty} \bar{X}_t \leq \bar{R}_0 := \sum_{\ell \in \mathbb{L}} R_0^\ell. \quad (21)$$

Writing profits (11) as  $\Pi_t^\ell = Y_t^\ell - r_t K_t^\ell - (v_t + \tau_t^\ell)X_t^\ell$  and exploiting the definition of transfers (9) or (10) one can sum the consumer's budget constraint (17) over all regions  $\ell$  and combine the result with the market clearing conditions (20) to obtain the evolution of world capital as

$$\sum_{\ell \in \mathbb{L}} K_{t+1}^\ell = \sum_{\ell \in \mathbb{L}} Y_t^\ell - c_x \sum_{\ell \in \mathbb{L}} X_t^\ell - \sum_{\ell \in \mathbb{L}} C_t^\ell. \quad (22)$$

Equation (22) can also be interpreted as a market clearing condition for the world commodity market.

Finally, for purposes of a compact definition of equilibrium combine (4), (5), and (6) to obtain regional climate damages as a function of past regional emissions given by

$$D_t^\ell = 1 - \exp\left(-\gamma^\ell \sum_{n=0}^{\infty} \delta_n \sum_{\ell \in \mathbb{L}} X_{t-n}^\ell\right) \quad \text{for all } \ell \in \mathbb{L}. \quad (23)$$

### *Definition of equilibrium*

We are now in a position to formally define a decentralized equilibrium for this economy.

#### **Definition 1**

An equilibrium of  $\mathcal{E}$  consists of climate taxes and transfers  $((\tau_t^\ell, T_t^\ell)_{\ell \in \mathbb{L}})_{t \geq 0}$ , an allocation  $A^* = ((K_t^{\ell*}, X_t^{\ell*}, C_t^{\ell*})_{\ell \in \mathbb{L}})_{t \geq 0}$ , and prices  $P^* = (r_t^*, v_t^*)_{t \geq 0}$  such that for all  $t = 0, 1, 2, \dots$ :

- (i) Factor inputs  $(K_t^{\ell*}, X_t^{\ell*})$  solve conditions (12) for given prices  $(r_t^*, v_t^*)$ , taxes  $\tau_t^\ell$ , and damages  $D_t^\ell$  determined by (23) for each region  $\ell \in \mathbb{L}$ .
- (ii) Prices  $P^*$  satisfy the Hotelling rule (15) and global fossil fuel consumption is consistent with the world resource constraint (21).
- (iii) Taxes and transfers and emissions are consistent with (9) or (10).
- (iv) Regional consumption  $(C_t^{\ell*})_{t \geq 0}$  satisfies the Euler equation (19) and constraint (18) with equality with discount factors  $(q_t^*)_{t \geq 0}$  determined by (13).
- (v) Initial capital  $(K_0^\ell)_{\ell \in \mathbb{L}}$  satisfies the capital market clearing condition (20) for  $t = 0$  and (22) holds for all  $t$  with output determined by (1) and damages by (23).

### *Properties of equilibrium*

The form of utility functions (7) combined with a frictionless capital market imply a world-consumption distribution that is constant over time. Thus, each region acquires a constant share of world consumption in each period. For later reference I state this result formally in the next lemma. The proof is analogous to Hillebrand & Hillebrand (2019) and therefore omitted.

#### **Lemma 1**

Equilibrium consumption of each region  $\ell \in \mathbb{L}$  is a constant fraction  $\mu^\ell \in ]0, 1[$  of world consumption  $\bar{C}_t^* := \sum_{\ell \in \mathbb{L}} C_t^{\ell*}$  in each period  $t$ , i.e.,

$$C_t^{\ell*} = \mu^\ell \bar{C}_t^* \quad \text{where } \mu^\ell = \frac{\Pi^\ell + r_0 K_0^{\ell,s} + (v_0 - c_x) R_0^\ell + T^\ell}{\sum_{k \in \mathbb{L}} (\Pi^k + r_0 K_0^{k,s} + (v_0 - c_x) R_0^k + T^k)}. \quad (24)$$

## 4 The Non-Cooperative Equilibrium

This section considers the non-cooperative equilibrium in which each region  $\ell$  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. In this non-cooperative scenario, transfers are determined by (9) excluding net transfers between regions. The 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 for capital and fossil fuels as given. The second step determines regional climate taxes such that the regionally optimal allocation obtains as a decentralized equilibrium.

### 4.1 Regional planning problem

#### *Constraints*

The planner in region  $\ell$  takes local initial stocks of capital  $K_0^{\ell,s}$  and fossil fuels  $R_0^\ell \geq 0$  as well as aggregate emissions  $(\bar{X}_{-t})_{t \geq 1}$  prior to  $t = 0$  as fixed parameters. Likewise, the sequence  $(\bar{X}_t^{-\ell})_{t \geq 0}$  of future emissions  $\bar{X}_t^{-\ell} := \sum_{k \in \mathbb{L} \setminus \{\ell\}} X_t^k$  from other regions as well as international prices  $P = (r_t, v_t)_{t \geq 0}$  are taken as given. I assume that these prices satisfy the Hotelling rule (15) as they will at equilibrium and define  $(q_t)_{t \geq 0}$  by (13).

A crucial deviation from the decentralized solution is that the planner in region  $\ell$  takes into account the impact of its own emissions and those of other regions on local climate damage  $D_t^\ell$  determined by (23). Using the previous notation, write damages as

$$D_t^\ell = 1 - \exp \left\{ -\gamma^\ell \sum_{n=0}^{\infty} \delta_n \left( X_{t-n}^\ell + \bar{X}_{t-n}^{-\ell} \right) \right\} \quad \text{for } \ell \in \mathbb{L}. \quad (25)$$

The regional planner chooses factor inputs to the production technology (1) in each period  $t$ . The decision also involves the accumulation of capital and extraction of fossil fuels. However, these variables are not necessarily fully employed in domestic production but can also be traded on global capital and resource markets at the given prices. As before, a superscript 's' signifies variables supplied to these markets. The regional stock of capital then evolves according to the resource condition

$$K_{t+1}^{\ell,s} = (1 - D_t^\ell) F_t^\ell(K_t^\ell, X_t^\ell) + r_t(K_t^{\ell,s} - K_t^\ell) + v_t(X_t^{\ell,s} - X_t^\ell) - c_x X_t^{\ell,s} - C_t^\ell. \quad (26)$$

It follows from (3) and the Hotelling rule (15) that the extraction sequence  $(X_t^{\ell,s})_{t \geq 0}$  chosen by region  $\ell$  generates total discounted revenue given again by (16). Using this and imposing again the No-Ponzi condition  $\lim_{T \rightarrow \infty} K_{T+1}^{\ell,s} q_T \geq 0$ , one can solve (26) forward to obtain the lifetime budget constraint

$$\sum_{t=0}^{\infty} q_t \left( r_t K_t^\ell + v_t X_t^\ell + C_t^\ell - (1 - D_t^\ell) F_t^\ell(K_t^\ell, X_t^\ell) \right) \leq r_0 K_0^{\ell,s} + (v_0 - c_x) R_0^\ell. \quad (27)$$

This condition somewhat parallels the consumer's condition (18). The main difference is that the planner chooses inputs to final production directly and, more importantly, takes into account the impact of fossil fuel inputs  $X_t^\ell$  on domestic climate damages via (25).

*The regional planning problem*

Using (25) and (27) the planning problem of region  $\ell \in \mathbb{L}$  can now be stated as follows.

$$\max_{(K_t^\ell, X_t^\ell, C_t^\ell)_{t \geq 0}} \left\{ U((C_t^\ell)_{t \geq 0}) \mid (25) \text{ and } (27) \text{ hold, } K_t^\ell, X_t^\ell, C_t^\ell \geq 0 \text{ for all } t = 0, 1, 2, \dots \right\}. \quad (28)$$

Clearly, the solution to (28) depends on the given emissions  $(\bar{X}_t^{-\ell})_{t \geq 0}$  of other regions and prices  $P = (r_t, v_t)_{t \geq 0}$ . Crucially, the planner is a 'price-taker' on international markets and does not take into account the impact of his decision on the determination of these prices as equilibrium outcomes.

*Solution to the regional planning problem*

Problem (28) is a constrained optimization problem that can be solved by standard Lagrangean methods. The details can be found in Section A.1 in Appendix A. This way, one can derive the following optimality conditions which characterize the solution in addition to the technological and resource constraints. First, consumption satisfies the Euler equation (19) and (27) holds with equality. Second, the marginal product of capital in period  $t$  equals its return  $r_t$  such that (12a) holds. Finally, resource input in period  $t$  earns a marginal product equal to its price  $v_t$  plus the total discounted marginal damage in production:

$$(1 - D_t^\ell) \partial_X F_t^\ell(K_t^\ell, X_t^\ell) = v_t + \sum_{n=0}^{\infty} \beta^n \left( C_{t+n}^\ell / C_t^\ell \right)^{-\sigma} \delta_n \gamma^\ell Y_{t+n}^\ell. \quad (29)$$

Intuitively, the damage-related term in (29) consists of three factors. First, a discount factor  $\beta^n (C_{t+n}^\ell / C_t^\ell)^{-\sigma}$  serving to measure damages in  $t+n$  in units of time  $t$  consumption. Second, the term  $\delta_n$  which measures the quantity of emissions at time  $t$  that are still in the atmosphere at time  $t+n$ . Third, the marginal loss in domestic output  $Y_{t+n}^\ell$  at time  $t+n$  caused by an additional unit of carbon in the atmosphere. Summation of these factors over all periods  $t, t+1, t+2, \dots$  then gives the total domestic damage generated by one additional unit of emissions in period  $t$ .

For later reference, we state the previous result formally in the next lemma.

**Lemma 2**

Let prices  $P = (r_t, v_t)_{t \geq 0}$  and emissions  $(\bar{X}_t^{-\ell})_{t \geq 0}$  of other regions be given. If the regional allocation  $(K_t^\ell, X_t^\ell, C_t^\ell)_{t \geq 0}$  solves (12a), (19), and (29) with  $D_t^\ell$  determined by (25) for all  $t = 0, 1, 2, \dots$  and satisfies (27) with equality, then it is a solution to the problem (28).

## 4.2 Non-cooperative solution as a Nash equilibrium

*The market maker*

In a non-cooperative equilibrium the decisions of all regions  $\ell \in \mathbb{L}$  determined as a so-

lution to (28) are mutually compatible in the sense that emissions of all other regions are correctly anticipated and market clearing on global capital and resource markets obtains in each period  $t$ . To formalize this idea, we embed the previous structure into the setup of a non-cooperative game and invoke the formal definition of a Nash equilibrium. Since the regional planning problem involves not only the decision variables from other regions, but also the prices of capital and fossil fuels, we introduce an additional player  $\ell = 0$  that will be referred to as a 'market-maker'. This player chooses prices  $P = (v_t, r_t)_{t \geq 0}$  as his strategy subject to the Hotelling rule (15). Since the Hotelling rule determines all future prices  $(v_t)_{t > 0}$  from the initial choice  $v_0$  and capital returns and choosing the sequence  $(r_t)_{t \geq 1}$  is equivalent to choosing the AD-prices  $(q_t)_{t \geq 0}$  in (13), we can identify the choice of player  $\ell = 0$  with the strategy  $(v_0, r_0, (q_t)_{t \geq 0})$ .

*Decision problem of the market maker*

We now set up the market maker's decision problem such that market clearing obtains along the Nash equilibrium defined below. Suppose player  $\ell = 0$  bases his choice of prices on the 'mismatch' between demand and supply on international markets determined by the allocations chosen by players.<sup>5</sup>

To this end, the resource price  $v_0$  is chosen to maximize the value of excess demand in the resource market. Formally, the price is a solution to the linear problem

$$\max_{v_0} \left\{ (v_0 - c_x) \left( \sum_{t=0}^{\infty} \sum_{\ell \in \mathbb{L}} X_t^\ell - \bar{R}_0 \right) \middle| c_x \leq v_0 \leq v_0^{\max} \right\}. \quad (30a)$$

Here,  $v_0^{\max} > 0$  is some arbitrary upper bound chosen sufficiently large to exceed any possible equilibrium value  $v_0^{\text{nc}}$  defined below. Thus, the market maker sets the resource price to its minimal value  $v_0 = c_x$  if the total demand for resources  $\sum_{t=0}^{\infty} \sum_{\ell \in \mathbb{L}} X_t^\ell$  summed over all regions and periods is lower than the available resource stock  $\bar{R}_0$ . Conversely, if resource demand exceeds this stock, the resource price is set to its maximum value  $v_0 = v_0^{\max}$ . It follows that problem (30a) has an interior solution  $c_x < v_0 < v_0^{\max}$  (in fact, infinitely many) if and only if the resource constraint (21) holds with equality such that total demand exhausts the global stock.

In a similar fashion, the market maker determines  $r_0$  and the values  $q_t$  for  $t = 0, 1, 2, \dots$  based on the excess demand for capital in  $t = 0$  and in the consumption good market in period  $t$ , respectively. Formally, these problems read

$$\max_{r_0} \left\{ r_0 \sum_{\ell \in \mathbb{L}} (K_0^\ell - K_0^{\ell,s}) \middle| 0 \leq r_0 \leq r_0^{\max} \right\} \quad (30b)$$

and, for each  $t = 0, 1, 2, \dots$

$$\max_{q_t} \left\{ q_t \sum_{\ell \in \mathbb{L}} (C_t^\ell + c_x X_t^\ell + K_{t+1}^\ell - (1 - D_t^\ell) F_t^\ell(K_t^\ell, X_t^\ell)) \middle| 0 \leq q_t \leq q_t^{\max} \right\}. \quad (30c)$$

<sup>5</sup>This idea has been used in finite-dimensional Walrasian economies to construct a price correspondence of which equilibrium prices obtain as fixed points. Details of this approach can be found, e.g., in Mas-Colell, Whinston & Green (1995, Section 17.C).

Again, the upper bounds  $r_0^{\max}$  and  $q_t^{\max}$  are chosen sufficiently large and the initial distribution of capital  $(K_0^{\ell,s})_{\ell \in \mathbb{L}}$  entering (30b) is given and climate damage  $D_t^\ell$  in (30c) determined by (25) for each  $\ell$ . Linearity of each of the underlying problems then implies that existence of interior solutions to (30b) and (30c) is equivalent to the capital market clearing condition in (20) for  $t = 0$  and (22) for each  $t = 0, 1, 2, \dots$ <sup>6</sup>

*Definition of non-cooperative equilibrium*

Using  $\mathbb{L}_0 := \{0\} \cup \mathbb{L}$  as the set of players we can now define a Nash equilibrium as follows.

**Definition 2**

A non-cooperative (Nash) equilibrium of  $\mathcal{E}$  is an allocation  $A^{\text{nc}} = ((K_t^{\ell,\text{nc}}, X_t^{\ell,\text{nc}}, C_t^{\ell,\text{nc}})_{\ell \in \mathbb{L}})_{t \geq 0}$  and prices  $P^{\text{nc}} = (r_t^{\text{nc}}, v_t^{\text{nc}})_{t \geq 0}$  such that the following holds:

- (i) The regional allocation  $(K_t^{\ell,\text{nc}}, X_t^{\ell,\text{nc}}, C_t^{\ell,\text{nc}})_{t \geq 0}$  chosen by player  $\ell \in \mathbb{L}$  solves the planning problem (28) given prices  $P^{\text{nc}}$  and emissions  $(\bar{X}_t^{-\ell,\text{nc}})_{t \geq 0}$  of other regions.
- (ii) Prices  $P^{\text{nc}}$  chosen by player  $\ell = 0$  satisfy the Hotelling rule (15) and  $(v_0^{\text{nc}}, r_0^{\text{nc}})$  and  $q_t^{\text{nc}}$  defined by (13) are solutions to the decision problems (30a)-(30c) for all  $t \geq 0$ .

It is worth noting that (21) may or may not bind along the non-cooperative equilibrium. If it does, fossil fuels carry a scarcity rent implying  $v_0 > c_x$  and, by (15),  $v_t > c_x$  for all  $t$ . On the other hand, if  $\sum_{t=0}^{\infty} \sum_{\ell \in \mathbb{L}} X_t^{\ell,\text{nc}} < \bar{R}_0$ , the solution to problem (30a) satisfies  $v_0 = c_x$  and implies  $v_t = c_x$  for all  $t$  by (15). In this case, fossil fuels are abundant and there is no scarcity rent.

*Time-consistency of the non-cooperative solution*

The non-cooperative equilibrium is time-consistent in the sense that in each future period  $t = N \geq 1$ , each player if permitted to re-optimize will stick to his original strategy provided everybody else does. In other words, the Nash equilibrium of the non-cooperative game defined above satisfies the one-shot deviation principle, i.e., no player can increase their pay-off by singularly deviating from the equilibrium strategy in any period. Hence, the non-cooperative equilibrium from Definition 2 is time-consistent or subgame perfect. Formally, we have

**Proposition 1**

Let  $N \geq 0$  be arbitrary and suppose all players  $\ell \in \mathbb{L}_0$  followed the strategies of the non-cooperative equilibrium up to time  $t = N - 1$ . Then, the continuation strategies  $(K_t^{\ell,\text{nc}}, X_t^{\ell,\text{nc}}, C_t^{\ell,\text{nc}})_{t \geq N}$  for each player  $\ell \in \mathbb{L}$  and  $(r_t^{\text{nc}}, v_t^{\text{nc}})_{t \geq N}$  for player  $\ell = 0$  constitute a non-cooperative (Nash) equilibrium at stage  $t = N$ .

A stronger version of this result would be a Markov-perfect equilibrium where all strategies are generated by time-invariant decision rules defined on a suitable state

<sup>6</sup>Since the choices of  $r_0$ ,  $v_0$ , and  $(q_t)_{t \geq 0}$  are independent, one could also determined them simultaneously by maximizing the sum of (30a), (30b), and (30c) summed over all  $t = 0, 1, 2, \dots$

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space. This concept is widely used in game-theoretic studies of the climate problem, see, e.g., Harstad (2016). In the present setting with time-varying production functions (1) due to population growth, technological progress, etc., it is in general not possible to obtain such a time-invariant structure. Therefore, subgame-perfectness demonstrated in this section appears to be the strongest robustness result possible in our model.

### 4.3 Regionally optimal climate policy

#### *Implementing the non-cooperative solution*

Returning to the decentralized equilibrium discussed in Section 3, we seek to implement the non-cooperative solution as a decentralized equilibrium. This requires determining the climate tax policy  $(\tau_t^\ell)_{t \geq 0}$  for each region  $\ell$  such that the equilibrium allocation and price system satisfy  $A^* = A^{\text{nc}}$  and  $P^* = P^{\text{nc}}$ . Formally, this can be accomplished by ensuring that the optimality conditions determining the non-cooperative solution coincide with the equilibrium conditions from Definition 1.

#### *Regionally optimal climate tax*

Along the non-cooperative equilibrium, the regional lifetime budget constraint (27) holds with equality. Using the definition of profits in (11) and the form of transfers (9), we obtain

$$(1 - D_t^\ell)F_t^\ell(K_t^\ell, X_t^\ell) - r_t K_t^\ell - v_t X_t^\ell = \Pi_t^\ell + T_t^\ell. \quad (31)$$

Using this in (27) we obtain the consumer's lifetime budget constraint (18) with equality as required. Furthermore, invoking Lemma 2, we see that the Euler equations (19) are automatically satisfied and so is the optimality condition (12a) with respect to capital input. The price sequence  $P^{\text{nc}}$  satisfies the Hotelling rule (15) by assumption. Finally, comparing the optimality conditions (12b) and (29) with respect to fossil fuel inputs, we can see that implementing the regionally optimal solution to (28) requires choosing the regional climate tax according to the rule

$$\tau_t^\ell = \sum_{n=0}^{\infty} \beta^n \left( C_{t+n}^\ell / C_t^\ell \right)^{-\sigma} \delta_n \gamma^\ell Y_{t+n}^\ell. \quad (32)$$

Hence, if taxes are determined by the tax rule (32), all conditions determining the decentralized and non-cooperative solution coincide. We state the previous result formally in the following theorem.

#### **Theorem 1**

*Suppose each region  $\ell \in \mathbb{L}$  chooses a climate tax policy  $(\tau_t^\ell)_{t \geq 0}$  according to the rule (32) and consumers in region  $\ell$  receive transfers determined by (9). Then, the induced equilibrium allocation and prices satisfy  $A^* = A^{\text{nc}}$  and  $P^* = P^{\text{nc}}$ .*

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By Lemma 1, equilibrium consumption satisfies  $C_t^\ell = \mu^\ell \bar{C}_t$  permitting to replace the discount factor in (32) by aggregate consumption. This yields (32) in equivalent form

$$\tau_t^\ell = \sum_{n=0}^{\infty} \beta^n \left( \bar{C}_{t+n} / \bar{C}_t \right)^{-\sigma} \delta_n \gamma^\ell Y_{t+n}^\ell. \quad (33)$$

Finally, along a balanced growth path where regional output and consumption grow at constant and identical rate  $g$ , (32) reduces to

$$\tau_t^\ell = \gamma^\ell Y_t^\ell \sum_{n=0}^{\infty} \left( \beta(1+g)^{1-\sigma} \right)^n \delta_n. \quad (34)$$

The formula (34) resembles the main result in Golosov et al. (2014) who derive the globally optimal climate tax in closed form and show that it can be expressed as a constant fraction of output determined by climate parameters and the discount factor.

## 5 Partial Cooperation and Coalitions

The previous section considered the fully non-cooperative case where each region solves its own planning problem (28). Clearly, there are many scenarios with at least some level of cooperation where some regions join forces and coordinate their climate policies by forming coalitions. Such cases with partial cooperation will be studied in this section.

### 5.1 A cooperative setup

#### *Coalitions and aggregation*

To formally describe a scenario with coalitions, let  $\mathcal{P}(\mathbb{L})$  be the power set of the set of regions  $\mathbb{L}$  consisting of all subsets of  $\mathbb{L}$ . Any non-empty subset  $\mathbb{L}' \in \mathcal{P}(\mathbb{L})$  will be referred to as a coalition. The case  $\mathbb{L}' = \mathbb{L}$  is called *the grand coalition* consisting of all regions. Let  $\mathbb{L}' \in \mathcal{P}(\mathbb{L})$  be an arbitrary coalition. In what follows, we index variables referring to the coalition as a whole by a superscript  $\mathbb{L}'$ . For variables referring to individual members, we continue to use the regional index  $\ell \in \mathbb{L}'$ . For example,  $R_0^{\mathbb{L}'} := \sum_{\ell \in \mathbb{L}'} R_0^\ell$  is the initial stock of fossil fuels owned by the coalition  $\mathbb{L}'$  while  $(X_t^\ell)_{t \geq 0}$  denotes fossil fuel consumption in member region  $\ell \in \mathbb{L}'$ . Based on this convention, a coalitional variable  $x^{\mathbb{L}'}$  obtains as the sum of the list of individual variables  $(x^\ell)_{\ell \in \mathbb{L}'}$ , i.e.,  $x^{\mathbb{L}'} = \sum_{\ell \in \mathbb{L}'} x^\ell$ .

#### *The coalitional planning problem*

Suppose the members of coalition  $\mathbb{L}'$  join forces by aggregating their resource stocks and capital endowments. Summing (27) over all regions in  $\mathbb{L}'$  one obtains the constraint

$$\sum_{t=0}^{\infty} q_t \left( \sum_{\ell \in \mathbb{L}'} \left( (1 - D_t^\ell) F_t^\ell(K_t^\ell, X_t^\ell) - r_t K_t^\ell - v_t X_t^\ell \right) - C_t^{\mathbb{L}'} \right) + r_0 K_0^{\mathbb{L}',s} + (v_0 - c_x) R_0^{\mathbb{L}'} \geq 0. \quad (35)$$



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Defining the complement  $-\mathbb{L}' := \mathbb{L} \setminus \mathbb{L}'$ , regional climate damages (23) can be written as

$$D_t^\ell = 1 - \exp\left(-\gamma^\ell \sum_{n=0}^{\infty} \delta_n \left(X_{t-n}^{\mathbb{L}'} + X_{t-n}^{-\mathbb{L}'}\right)\right) \quad \text{for } \ell \in \mathbb{L}' \quad (36)$$

Assume that coalition  $\mathbb{L}'$  maximizes the total utility attained by the aggregated consumption stream  $(C_t^{\mathbb{L}'})_{t \geq 0}$ . This approach is based on the separation principle established in Hillebrand & Hillebrand (2019) permitting to first determine an efficient solution by maximizing aggregate utility and then distributing consumption among coalition members based on some suitable weighting scheme. The distribution of consumption among coalition members corresponds to an imputation in the cooperative game defined below. Based on the previous idea, the coalitional planning problem can be stated as follows:

$$\max_{((K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}'}, C_t^{\mathbb{L}'})_{t \geq 0}} \left\{ U((C_t^{\mathbb{L}'})_{t \geq 0}) \mid (35), (36) \text{ hold, } K_t^\ell, X_t^\ell, C_t^{\mathbb{L}'} \geq 0 \text{ for all } t = 0, 1, 2, \dots \right\}. \quad (37)$$

As in the regional problem (28), emission  $(X_t^{-\mathbb{L}'})_{t \geq 0}$  of all other regions and global prices  $P = (r_t, v_t)_{t \geq 0}$  are taken as given in the decision (37). Further, the coalitional planner takes into account the impact of emission of coalition members on damages (36) in each member region  $\ell \in \mathbb{L}'$ .

#### *Solution to the coalitional planning problem*

It is again straightforward to solve the coalitional problem (37) using Lagrangean methods. The proof of the following result parallels the one of Lemma 2 and is omitted.

#### **Lemma 3**

Let prices  $P = (r_t, v_t)_{t \geq 0}$  and emissions  $(X_t^{-\mathbb{L}'})_{t \geq 0}$  of non-coalition members be given. If the allocation  $((K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}'}, C_t^{\mathbb{L}'})_{t \geq 0}$  solves conditions (12a) and

$$(1 - D_t^\ell) \partial_X F_t^\ell(K_t^\ell, X_t^\ell) = v_t + \sum_{n=0}^{\infty} \beta^n \left( C_{t+n}^{\mathbb{L}'} / C_t^{\mathbb{L}'} \right)^{-\sigma} \delta_n \sum_{k \in \mathbb{L}'} \gamma^k Y_{t+n}^k \quad (38)$$

for all  $\ell \in \mathbb{L}'$  with  $D_t^\ell$  determined by (36) and the Euler equation

$$C_{t+1}^{\mathbb{L}'} = C_t^{\mathbb{L}'} (\beta r_{t+1})^{\frac{1}{\sigma}} \quad (39)$$

for all  $t = 0, 1, 2, \dots$  and satisfies (35) with equality, then it is a solution to problem (37).

Note that (38) corrects the marginal product of fossil fuel in production by the discounted future climate damages of all coalition members.

## **5.2 Coalitional equilibrium**

#### *Coalition structures*

Now let  $\mathcal{L} = \{\mathbb{L}_1, \dots, \mathbb{L}_N\} \subset \mathcal{P}(\mathbb{L})$  be a partition of the set of all regions  $\mathbb{L}$  into  $1 \leq N \leq L$

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coalitions, i.e.,  $\cup_{n=1}^N \mathbb{L}_n = \mathbb{L}$  and  $\mathbb{L}_n \cap \mathbb{L}_m = \emptyset$  for all  $n \neq m$  where  $n, m \in \{1, \dots, N\}$ . Following Yi (1997), we call  $\mathcal{L}$  a *coalition structure*. Suppose the members of each coalition  $\mathbb{L}' \in \mathcal{L}$  solve a coalitional planning problem of the form (37). The market maker  $\ell = 0$  acts as in the previous section to enforce market clearing. Consistency of coalitional decisions leads to the following definition of a coalitional equilibrium.

**Definition 3**

Let  $\mathcal{L} \subset \mathcal{P}(\mathbb{L})$  be a coalition structure. A coalitional equilibrium is an allocation

$$\bar{A} = \left( \left( (K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}'}, C_t^{\mathbb{L}'} \right)_{t \geq 0} \right)_{\mathbb{L}' \in \mathcal{L}} \quad (40)$$

and a price system  $P = (r_t, v_t)_{t \geq 0}$  such that the following holds:

- (i) For each  $\mathbb{L}' \in \mathcal{L}$ , the allocation  $((K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}'}, C_t^{\mathbb{L}'})_{t \geq 0}$  solves the coalitional planning problem (37) given prices  $P$  and emissions  $(X_t^{-\mathbb{L}'})_{t \geq 0}$  of all other regions.
- (ii) Prices  $P$  chosen by player  $\ell = 0$  satisfy the Hotelling rule (15) and  $(v_0, r_0)$  and  $q_t$  defined by (13) are solutions to the decision problems (30a)-(30c) for all  $t \geq 0$ .

When we want to emphasize the dependence of coalitional equilibrium on the coalition configuration, we write  $\bar{A}^{\mathcal{L}}$  and  $P^{\mathcal{L}}$ . The bar-notation is used to emphasize that the distribution of consumption within a coalition is not determined and subject to an imputation to be bargained over by coalition members.

### 5.3 Decentralization of coalitional equilibrium

Based on the optimality condition (38), it is now straightforward to extend the results from Theorem 1 to the following theorem describing the climate policy under which the coalitional allocation is decentralized.

**Theorem 2**

Let  $\mathcal{L} \subset \mathcal{P}(\mathbb{L})$  be a coalition structure. For each coalition  $\mathbb{L}' \in \mathcal{L}$ , suppose all its members  $\ell \in \mathbb{L}'$  set taxes according to the rule

$$\tau_t^\ell = \tau_t^{\mathbb{L}'} := \sum_{n=0}^{\infty} \beta^n \left( \frac{C_{t+n}^{\mathbb{L}'}}{C_t^{\mathbb{L}'}} \right)^{-\sigma} \delta_n \sum_{k \in \mathbb{L}'} \gamma^k Y_{t+n}^k \quad \text{for all } \ell \in \mathbb{L}'. \quad (41)$$

Then, the coalitional equilibrium is decentralized.

Comparing (41) with the non-cooperative tax policy (33), we observe that the coalitional tax internalizes all marginal climate damages of coalition members whereas the non-cooperative tax policy internalizes only domestic damages. On a balanced growth path

where aggregate consumption and output in region of the coalition grow at constant rate  $g$ , the optimal tax formula (41) reduces again to

$$\tau_t^\ell = \tau_t^{\mathbb{L}'} = \sum_{k \in \mathbb{L}'} \gamma^k Y_t^k \sum_{n=0}^{\infty} (\beta(1+g)^{1-\sigma})^n \delta_n \quad \text{for all } \ell \in \mathbb{L}'. \quad (42)$$

Two coalition structures are of particular interest. The first one is  $\mathcal{L} = \{\{1\}, \dots, \{L\}\}$  where each region acts individually by forming its own coalition. In this case, Definition 3 coincides with the non-cooperative equilibrium from Definition 2 and so  $\bar{A}^{\mathcal{L}} \cong A^{\text{nc}}$ .<sup>7</sup> A second scenario is where  $\mathcal{L} = \{\mathbb{L}\}$  corresponding to the grand coalition consisting of all regions. Based on the tax formula (41) and its previous interpretation, one would expect that this grand coalition delivers the globally efficient carbon tax that internalizes all global climate damages. The following section will show that this is indeed the case.

## 6 Global Efficiency and Incentives for Cooperation

This section compares the previously derived non-cooperative solutions to the globally efficient solution that obtains under full cooperation between regions.<sup>8</sup> We will also study the incentives for cooperation and show that transfer policies exist such that all regions are better off under full cooperation relative to the non-cooperative outcome.

### 6.1 The efficient solution

*The global planning problem*

Consider a global planner choosing an aggregate allocation  $\bar{A} = ((K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}}, \bar{C}_t)_{t \geq 0}$  consisting of production inputs for each region along with aggregate global consumption. The term 'aggregate' signified by the bar notation reflects the fact that the allocation  $\bar{A}$  specifies only aggregate consumption, but not its distribution across regions. Note however that this aggregation only refers to consumption while production inputs are specified for all regions. The planner takes into account the impact of emissions on climate damage via (23), the global resource constraint (21), and the feasibility constraint

$$\bar{C}_t \leq \sum_{\ell \in \mathbb{L}} \left( (1 - D_t^\ell) F_t^\ell(K_t^\ell, X_t^\ell) - c_x X_t^\ell - K_{t+1}^\ell \right) \quad \text{for all } t = 0, 1, 2, \dots \quad (43)$$

Furthermore, the capital allocation  $(K_0^\ell)_{\ell \in \mathbb{L}}$  in  $t = 0$  is subject to the initial condition

$$\sum_{\ell \in \mathbb{L}} K_0^\ell \leq \bar{K}_0^s := \sum_{\ell \in \mathbb{L}} K_0^{\ell, s}. \quad (44)$$

<sup>7</sup>Due to the slightly different arrangement of terms in  $\bar{A}^{\mathcal{L}}$  and  $A^{\text{nc}}$ , I write  $\bar{A}^{\mathcal{L}} \cong A^{\text{nc}}$  to mean that the two allocations are isomorphic rather than directly identical.

<sup>8</sup>This is the scenario studied in Hillebrand & Hillebrand (2019) in a slightly different setup.

Based on these constraints, the global planner maximizes utility of a fictitious world representative consumer who consumes aggregate consumption  $\bar{C}_t$  in each period  $t$ . Formally, the global planning problem can be stated as:

$$\max_{((K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}}, \bar{C}_t)_{t \geq 0}} \left\{ U((\bar{C}_t)_{t \geq 0}) \mid (21), (23), (43), (44) \text{ hold, } K_t^\ell, X_t^\ell, \bar{C}_t \geq 0 \text{ for all } t \geq 0, \ell \in \mathbb{L} \right\}. \quad (45)$$

*Conditions for efficiency*

A solution to the global planning problem (45) is called an *efficient aggregate allocation* denoted by  $\bar{A}^{\text{eff}} = ((K_t^{\ell, \text{eff}}, X_t^{\ell, \text{eff}})_{\ell \in \mathbb{L}}, \bar{C}_t^{\text{eff}})_{t \geq 0}$ . The following lemma characterizes the efficient solution formally. The proof can be found in Section A.3 in Appendix A.

**Lemma 4**

If the aggregate allocation  $\bar{A} = ((K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}}, \bar{C}_t)_{t \geq 0}$  satisfies the feasibility conditions (43) and (44) with equality, the intratemporal efficiency conditions

$$(1 - D_t^\ell) \partial_K F_t^\ell(K_t^\ell, X_t^\ell) = (1 - D_t^k) \partial_K F_t^k(K_t^k, X_t^k) \quad (46a)$$

$$(1 - D_t^\ell) \partial_X F_t^\ell(K_t^\ell, X_t^\ell) = (1 - D_t^k) \partial_X F_t^k(K_t^k, X_t^k) \quad (46b)$$

for all  $k, \ell \in \mathbb{L}$ , the intertemporal efficiency conditions

$$\frac{\beta \bar{C}_{t+1}^{-\sigma}}{\bar{C}_t^{-\sigma}} (1 - D_{t+1}^\ell) \partial_K F_{t+1}^\ell(K_{t+1}^\ell, X_{t+1}^\ell) = 1 \quad (46c)$$

$$\frac{\beta \bar{C}_{t+1}^{-\sigma}}{\bar{C}_t^{-\sigma}} \left( (1 - D_{t+1}^\ell) \partial_X F_{t+1}^\ell(K_{t+1}^\ell, X_{t+1}^\ell) - c_x - \hat{t}_{t+1} \right) = (1 - D_t^\ell) \partial_X F_t^\ell(K_t^\ell, X_t^\ell) - c_x - \hat{t}_t \quad (46d)$$

for all  $\ell \in \mathbb{L}$  with damages determined by (23) and

$$\hat{t}_t := \sum_{n=0}^{\infty} \beta^n \left( \bar{C}_{t+n} / \bar{C}_t \right)^{-\sigma} \delta_n \sum_{k \in \mathbb{L}} \gamma^k Y_{t+n}^k \quad (47)$$

for all  $t = 0, 1, 2, \dots$  as well as the transversality condition  $\lim_{T \rightarrow \infty} \beta^T \bar{C}_T^{-\sigma} \sum_{\ell \in \mathbb{L}} K_{T+1}^\ell = 0$  and the resource constraint (21), then it is a solution to (45).

Intuitively, the efficient solution leads to intertemporally efficient consumption and resource extraction ((46c) and (46d)) and equalizes marginal products of production factors across all regions ((46a) and (46b)) and corrects the marginal product of fossil fuels by the term in (47) representing total discounted future damages from emissions.

## 6.2 Decentralization of the efficient solution

*Efficient carbon taxes*

We now explore conditions on the climate policy under which the decentralized equilibrium allocation  $A^*$  is efficient. Formally, this is the case if and only if for all  $t = 0, 1, 2, \dots$

$$K_t^{\ell*} = K_t^{\ell, \text{eff}} \quad \text{and} \quad X_t^{\ell*} = X_t^{\ell, \text{eff}} \quad \text{for all } \ell \in \mathbb{L} \quad \text{and} \quad \sum_{\ell \in \mathbb{L}} C_t^* = \bar{C}_t^{\text{eff}}. \quad (48)$$

Climate tax policies under which (48) holds will be termed efficient and denoted by  $(\tau_t^{\text{eff}})_{t \geq 0}$ . Note that such a policy will necessarily be uniform across all regions. Following theorem provides a complete characterization of the efficient carbon tax.

**Theorem 3**

Suppose in each period  $t = 0, 1, 2, \dots$  all regions  $\ell \in \mathbb{L}$  choose uniform carbon taxes given by

$$\tau_t^{\text{eff}} := \sum_{n=0}^{\infty} \beta^n \left( \bar{C}_{t+n}^{\text{eff}} / \bar{C}_t^{\text{eff}} \right)^{-\sigma} \delta_n \sum_{k \in \mathbb{L}} \gamma^k Y_{t+n}^{k, \text{eff}}. \quad (49)$$

Then the equilibrium allocation  $A^* = ((K_t^{\ell*}, X_t^{\ell*}, C_t^{\ell*})_{\ell \in \mathbb{L}})_{t \geq 0}$  is efficient, i.e., (48) holds.

*Efficiency of the grand coalition*

Comparing the form (49) of carbon taxation with the coalitional tax policy (41), we see that the efficient tax internalizes global marginal climate damages while the coalitional tax internalizes climate damages of coalition members. As a consequence, the two policies coincide in the case of a grand coalition where  $\mathbb{L}' = \mathbb{L}$ . Then, by virtue of Theorem 3, the induced equilibrium allocation is efficient. This is stated in the next result.

**Proposition 2**

The grand coalition  $\mathcal{L} = \{\mathbb{L}\}$  chooses the efficient carbon tax (49) and the associated coalitional equilibrium is efficient, i.e.,  $\bar{A}^{\mathcal{L}} \cong \bar{A}^{\text{eff}}$ .

The distribution  $(\mu^\ell)_{\ell \in \mathbb{L}}$  of aggregate consumption  $(\bar{C}_t^{\text{eff}})_{t \geq 0}$  depends on whether there are transfers between regions. If there is no re-distribution, transfers are determined by (9) and consumption shares follow from equation (24). In a cooperative setup, however, transfers can potentially be used to incentivize regions to cooperate. The existence and form of such transfer policies is explored next.

### 6.3 Incentive-compatible transfer policies

*Welfare gain under cooperation*

Denote the consumption distribution along the non-cooperative equilibrium by  $(\mu^{\ell, \text{nc}})_{\ell \in \mathbb{L}}$  and aggregate consumption by  $\bar{C}_t^{\text{nc}} := \sum_{\ell \in \mathbb{L}} C_t^{\ell, \text{nc}}$ . Observe that the aggregate allocation  $\bar{A}^{\text{nc}} = ((K_t^{\ell, \text{nc}}, X_t^{\ell, \text{nc}})_{\ell \in \mathbb{L}}, \bar{C}_t^{\text{nc}})_{t \geq 0}$  associated with the non-cooperative equilibrium satisfies all the constraints in the global planning problem (45). Therefore, the implied total welfare must be less than at the efficient equilibrium, i.e.,<sup>9</sup>

$$\bar{U}^{\text{nc}} := U((\bar{C}_t^{\text{nc}})_{t \geq 0}) < U((\bar{C}_t^{\text{eff}})_{t \geq 0}) =: \bar{U}^{\text{eff}}. \quad (50)$$

<sup>9</sup>The strict inequality can be inferred from Theorems 1 and 3 by observing that taxes along the non-cooperative equilibrium are determined by (32) rather than by (49). Therefore,  $\bar{A}^{\text{nc}}$  cannot be efficient.

We now explore whether this efficiency gain can be distributed such that each region is better-off under efficient taxation relative to the fully non-cooperative equilibrium.

*Pareto-improving consumption shares*

To induce a Pareto-improvement under efficient taxation relative to the non-cooperative equilibrium, each region  $\ell \in \mathbb{L}$  must receive a consumption share  $\mu^\ell$  such that

$$U((\mu^\ell \bar{C}_t^{\text{eff}})_{t \geq 0}) \geq U((\mu^{\ell, \text{nc}} \bar{C}_t^{\text{nc}})_{t \geq 0}). \quad (51)$$

Exploiting the form of utility (7), we can determine explicit lower bounds  $\mu_{\text{crit}}^\ell$  for this share such that (51) holds whenever  $\mu^\ell \geq \mu_{\text{crit}}^\ell$ . These shares are characterized in the following result. The proof can be found in Section A.5 in Appendix A.

**Lemma 5**

*Under efficient taxation (49) of all regions, suppose each region  $\ell \in \mathbb{L}$  receives a consumption share that satisfies*

$$\mu^\ell \geq \mu_{\text{crit}}^\ell := \begin{cases} \mu^{\ell, \text{nc}} \left( \bar{U}^{\text{nc}} / \bar{U}^{\text{eff}} \right)^{\frac{1}{1-\sigma}} & \text{if } \sigma > 0, \sigma \neq 1 \\ \mu^{\ell, \text{nc}} \cdot e^{-(1-\beta)(\bar{U}^{\text{eff}} - \bar{U}^{\text{nc}})} & \text{if } \sigma = 1. \end{cases} \quad (52)$$

*Then, the induced disaggregated efficient allocation  $A = ((K_t^{\ell, \text{eff}}, X_t^{\ell, \text{eff}}, \mu^\ell \bar{C}_t^{\text{eff}})_{\ell \in \mathbb{L}})_{t \geq 0}$  Pareto improves the non-cooperative allocation  $A^{\text{nc}} = ((K_t^{\ell, \text{nc}}, X_t^{\ell, \text{nc}}, C_t^{\ell, \text{nc}})_{\ell \in \mathbb{L}})_{t \geq 0}$ .*

Noting that  $\mu_{\text{crit}}^\ell < \mu^{\ell, \text{nc}}$  for all  $\ell \in \mathbb{L}$ , condition (52) holds in particular if  $\mu^\ell = \mu^{\ell, \text{nc}}$ , i.e., each region attains the same consumption share as in the non-cooperative equilibrium.

*Pareto-improving transfer shares*

To explore how transfers between regions can be designed such that (52) holds, suppose regions pool their tax revenue and agree on a transfer policy  $(\theta^\ell)_{\ell \in \mathbb{L}}$  determining transfer payments as in (10). Let  $\bar{A}^{\text{eff}}$  be the efficient allocation and define the induced equilibrium prices  $P^{\text{eff}} = (r_t^{\text{eff}}, v_t^{\text{eff}})_{t \geq 0}$  by setting

$$r_t^{\text{eff}} := (1 - D_t^{\ell, \text{eff}}) \partial_K F_t^\ell(K_t^{\ell, \text{eff}}, X_t^{\ell, \text{eff}}) \quad \text{and} \quad v_t^{\text{eff}} := (1 - D_t^{\ell, \text{eff}}) \partial_X F_t^\ell(K_t^{\ell, \text{eff}}, X_t^{\ell, \text{eff}}) \quad (53)$$

for  $t = 0, 1, 2, \dots$  with climate damages  $D_t^{\ell, \text{eff}}$  determined by (23). Note that the quantities in (53) are well-defined, i.e., independent of the regional index  $\ell$  due to (46a) and (46b) and satisfy the Hotelling rule (15) due to (46d). Denote by  $(q_t^{\text{eff}})_{t \geq 0}$  the induced Arrow-Debreu prices defined by (13) and let  $\bar{T}_t^{\text{eff}} := \sum_{\ell \in \mathbb{L}} \tau_t^{\text{eff}} X_t^{\ell, \text{eff}}$  denote total tax revenue and  $\Pi_t^{\ell, \text{eff}} := Y_t^{\ell, \text{eff}} - r_t^{\text{eff}} K_t^{\ell, \text{eff}} - (v_t^{\text{eff}} + \tau_t^{\text{eff}}) X_t^{\ell, \text{eff}}$  final profits in region  $\ell$  at time  $t$ . As before, write the induced lifetime profit incomes as  $\Pi^{\ell, \text{eff}} := \sum_{t=0}^{\infty} q_t^{\text{eff}} \Pi_t^{\ell, \text{eff}}$  and define  $\bar{\Pi}^{\text{eff}} := \sum_{\ell \in \mathbb{L}} \Pi^{\ell, \text{eff}}$  and total tax revenue  $\bar{T}^{\text{eff}} := \sum_{t=0}^{\infty} q_t^{\text{eff}} \bar{T}_t^{\text{eff}}$ . Then, we can use the result from Lemma 1 and condition (24) to establish the following linear relation between consumption shares  $(\mu^\ell)_{\ell \in \mathbb{L}}$  and transfer shares  $(\theta^\ell)_{\ell \in \mathbb{L}}$  along the efficient equilibrium:

$$\mu^\ell = \frac{\Pi^{\ell, \text{eff}} + r_0^{\text{eff}} K_0^{\ell, s} + (v_0^{\text{eff}} - c_x) R_0^\ell + \theta^\ell \bar{T}^{\text{eff}}}{\bar{\Pi}^{\text{eff}} + r_0^{\text{eff}} \bar{K}_0^s + (v_0^{\text{eff}} - c_x) \bar{R}_0 + \bar{T}^{\text{eff}}} \quad \text{for all } \ell \in \mathbb{L}. \quad (54)$$

---

Solving (54) for  $\theta^\ell$  and combining it with the result from Lemma 5 gives the following complete characterization of incentive-compatible transfer policies inducing a Pareto-improvement over the non-cooperative solution.

**Theorem 4**

Define  $(\mu^{\ell,\text{crit}})_{\ell \in \mathbb{L}}$  as in Lemma 5. Suppose each region  $\ell \in \mathbb{L}$  chooses efficient taxes determined by (41) and receives a constant share  $\theta^\ell$  of global tax revenue satisfying

$$\theta^\ell \geq \theta_{\text{crit}}^\ell := \mu^{\ell,\text{crit}} + \frac{\mu^{\ell,\text{crit}} \left( \bar{\Pi}^{\text{eff}} + r_0^{\text{eff}} \bar{K}_0^s + (v_0^{\text{eff}} - c_x) \bar{R}_0 \right) - \left( \Pi^{\ell,\text{eff}} + r_0^{\text{eff}} K_0^{\ell,s} + (v_0^{\text{eff}} - c_x) R_0^\ell \right)}{\bar{T}^{\text{eff}}}.$$

Then, all regions are better-off relative to non-cooperative equilibrium, i.e., (51) holds.

Since the minimal transfer shares defined in Theorem 4 satisfy

$$\sum_{\ell \in \mathbb{L}} \theta_{\text{crit}}^\ell = \sum_{\ell \in \mathbb{L}} \mu^{\ell,\text{crit}} - \frac{\left( \sum_{\ell \in \mathbb{L}} \mu^{\ell,\text{crit}} - 1 \right) \left( \bar{\Pi}^{\text{eff}} + r_0^{\text{eff}} \bar{K}_0^s + (v_0^{\text{eff}} - c_x) \bar{R}_0 \right)}{\bar{T}^{\text{eff}}} < 1, \quad (55)$$

the set of transfer policies  $(\theta^\ell)_{\ell \in \mathbb{L}}$  satisfying the conditions of Theorem 4 is non-empty.

*Pareto-improvements relative to partial cooperation*

The previous results characterize the form of transfer policies such that the fully cooperative solution with efficient taxation yields a Pareto-improvement relative to the fully non-cooperative outcome. This result can be extended to obtain a Pareto improvement relative to any initial equilibrium with partial cooperation and an arbitrary coalition structure. The associated transfer shares can also be derived in closed form based on the same principles as in the non-cooperative case studied in this section.

## 7 Quantitative results

### 7.1 Regional structure and coalition scenarios

This section illustrates and quantifies the theoretical results based on calibrated parameter values chosen to match selected empirical targets. Specifically, the simulations include the non-cooperative and fully cooperative case as well as two additional scenarios with partial cooperation where key regions do not join the global climate agreement.

*Time structure*

One time period  $t$  in the model represents ten years which is a standard choice in the literature. The initial model period  $t = 0$  represents the years 2011–2020 and is referred to as the baseline period 2015. Subsequent periods representing years 2021–2030, 2031–2040, etc. are also referred to by their midpoints 2025, 2035, etc. Flow variables such as production output or emissions are generally aggregated over the entire period.

### Regions

Setting  $L = 10$  the simulations distinguish ten regions specified in Table 1. This choice of regions is small enough to allow for a compact presentation of the results and large enough to identify key players in past climate agreements as separate regions. Further details on the construction of regions can be found in Section B.3 in Appendix B.

Table 1: Regions in the simulation model

Region	Label	Index $\ell$	Region	Label	Index $\ell$
United States	USA	1	India	IND	6
OECD Europe	OEU	2	Russia	RUS	7
Australia & New Zealand	ANZ	3	Brazil	BRA	8
Other High Income	OHI	4	Developing countries	DEV	9
China	CHN	5	Low Income Countries	LIC	10

### Coalition scenarios

To capture different levels of cooperation among regions, I distinguish four coalition structures detailed in the following table. Scenario 1 represents the fully non-cooperative

Table 2: Coalition structures used in the simulations

Scenario	Description	Coalition structure
1	Full non-cooperation	$\mathcal{L} = \{\{\ell\}   \ell \in \mathbb{L}\} = \{\{1\}, \{2\}, \dots, \{10\}\}$
2	Full cooperation (grand coalition)	$\mathcal{L} = \{\mathbb{L}\} = \{\{1, \dots, 10\}\}$
3	Grand coalition except US	$\mathcal{L} = \{\mathbb{L} \setminus \{1\}, \{1\}\}$
4	Grand coalition except China	$\mathcal{L} = \{\mathbb{L} \setminus \{5\}, \{5\}\}$

case studied in Section 4 while Scenario 2 is the opposite extreme with full cooperation inducing the efficient outcome discussed in Section 6. The remaining Scenarios 3 and 4 consider cases with partial cooperation studied in Section 5 where either the US or China decides not to cooperate and breaks away from the grand coalition. The last two scenarios permit to evaluate and quantify the relative importance of the U.S. and China for the success of a global climate agreement.

## 7.2 Functional forms and parameters

### Production sector

Similar to Hassler et al. (2021) production function  $F_t^\ell : \mathbb{R}_+^2 \rightarrow \mathbb{R}_+$  in (1) is specified as

$$F_t^\ell(K, X) = \left[ \kappa \left( K^\alpha (h_t^\ell N_t^\ell)^{1-\alpha} \right)^{\frac{\varepsilon-1}{\varepsilon}} + (1-\kappa) (e_t^\ell X)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\varepsilon}{\varepsilon-1}}, \quad 0 < \kappa < 1, 0 < \alpha < 1, \varepsilon > 0. \quad (56)$$



---

Here,  $N_t^\ell$  and  $h_t^\ell$  denote population size and labor efficiency while  $e_t^\ell$  represents energy efficiency in region  $\ell$  at time  $t$ . Parameter  $\varepsilon$  controls the elasticity of substitution between fossil energy and the capital-labor aggregate. Variables  $h_t^\ell$  and  $e_t^\ell$  in (56) capture labor-augmenting and energy-augmenting technical change, respectively. They both grow at constant exogenous rates  $g_h \geq 0$  and  $g_e \geq 0$  identical for all regions such that

$$h_t^\ell = (1 + g_h)^t h_{t-1}^\ell \quad \text{and} \quad e_t^\ell = (1 + g_e)^t e_{t-1}^\ell \quad \text{for all } t \geq 1. \quad (57)$$

#### *Resource sector*

I abstract from the resource scarcity problem studied in Hassler et al. (2021) by formally setting  $R_0 = \infty$ . This seems empirically justified because fossil energy in my model comprises all kinds of fossil fuels including coal which is known to be relatively abundant. This assumption implies a constant resource price  $v_t = c_x$  for all  $t$ .

#### *Climate model*

I parameterize the climate model (5) to be consistent with recent evidence from Rezai & van der Ploeg (2021) by setting  $\delta_n = 1$  for all  $n = 0, 1, 2, \dots$ . Then, the climate state  $S_t$  in period  $t$  represents cumulative emissions since 1750 and evolves as<sup>10</sup>

$$S_t = S_{t-1} + \bar{X}_t = S_{-1} + \sum_{k=0}^t \bar{X}_k \quad \text{for all } t = 0, 1, 2, \dots \quad (58)$$

Here,  $S_{-1}$  is the level of atmospheric carbon at the beginning of  $t = 0$  corresponding to the end of year 2010. Based on (58), global temperature in period  $t$  is a linear function of cumulative emissions, i.e.,

$$TEMP_t = TEMP_{t-1} + \xi \cdot \bar{X}_t = TEMP_{-1} + \xi \cdot \sum_{k=0}^t \bar{X}_k \quad \text{for } t = 0, 1, 2, \dots \quad (59)$$

Here,  $TEMP_{-1}$  denotes temperature at the end of year 2010 relative to the pre-industrial level. Equation (59) is precisely the temperature model used in Rezai & van der Ploeg (2021) replacing the so-called Arrhenius relation used by Golosov et al. (2014).

## 7.3 Calibration

#### *Calibration targets*

The growth rates of labor and energy efficiency are chosen identical to obtain an annual growth rate of about 1% which is a conservative estimate. This determines the growth rates per decade  $g_h = g_e = 0.105 = 10.5\%$ . Initial productivity parameters  $h_0^\ell$  and  $e_0^\ell$  in (57) are chosen such that the model matches empirically observed regional output and emissions displayed in the following table in the baseline period  $t = 0$ . Details on this and the data in Table 3 are provided in Sections B.2 and B.3 in Appendix B.

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<sup>10</sup>In fact, (58) also obtains as a special case of the model of the carbon cycle from Golosov et al. (2014) when their share of permanent carbon  $\phi_L$  is set to one.

Table 3: Calibration targets for baseline period 2011-2020

Variable	Units	USA	OEU	ANZ	OHI	CHN	IND	RUS	BRA	DEV	LIC
$Y_0^{\ell, \text{target}}$	Trn.U.S.\$	189.5	230.5	13.4	133.5	186.0	73.8	38.0	30.7	124.8	121.2
$X_0^{\ell, \text{target}}$	GtC	14.5	10.2	1.2	10.5	28.4	6.1	4.5	1.4	10.6	6.5

### *Production parameters*

The literature contains a broad range of estimates for the elasticity of substitution  $\varepsilon$ . Papageorgiou et al. (2017) argue that this elasticity 'significantly exceeds unity' and estimate it to be about 2. Hassler et al. (2021) obtain a much smaller value of about 0.02 in their estimation for the U.S. economy. Choosing  $\varepsilon = 0.75$  is somewhat in the middle of these estimates and implies that fossil energy is a gross complement to other inputs. For  $\varepsilon = 1$ ,  $1 - \kappa$  would be the value of fossil energy relative to GDP. Empirical numbers put this share at about 5%, which is the value also used by Hassler et al. (2021). Alternative specifications as high as  $1 - \kappa = 0.2$  did not significantly affect the quantitative results reported below. I also follow Hassler et al. (2021) by setting  $\alpha = 0.2632$ .

Empirically, coal makes up by far the largest share of available stocks of fossil fuels. For this reason, extraction costs are set to 43 U.S. \$ per physical ton of the resource which is the value of extraction costs per ton of coal used in Golosov et al. (2014). With a carbon content of 0.5441 tons of C per physical ton of coal, this implies extraction costs of about 79\$ per ton of carbon corresponding to the value  $c_x = 0.000043/0.5441 = 0.000079$ .

### *Climate parameters*

Setting  $S_{-1} = 248.68$  GtC the climate state at the beginning of  $t = 0$  is consistent with atmospheric carbon concentration of 829.68 GtC at the end of 2010 relative to the pre-industrial level of 581 GtC. Rezai & van der Ploeg (2021) set the intensity parameter in (59) to  $2^\circ\text{C}/\text{TtC}$ . Since I measure emissions in GtC, this value is rescaled to  $\xi = 0.002$ . Temperature at the beginning of  $t = 0$  is  $TEMP_{-1} = 0.66^\circ\text{C}$  based on NASA (2018).

Damage parameters are notoriously hard to measure but tend to be much higher for poorer countries. The choices in Table 7.3 are in line with Hillebrand & Hillebrand (2023) but adapted to the more disaggregated regional setting employed here.

Table 4: Climate damage parameters.

Region:	USA	OEU	ANZ	OHI	CHN	IND	RUS	BRA	DEV	LIC
$\gamma^\ell \cdot 10^5$	4.12	2.05	2.05	2.05	4.12	6.22	6.22	6.22	6.22	8.33

### *Consumer sector*

Restricting consumer utility as in (7), I choose  $\sigma = 1$  corresponding to a logarithmic utility function. A realistic annual discount rate of 1.5% implies a discount factor  $\beta = 0.985^{10}$ . These values are identical to the ones used by Golosov et al. (2014) in their

benchmark scenario. The initial global capital stock is set to  $\bar{K}_0 = 0.2$ . This value avoids a transitory effect due to capital adjustments in the initial periods.

### Population

Population  $(N_t^\ell)_{t \geq 0}$  evolves exogenously and becomes constant for  $t \geq 9$  corresponding to the year 2100. Values before 2100 are chosen based on current and projected population sizes from the United Nations (2024). Details can be found in Section B.2 in Appendix B. Following figures depict the evolution of population in the different regions.

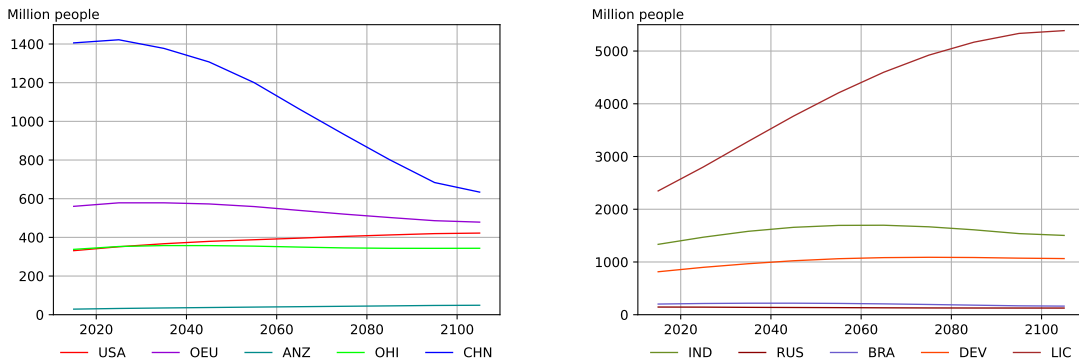


Figure 1: Current and projected regional population size.

### Computation

I use a version of the algorithm developed in Hillebrand & Hillebrand (2023). This approach identifies the forward-recursive structure of the model and determines initial consumption  $\bar{C}_0$  based on the shooting-principle. The factor allocation in period  $t$  is determined as a fixed point of a self-map updating regional outputs and factor cost shares in final production. Details can be found in Section B.1 in Appendix B.

## 7.4 Results

Following figures depict the evolution of key economic and climate variables for the four policy scenarios under scrutiny.

### Regional carbon taxes

Figure 2 shows the evolution of regional carbon taxes for each scenario. The values for period  $t = 1$  corresponding to the years 2021-2030 are reported in Table 5 below.

In all cases considered, taxes increase over time due to growth in real GDP. As one would expect from the tax formulae (32), (49), and (41), full cooperation leads to the highest and non-cooperation to the lowest levels of taxation. For this reason, the non-cooperative solution represents a lower bound of taxes in any cooperative scenario: In 2021, carbon taxes under non-cooperation are less than 20  $\$/tCO_2$  for all regions except in low income countries which set a much higher carbon tax equal to 26.20  $\$/tCO_2$

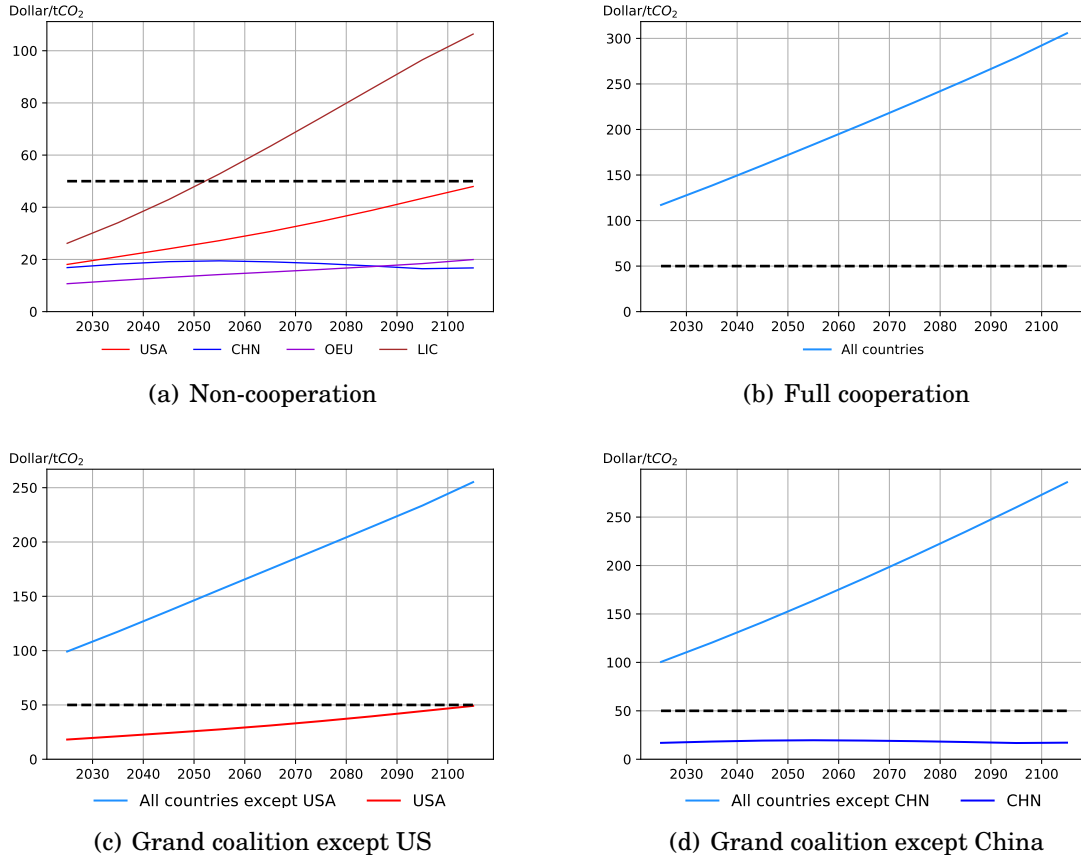


Figure 2: Regional climate taxes.

Table 5: Climate taxes in 2025 under full, partial, and non-cooperation in  $\$/t\ CO_2$ .

Scenario	USA	OEU	AUS	OHI	CHN	IND	RUS	BRA	DEV	LIC
1	18.1	10.7	0.7	6.3	16.9	11.0	5.1	4.4	18.6	26.2
2	117.1	117.1	117.1	117.1	117.1	117.1	117.1	117.1	117.1	117.1
3	18.2	99.2	99.2	99.2	99.2	99.2	99.2	99.2	99.2	99.2
4	100.5	100.5	100.5	100.5	16.9	100.5	100.5	100.5	100.5	100.5

reflecting higher regional damages internalized by the tax.

Under full cooperation, regions introduce a global carbon tax of 117.10 $\$/tCO_2$  in 2021. This value is more than three times larger than the 34 $\$$  reported in Golosov et al. (2014) and Hillebrand & Hillebrand (2019) for the year 2010 and much higher than the 17.70 $\$$  obtained by Nordhaus (2014) for 2015. Part of the increase is due to world GDP growth from 2010 to 2020. The main driver, however, is the climate model (58) which - unlike the model in Golosov et al. (2014) and DICE- assumes zero decay in atmospheric carbon. Over time the optimal tax increases again reflecting the growth trend of real GDP in each region to reach a value of 370  $\$/tCO_2$  in 2120 and of 982  $\$/tCO_2$  in 2220.

In Scenario 3 where all regions except the U.S. form a coalition, the coalitional tax is 99.20 \$/t CO<sub>2</sub> while the U.S. imposes a much lower tax of merely 18.20 \$/tCO<sub>2</sub>. A symmetric picture emerges for Scenario 4 where instead China breaks away from the grand coalition imposing a domestic tax of 16.90\$/t CO<sub>2</sub> while the coalition sets a much higher tax of 100.50 \$/tCO<sub>2</sub>. In both cases, the coalitional tax is lower than for the grand coalition because damages in the deviating country are no longer internalized.

*Regional emissions*

It is clear that any successful climate policy must lead to drastic reductions of global CO<sub>2</sub>-emissions. Figure 3 depicts the evolution of regional and global emissions in the four political scenarios. Table 6 shows regional emissions in the initial years 2021-2030.

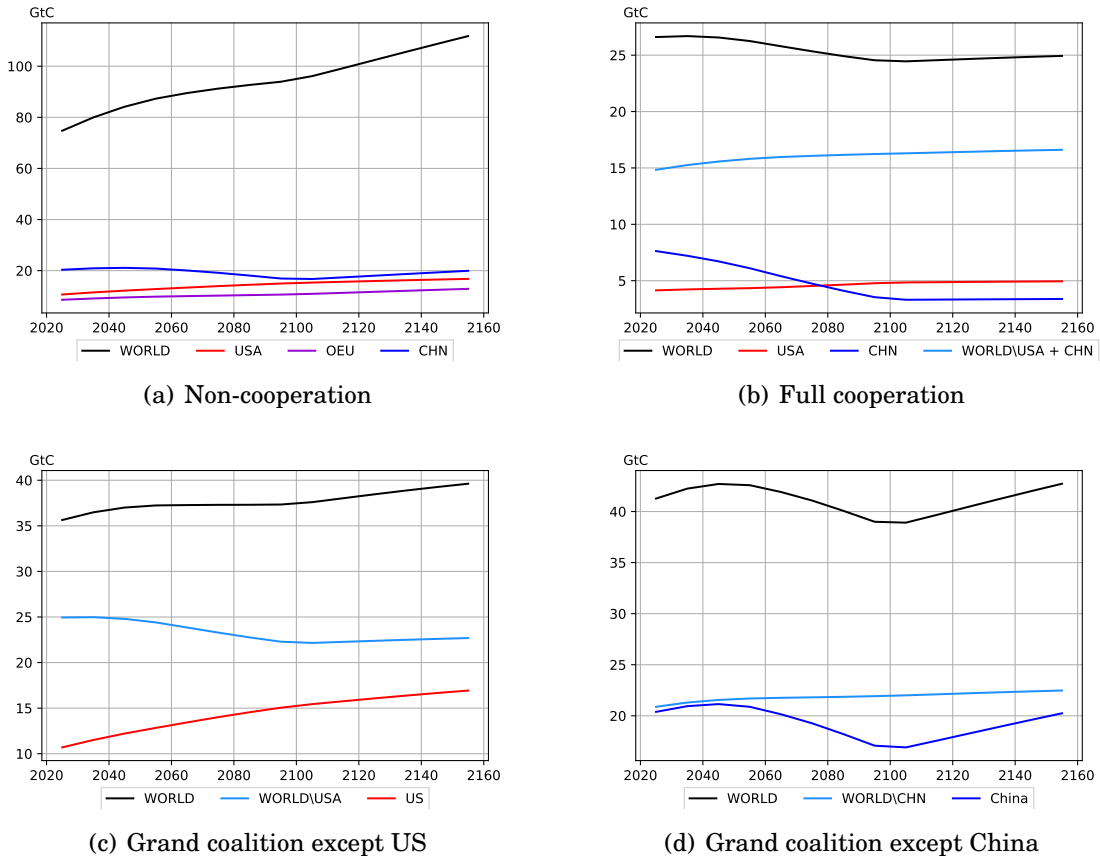


Figure 3: Regional emissions.

Introducing the optimal global tax in Scenario 2 leads to a substantial and permanent reduction in emissions. At the global level, emissions during the first decade 2021-2030 decline by about 64% relative to Scenario 1 with non-cooperation. In absolute terms, this corresponds to a reduction of about 48 GtC. This immediate reduction in absolute and relative terms is a little less pronounced but still sizable for the two Scenarios 3

Table 6: Regional emissions from 2021-2030 in GtC.

Scenario	USA	OEU	AUS	OHI	CHN	IND	RUS	BRA	DEV	LIC	World
1	10.7	8.6	1.5	10.0	20.4	5.4	4.2	1.4	8.0	4.7	74.7
2	4.1	2.9	0.4	3.0	7.6	1.8	1.2	0.4	3.1	2.1	26.6
3	10.7	3.2	0.4	3.3	8.5	2.0	1.3	0.4	3.5	2.3	35.6
4	4.6	3.2	0.4	3.2	20.4	2.0	1.3	0.4	3.5	2.3	41.3

and 4 with partial cooperation: A global coalition without the U.S. reduces global CO<sub>2</sub> emissions by 52% corresponding to -39 GtC, a coalition without China by -33.5 GtC corresponding to a decline of 45%.

At the regional level, there are sizable differences in emissions for each political scenario: Under full cooperation, the most drastic reduction occurs in China where emissions decline by -12.7 GtC (-62%) in 2025 relative to non-cooperation, followed by the U.S. where the decline is -6.5 GtC (-61%). For all three cooperative scenarios, the initial reduction in emissions within the global coalition is essentially preserved and emissions rise only slightly or even decline over the entire time window. This is in stark contrast to global emissions in the non-cooperative Scenario 1 and emissions in the non-cooperating region in Scenarios 3 and 4 which all continue to grow over time. As a consequence, the deviating country acquires an every increasing share of global emissions and in the long run becomes the main offender in both Scenarios 3 and 4. With China, this increase is temporarily attenuated until about 2100 due to the predicted decline in its population. After this, emissions continue to increase exponentially.

#### Climate and temperature

Figure 4 depicts atmospheric carbon and global temperature in the four scenarios. Here, an important benchmark is the 2°-target set by the Paris Agreement (cf. UN-FCCC (2015)) which aims to limit global warming to two degrees.

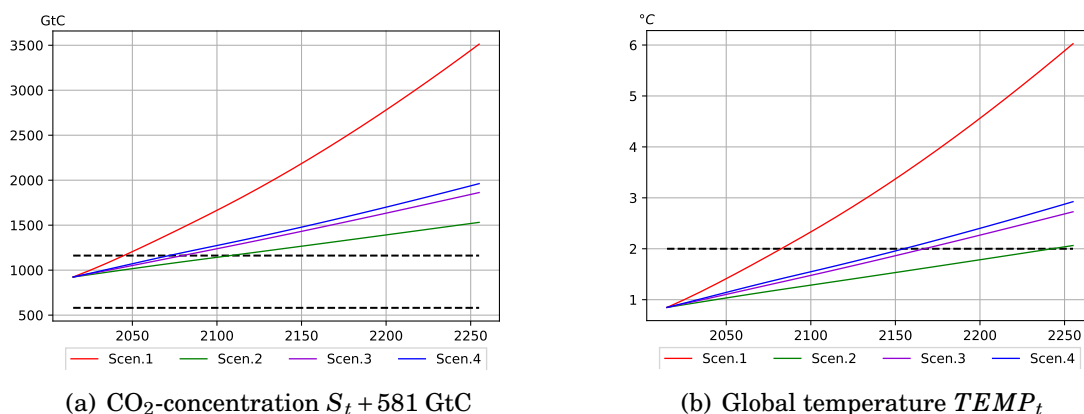


Figure 4: Atmospheric carbon concentration and global temperature.

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The figure reveals that full cooperation limits global warming to two degrees for the next 230 years until 2250 and until 2150 if either the U.S. or China breaks away from the grand coalition. By contrast, the two-degree target will be exceeded in the second half of the century before 2080 if countries do not cooperate. The key insight here is that at least some level of global cooperation is needed for the world to achieve the two degree target and there is no way to achieve it if countries act on their own.

## 8 Conclusions

The present paper provides closed-form solutions of optimal climate policies under different scenarios of cooperation between regions. These results provide the basis for understanding the quantitative effects of climate policy for a given coalition structure. They also hold the key for designing the redistribution scheme discussed in this paper under which all countries have an incentive to cooperate and participate in a global climate agreement to implement the efficient level of taxation.

One goal of future research is to better understand the formation process of coalitions and their stability. A recent study of this type can be found in Vosooghi, Arvaniti & van der Ploeg (2022) who determine the equilibrium coalition structure endogenously. As their setup does not allow for trade between countries, it would be interesting to extend their results to a setting with regional trade as assumed in this paper.

A second line of research would be to make technological change endogenous and directed as do Acemoglu et al.(2012) and Hassler et al. (2021). Understanding the impact of regional technological change and its spill-over to other regions as well as the scope for direct technology transfers across regions is likely to be a key factor in solving the climate problem. Such an innovation policy could complement the incentives set by tax policies studied in this paper.

## A Mathematical results and proofs

### A.1 Proof of Lemma 2

The boundary behavior (2) of each  $F_t^\ell$  and utility function (7) ensure that any solution to (28) satisfies  $K_t^\ell > 0$ ,  $X_t^\ell > 0$ , and  $C_t^\ell > 0$ . Thus, one can dispense with non-negativity constraints and use (27) as the single constraint. Define the Lagrangean function

$$\mathcal{L}\left((K_t^\ell, X_t^\ell, C_t^\ell)_{t \geq 0}, \lambda\right) := \sum_{t=0}^{\infty} \beta^t u(C_t^\ell) + \lambda \left( \sum_{t=0}^{\infty} q_t \left( e^{-\gamma^\ell \sum_{n=0}^{\infty} \delta_n (X_{t-n}^\ell + X_{t-n}^{-\ell})} F_t^\ell(K_t^\ell, X_t^\ell) - r_t K_t^\ell - v_t X_t^\ell - C_t^\ell \right) + r_0 K_0^{\ell, s} + (v_0 - c_x) R_0^\ell \right).$$

For each  $t = 0, 1, 2, \dots$  the derivatives with respect to consumption and capital read:

$$\frac{\partial \mathcal{L}((K_t^\ell, X_t^\ell, C_t^\ell)_{t \geq 0}, \lambda)}{\partial C_t^\ell} = \beta^t u'(C_t^\ell) - \lambda q_t \stackrel{!}{=} 0 \quad (60a)$$

$$\frac{\partial \mathcal{L}((K_t^\ell, X_t^\ell, C_t^\ell)_{t \geq 0}, \lambda)}{\partial K_t^\ell} = \lambda q_t \left( e^{-\gamma^\ell \sum_{n=0}^{\infty} \delta_n (X_{t-n}^\ell + X_{t-n}^{\ell-})} \partial_K F_t^\ell(K_t^\ell, X_t^\ell) - r_t \right) \stackrel{!}{=} 0 \quad (60b)$$

Solving (60a) gives  $\lambda = \beta^t u'(C_t^\ell)/q_t$  for all  $t$  which together with (13) implies the Euler equation (19). Moreover,  $\lambda > 0$  implies that (27) holds with equality by virtue of the Kuhn-Tucker theorem. Equation (60b) implies (12a). Finally, the partial derivative with respect to fossil fuels reads:

$$\frac{\partial \mathcal{L}((K_t^\ell, X_t^\ell, C_t^\ell)_{t \geq 0}, \lambda)}{\partial X_t^\ell} = \lambda q_t \left( (1 - D_t^\ell) \partial_X F_t^\ell(K_t^\ell, X_t^\ell) - v_t - \sum_{n=0}^{\infty} \frac{q_{t+n}}{q_t} \gamma^\ell \delta_n Y_{t+n}^\ell \right) \stackrel{!}{=} 0 \quad (61)$$

with  $D_t^\ell$  defined as in (23) and  $Y_t^\ell$  as in (1). Rearranging (61) using that by virtue of (13) and (19)  $q_{t+n}/q_t = \beta^n (C_{t+n}/C_t)^{-\sigma}$  implies (29).  $\blacksquare$

## A.2 Proof of Proposition 1

Define the wealth of the consumer in region  $\ell \in \mathbb{L}$  at the beginning of  $t = 0, 1, 2, \dots$  as

$$W_t^\ell := r_t K_t^{\ell, s} + (v_t - c_x) R_t^\ell \quad (62)$$

where  $R_t^\ell$  is the regional resource stock at the beginning of period  $t$  determined recursively as

$$R_{t+1}^\ell = R_t^\ell - X_t^{\ell, s} \quad \text{for all } t = 0, 1, 2, \dots \quad (63)$$

Intuitively, wealth  $W_t^\ell$  consist of capital income and the value of the current resource stock net of extraction costs in period  $t$ . Note that initial wealth  $W_0^\ell$  appears on the right-hand side of the lifetime budget constraint (27).

Combining definition (62) and (63) with the period-budget constraint (17), the evolution of the wealth sequence  $(W_t^\ell)_{t \geq 0}$  is determined recursively by the equation

$$W_{t+1}^\ell = r_{t+1} \left( W_t^\ell + (1 - D_t^\ell) F_t^\ell(K_t^\ell, X_t^\ell) - r_t K_t^\ell - v_t X_t^\ell - C_t^\ell \right) \quad \text{for all } t = 0, 1, 2, \dots \quad (64)$$

with the initial value  $W_0^\ell$  determined by (62) from the given initial values  $K_0^{\ell, s}$  and  $R_0^\ell$ . Solving (64) forward one obtains initial wealth at the beginning of time  $t = N > 0$  as:

$$q_N W_N^\ell = \sum_{t=0}^{N-1} q_t \left( (1 - D_t^\ell) F_t^\ell(K_t^\ell, X_t^\ell) - C_t^\ell - r_t K_t^\ell - v_t X_t^\ell \right) + W_0^\ell. \quad (65)$$



Observe that although the consumer's net capital position  $K_t^{\ell,s}$  and regional extraction  $X_t^{\ell,s}$  are, in general, indeterminate at equilibrium, the consumer's wealth position is uniquely determined recursively by (65).

Consider now the behavior of the consumer in region  $\ell \in \mathbb{L}$  in some period  $t = N \geq 1$ . Let previous wealth  $W_{N-1}^\ell$  and the strategies of all regions  $(K_t^\ell, X_t^\ell, C_t^\ell)_{0 \leq t < N}$  as well as the sequence  $(r_t, v_t)_{0 \leq t < N}$  chosen by the market maker prior to period  $t = N$  be given. In particular, aggregate emissions  $(\bar{X}_t)_{t < N}$  prior to period  $t = N$  are given. Suppose in period  $t = N$  each player  $\ell \in \mathbb{L}$  chooses an updated strategy  $(C_t^\ell, X_t^\ell, K_t^\ell)_{t \geq N}$  to maximize the remaining utility

$$U_N((C_t^\ell)_{t \geq N}) = \sum_{t=N}^{\infty} \beta^t u(C_t^\ell) \quad (66)$$

subject to the updated time  $N$  lifetime budget constraint

$$\sum_{t=N}^{\infty} q_{t,N} \left( C_t^\ell + r_t K_t^\ell + v_t X_t^\ell - (1 - D_t^\ell) F_t^\ell(K_t^\ell, X_t^\ell) \right) \leq W_N^\ell \quad (67)$$

where  $q_{t,N} := q_t/q_N = \prod_{n=N+1}^t r_n^{-1}$  and  $W_N^\ell$  determined by (65) or, equivalently, by (64) setting  $t = N - 1$ . The time- $N$  re-optimization problem of player  $\ell \in \mathbb{L}$  then reads:

$$\max_{(C_t^\ell, X_t^\ell, K_t^\ell)_{t \geq N}} \left\{ U_N((C_t^\ell)_{t \geq N}) \mid C_t^\ell, K_t^\ell, X_t^\ell \geq 0 \text{ for all } t \geq N, (67) \text{ holds} \right\}. \quad (68)$$

The following lemma describes the properties of solutions to (68). The proof parallels the one of Lemma 2 and is therefore omitted.

### Lemma 6

*If the sequence  $(C_t^\ell, X_t^\ell, K_t^\ell)_{t \geq N}$  satisfies (12a), (19), and (29) with  $D_t^\ell$  determined by (25) for all  $t \geq N$  as well as (67) with equality, then it is a solution to problem (68).*

In a similar vein, suppose the market maker  $\ell = 0$  is permitted to update his strategy as well by choosing values  $(r_t, v_t)_{t \geq N}$  subject to the Hotelling rule (15). Clearly, this choice is equivalent to choosing values  $v_N$  and  $r_N$  and  $q_{t,N}$  for all  $t > N$ . Suppose these choices are made to maximize the values  $(v_N - c_x) \sum_{\ell \in \mathbb{L}} (R_N^\ell - \sum_{t=N}^{\infty} X_t^\ell)$ ,  $r_N (\sum_{\ell \in \mathbb{L}} K_N^\ell - \bar{K}_N^s)$ , and  $q_{t,N} \sum_{\ell \in \mathbb{L}} (C_t^\ell + r_t K_t^\ell + v_t X_t^\ell - (1 - D_t^\ell) F_t^\ell(K_t^\ell, X_t^\ell))$  for all  $t \geq N$ , respectively. Here,  $\bar{K}_N^s := \sum_{\ell \in \mathbb{L}} ((1 - D_{N-1}^\ell) F_{N-1}^\ell(K_{N-1}^\ell, X_{N-1}^\ell) - C_{N-1}^\ell - c_x X_{N-1}^\ell)$  is world capital supply in period  $N$ . Combining this behavior with that of players  $\ell \in \mathbb{L}$ , we can define a time  $N$  Nash equilibrium as a list of continuation strategies  $(C_t^\ell, X_t^\ell, K_t^\ell)_{t \geq N}$  for each  $\ell \in \mathbb{L}$  and  $(r_t, v_t)_{t \geq N}$  for  $\ell = 0$  which solve the updated decision problems at time  $N$  given previous decisions. Now suppose until time  $N - 1$ , all players followed the strategies prescribed by the non-cooperative equilibrium. Formally, each player  $\ell \in \mathbb{L}$  chose  $(K_t^{\ell,nc}, X_t^{\ell,nc}, C_t^{\ell,nc})_{0 \leq t < N}$  as their strategy and the market maker  $\ell = 0$  chose  $(r_t^{nc}, v_t^{nc})_{0 \leq t < N}$ . Then, the continuation strategies  $(K_t^{\ell,nc}, X_t^{\ell,nc}, C_t^{\ell,nc})_{t \geq N}$  for each player  $\ell \in \mathbb{L}$  are clearly feasible, provided the market maker chooses  $(r_t^{nc}, v_t^{nc})_{t \geq N}$ . Moreover, these strategies satisfy the optimality conditions from Lemma 6, implying that each player will find it advantageous to stick to these strategies, provided everybody else does. ■

### A.3 Proof of Lemma 4

To derive the optimality conditions (46), I again adopt a standard Lagrangean approach. The boundary behavior (2) of each  $F_t^\ell$  and of the utility function (7) ensures that any solution to (45) satisfies  $K_t^\ell > 0$ ,  $X_t^\ell > 0$ , and  $\bar{C}_t > 0$  for all  $t$  and  $\ell$  permitting to dispense with non-negativity constraints. Define the Lagrangean function

$$\begin{aligned} \mathcal{L} \left( (K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}}, \bar{C}_t)_{t \geq 0}, (\lambda_t)_{t \geq 0}, \mu_X, \mu_K \right) := & \sum_{t=0}^{\infty} \beta^t u(\bar{C}_t) + \mu_X \left( \bar{R}_0 - \sum_{t=0}^{\infty} \sum_{\ell \in \mathbb{L}} X_t^\ell \right) \\ & + \sum_{t=0}^{\infty} \lambda_t \left( \sum_{\ell \in \mathbb{L}} e^{-\gamma^\ell \sum_{n=0}^{\infty} \delta_n \sum_{k \in \mathbb{L}} X_{t-n}^k} F_t^\ell(K_t^\ell, X_t^\ell) - \bar{C}_t - \sum_{\ell \in \mathbb{L}} K_{t+1}^\ell - c_x \sum_{\ell \in \mathbb{L}} X_t^\ell \right) + \mu_K \sum_{\ell \in \mathbb{L}} (K_0^{\ell,s} - K_0^\ell). \end{aligned}$$

For each  $t = 0, 1, 2, \dots$  and  $\ell \in \mathbb{L}$  the first order conditions read :

$$\frac{\partial \mathcal{L}(-)}{\partial \bar{C}_t} = \beta^t u'(\bar{C}_t) - \lambda_t \stackrel{!}{=} 0 \quad \text{for all } t = 0, 1, 2, \dots \quad (69a)$$

$$\frac{\partial \mathcal{L}(-)}{\partial K_0^\ell} = \lambda_0 (1 - D_0^\ell) \partial_K F_0^\ell(K_0^\ell, X_0^\ell) - \mu_K \stackrel{!}{=} 0 \quad \text{for all } \ell \in \mathbb{L} \quad (69b)$$

$$\frac{\partial \mathcal{L}(-)}{\partial K_t^\ell} = \lambda_t (1 - D_t^\ell) \partial_K F_t^\ell(K_t^\ell, X_t^\ell) - \lambda_{t-1} \stackrel{!}{=} 0 \quad \text{for all } \ell \in \mathbb{L} \text{ and } t = 1, 2, 3, \dots \quad (69c)$$

$$\begin{aligned} \frac{\partial \mathcal{L}(-)}{\partial X_t^\ell} = & -\mu_X + \lambda_t \left( (1 - D_t^\ell) \partial_X F_t^\ell(K_t^\ell, X_t^\ell) - c_x \right) \\ & - \sum_{n=0}^{\infty} \lambda_{t+n} \delta_n \sum_{k \in \mathbb{L}} \gamma^k Y_{t+n}^k \stackrel{!}{=} 0 \quad \text{for all } \ell \in \mathbb{L} \text{ and } t = 0, 1, 2, \dots \end{aligned} \quad (69d)$$

Solving (69a) gives

$$\lambda_t = \beta^t u'(\bar{C}_t) = \beta^t \bar{C}_t^{-\sigma} \quad \text{for all } t = 0, 1, 2, \dots \quad (70)$$

Using (70) in (69c) gives the Euler equation (46c). Since the term  $\beta \bar{C}_{t+1}^{-\sigma} / \bar{C}_t^{-\sigma}$  in (46c) is independent of  $\ell$ , this equation and (69b) imply (46a). Furthermore, solving (69d) using (70) and defining  $\hat{\tau}_t$  as in (47) gives

$$\mu_X = \lambda_t \left( (1 - D_t^\ell) \partial_X F_t^\ell(K_t^\ell, X_t^\ell) - c_x - \hat{\tau}_t \right) \quad \text{for all } \ell \in \mathbb{L} \text{ and } t = 0, 1, 2, \dots \quad (71)$$

Since the l.h.s. in (71) and the term  $\hat{\tau}_t$  are both independent of the regional index  $\ell$ , this implies (46b). Further, since the l.h.s. in (71) is also independent of time, combining it with (70) gives (46d). Equations (69b) and (70) imply  $\mu_K > 0$  and  $\lambda_t > 0$  such that (43) and (44) hold with equality by means of the Kuhn-Tucker theorem. The transversality condition ensures that consumption does not implode.

Remark: The term  $\hat{x}_t := \mu_X / \lambda_t$  plays the role of a scarcity rent which by (71) evolves as

$$\hat{x}_{t+1} = \mu_X / \lambda_{t+1} = \frac{\lambda_t}{\lambda_{t+1}} \hat{x}_t = \frac{\bar{C}_t^{-\sigma}}{\beta \bar{C}_{t+1}^{-\sigma}} \hat{x}_t \quad \text{for all } t = 0, 1, 2, \dots \quad (72)$$

---

This corresponds to the variable  $v_t - c_x$  along the decentralized equilibrium. The initial value  $\hat{x}_0 = \mu_X/\lambda_0$  ensures that either  $\sum_{t=0}^{\infty} \sum_{\ell \in \mathbb{L}} X_t^\ell = \bar{R}_0$  or  $\sum_{t=0}^{\infty} \sum_{\ell \in \mathbb{L}} X_t^\ell < \bar{R}_0$  in which case  $\mu_X = 0$  by the Kuhn-Tucker Theorem and  $\hat{x}_0 = 0$ . In the latter case, by (71)

$$(1 - D_t^\ell) \partial_X F_t^\ell(K_t^\ell, X_t^\ell) = c_x + \hat{\tau}_t \quad \text{for all } \ell \in \mathbb{L} \text{ and } t = 0, 1, 2, \dots \quad (73)$$

This corresponds to the case  $v_t = c_x$  along the decentralized solution. ■

## A.4 Proof of Theorem 3

We must show that the equations from Lemma 4 generating the efficient allocation are satisfied at equilibrium if taxes are chosen based on (49). This result holds independently of how transfers  $(T_t^\ell)_{t \geq 0}$  are determined.

The final sector's optimality condition (12a) implies equalization of capital returns (46a). Further, under uniform taxation, optimality condition (12b) implies that marginal products of fossil fuels equalize as required by (46b). Further, the Euler equation (19) can be aggregated and combining it with (12a) to replace the return on capital by its marginal product yields the aggregate Euler equation (46c).

Further, solving (12b) for  $v_t$  and substituting the result into the Hotelling rule (15) using the form of taxes (49) and replacing again the capital return  $r_{t+1}$  by its marginal product based on (12a) gives (46d). At equilibrium, the capital market clearing condition (20) for  $t = 0$ , the world resource constraint (21), and the commodity market equilibrium condition (22) hold directly. Finally, using the capital market clearing condition (20) the individual transversality conditions can be aggregated based on (46c) to obtain the aggregate version in Lemma 4. For this, one can use the (arbitrary but given) sequence of transfers  $(T_t^\ell)_{t \geq 0}$  and assume an arbitrary extraction sequence  $(X_t^{\ell,s})_{t \geq 0}$  consistent with (3) and satisfying  $\sum_{\ell \in \mathbb{L}} X_t^{\ell,s} = \sum_{\ell \in \mathbb{L}} X_t^\ell$  for all  $t$ . Then, one can use (17) to recursively obtain the sequence  $(K_{t+1}^{\ell,s})$  satisfying the capital market clearing condition in (20) and the transversality condition  $\lim_{t \rightarrow \infty} K_{t+1}^{\ell,s} \beta^t u'(C_t^{\ell,*})/u'(C_0^{\ell,*}) = \lim_{t \rightarrow \infty} K_{t+1}^{\ell,s} \beta^t u'(\bar{C}_t^*)/u'(\bar{C}_0^*) = 0$ . Aggregating this condition over all regions using the capital market clearing condition in (20) then gives the result. ■

## A.5 Proof of Lemma 5

The argument depends on parameter  $\sigma$  in (7). We distinguish the following cases. First, assume that  $\sigma \neq 1$  in (7). Then,  $U$  is homogenous of degree  $1 - \sigma > 0$  permitting to write the utilities in (51) as

$$U((\mu^\ell \bar{C}_t^{\text{eff}})_{t \geq 0}) = (\mu^\ell)^{1-\sigma} \bar{U}^{\text{eff}} \quad \text{and} \quad U((\mu^{\ell,\text{nc}} \bar{C}_t^{\text{nc}})_{t \geq 0}) = (\mu^{\ell,\text{nc}})^{1-\sigma} \bar{U}^{\text{nc}}. \quad (74)$$

Suppose  $\sigma < 1$ . Then,  $U$  is positive-valued and solving (74) for  $\mu^\ell$  using  $\bar{U}^{\text{eff}} > 0$  gives the following condition for the consumption share of region  $\ell$ :

$$\mu^\ell \geq \mu_{\text{crit}}^\ell := \mu^{\ell, \text{nc}} \left( \bar{U}^{\text{nc}} / \bar{U}^{\text{eff}} \right)^{\frac{1}{1-\sigma}}. \quad (75)$$

Since  $0 < \bar{U}^{\text{nc}} / \bar{U}^{\text{eff}} < 1$  and  $\sigma < 1$ , we have  $\mu_{\text{crit}}^\ell < \mu^{\ell, \text{nc}}$  as claimed.

Suppose  $\sigma > 1$ . Then,  $U$  is negative-valued and solving (74) for  $\mu^\ell$  yields again the same condition (75). Since now  $\bar{U}^{\text{nc}} / \bar{U}^{\text{eff}} > 1$ ,  $\sigma > 1$  implies  $\mu_{\text{crit}}^\ell < \mu^{\ell, \text{nc}}$  again.

As a second case, assume that  $\sigma = 1$  implying logarithmic period utility in (7). Then,

$$U((\mu^\ell \bar{C}_t^{\text{eff}})_{t \geq 0}) = \frac{\log(\mu^\ell)}{1-\beta} + \bar{U}^{\text{eff}} \quad \text{and} \quad U((\mu^{\ell, \text{nc}} \bar{C}_t^{\text{nc}})_{t \geq 0}) = \frac{\log(\mu^{\ell, \text{nc}})}{1-\beta} + \bar{U}^{\text{nc}}. \quad (76)$$

Using this result in (74) and solving again for  $\mu^\ell$  gives

$$\mu^\ell \geq \mu_{\text{crit}}^\ell := \mu^{\ell, \text{nc}} \cdot e^{-(1-\beta)(\bar{U}^{\text{eff}} - \bar{U}^{\text{nc}})}. \quad (77)$$

Again,  $\bar{U}^{\text{eff}} > \bar{U}^{\text{nc}}$  implies that  $\mu_{\text{crit}}^\ell < \mu^{\ell, \text{nc}}$  also in this case. ■

## B Details on the simulations

This section provides additional details on the computation and calibration strategy and the data.

### B.1 Computational details

*Equilibrium conditions for period  $t$*

Consider an arbitrary period  $t \geq 0$ . Let aggregate capital supply  $\bar{K}_t^s$ , exogenous population and productivity variables  $(N_t^\ell, h_t^\ell, e_t^\ell)_{\ell \in \mathbb{L}}$ , and the climate state  $S_{t-1}$  from the previous period be given. Based on the approximation formula (42), suppose taxes in region  $\ell \in \mathbb{L}$  are determined by

$$\tau_t^\ell = \sum_{k \in \mathbb{L}_\ell} \gamma^k Y_t^k \sum_{n=0}^{\infty} \beta^n \delta_n \quad (78)$$

where  $\mathbb{L}_\ell \subset \mathbb{L}$  is the coalition that region  $\ell$  is a member of.<sup>11</sup> Using the CES-form of production (56) and defining the cost shares

$$\eta_{K,t}^\ell := \frac{\kappa ((K_t^\ell)^\alpha (h_t^\ell N_t^\ell)^{1-\alpha})^{\frac{\varepsilon-1}{\varepsilon}}}{(F_t^\ell(K_t^\ell, X_t^\ell))^{\frac{\varepsilon-1}{\varepsilon}}} \quad \text{and} \quad \eta_{X,t}^\ell := \frac{(1-\kappa)(e_t^\ell X_t^\ell)^{\frac{\varepsilon-1}{\varepsilon}}}{(F_t^\ell(K_t^\ell, X_t^\ell))^{\frac{\varepsilon-1}{\varepsilon}}} = 1 - \eta_{K,t}^\ell \quad (79)$$

<sup>11</sup>In particular,  $\mathbb{L}_\ell = \{\ell\}$  in the non-cooperative and  $\mathbb{L}_\ell = \mathbb{L}$  in the fully cooperative case. I compared the approximated value (78) ex-post to the true solution (41) to show that the approximation is excellent.

one can write final sector's optimality conditions (12) as

$$r_t = \alpha \eta_{K,t}^\ell Y_t^\ell / K_t^\ell \quad \text{and} \quad c_x + \sum_{k \in \mathbb{L}_\ell} \gamma^k Y_t^k \sum_{n=0}^{\infty} \beta^n \delta_n = \eta_{X,t}^\ell Y_t^\ell / X_t^\ell, \quad \ell \in \mathbb{L}. \quad (80)$$

Moreover, using (58) and (4) in (6) permits to write final output in region  $\ell$  as

$$Y_t^\ell = \exp \left( -\gamma^\ell \left( S_{t-1} + \sum_{k \in \mathbb{L}} X_t^k \right) \right) F_t^\ell(K_t^\ell, X_t^\ell). \quad (81)$$

The temporary equilibrium problem is to determine the factor allocation  $(K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}}$  consistent with optimal producer behavior (80) and the market clearing condition

$$\sum_{\ell \in \mathbb{L}} K_t^\ell = \bar{K}_t^s \quad (82)$$

with outputs  $(Y_t^\ell)_{\ell \in \mathbb{L}}$  determined by (81) and cost shares as in (79). Rearranging the first condition in (80) and summing over all regions using (82) gives

$$r_t = \alpha \sum_{\ell \in \mathbb{L}} \eta_{K,t}^\ell Y_t^\ell / K_t^s. \quad (83)$$

Using (83) in (80) and re-arranging both conditions, exploiting that  $\eta_{X,t}^\ell = 1 - \eta_{K,t}^\ell$  gives

$$K_t^\ell = \frac{\eta_{K,t}^\ell Y_t^\ell}{\sum_{h \in \mathbb{L}} \eta_{K,t}^h Y_t^h} \cdot K_t^s \quad \text{and} \quad X_t^\ell = \frac{(1 - \eta_{K,t}^\ell) Y_t^\ell}{c_x + \sum_{k \in \mathbb{L}_\ell} \gamma^k Y_t^k \sum_{n=0}^{\infty} \beta^n \delta_n}. \quad (84)$$

Next we show how the temporary equilibrium problem can be computed numerically.

*Computing the factor allocation in period  $t$ .*

Let arbitrary values  $\hat{H} := (\hat{Y}_t^\ell, \hat{\eta}_{K,t}^\ell)_{\ell \in \mathbb{L}} \in \mathbb{H} := (\mathbb{R}_{++} \times [0, 1])^L$  be given. Using  $\hat{H}$  in (84) determines the implied factor allocation  $\hat{G} := (\hat{K}_t^\ell, \hat{X}_t^\ell)_{\ell \in \mathbb{L}} \in \mathbb{G} := \mathbb{R}_{++}^{2L}$ . This step defines a first mapping  $\Phi_G : \mathbb{H} \rightarrow \mathbb{G}$ ,  $\hat{H} \mapsto \Phi_G(\hat{H}) := \hat{G}$ . Substituting the values  $\hat{G}$  back into (79) and (81) yields the updated values  $\tilde{H} := (\tilde{Y}_t^\ell, \tilde{\eta}_{K,t}^\ell)_{\ell \in \mathbb{L}} \in \mathbb{H}$  defining a second mapping  $\Phi_H : \mathbb{G} \rightarrow \mathbb{H}$ ,  $\hat{G} \mapsto \Phi_H(\hat{G}) := \tilde{H}$ . The composition  $\Phi := \Phi_H \circ \Phi_G : \mathbb{H} \rightarrow \mathbb{H}$ ,  $\hat{H} \mapsto \Phi(\hat{H}) := \tilde{H}$  is a self-map on  $\mathbb{H}$  and the equilibrium solution  $H := (Y_t^\ell, \eta_{K,t}^\ell)_{\ell \in \mathbb{L}}$  is a fixed point of  $\Phi$ . It turned out that  $\Phi$  is globally asymptotically stable such that simply iterating  $\Phi$  forward, starting with an arbitrary guess  $H_0$  yields the equilibrium solution  $\lim_{n \rightarrow \infty} \Phi^n(H_0) = H = (Y_t^\ell, \eta_{K,t}^\ell)_{\ell \in \mathbb{L}}$ . The implied factor allocation then obtains as  $G = (K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}} = \Phi_G(H)$ .

*Equilibrium state dynamics*

The endogenous state variable in period  $t$  is  $\xi_t = (\bar{K}_{t+1}^s, \bar{C}_t, S_t)$ . To uncover the forward-recursive structure of equilibrium, let the previous state  $\xi_{t-1}$  in period  $t$  be given. Using  $\bar{K}_t^s$  and  $S_{t-1}$  along with the exogenous variables  $(N_t^\ell, h_t^\ell, e_t^\ell)_{\ell \in \mathbb{L}}$  we can determine the factor allocation  $(K_t^\ell, X_t^\ell)_{\ell \in \mathbb{L}}$  and regional outputs  $(Y_t^\ell)_{\ell \in \mathbb{L}}$  and the auxiliary variables  $(\eta_{K,t}^\ell, \eta_{X,t}^\ell)_{\ell \in \mathbb{L}}$  as described in the previous step. Using the implied aggregate emissions

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$\bar{X}_t := \sum_{\ell \in \mathbb{L}} X_t^\ell$  in (58) determines the new climate state  $S_t$ . Computing the implied capital return  $r_t$  as in (83), current aggregate consumption follows from the Euler equation  $\bar{C}_t = \beta r_t \bar{C}_{t-1}$ . Aggregate capital supply  $\bar{K}_{t+1}^s$  then follows from the resource constraint (22), completing the determination of  $\xi_t$ .

Given initial world capital  $\bar{K}_0^s$  and the climate state  $S_{-1}$ , we determine initial aggregate consumption  $\bar{C}_{-1}$  (or, equivalently,  $\bar{C}_0 = (\beta r_0)^{1/\sigma} \bar{C}_{-1}$ ) such that the transversality condition  $\lim_{t \rightarrow \infty} \beta^t \bar{K}_{t+1}^s / \bar{C}_t = 0$  holds, i.e., consumption neither explodes nor implodes. It turned out that there is always a unique value  $\bar{C}_0$  for which this is the case.

## B.2 Calibration details

### *Determining productivity parameters*

Let the initial climate state  $S_{-1}$  and initial capital supply  $\bar{K}_0^s$  in  $t = 0$  be given. For each region  $\ell \in \mathbb{L}$ , set output and emissions to the target levels defined in Table 3, i.e.,  $Y_0^\ell = Y_0^{\ell, \text{target}}$  and  $X_0^\ell = X_0^{\ell, \text{target}}$ . Consider the non-cooperative scenario where each region sets taxes based on the approximation (34). Then, initial regional taxes compute as  $\tau_0^\ell = \gamma^\ell Y_0^\ell \sum_{n=0}^{\infty} \beta^n \delta_n$ . Using this result and the given values of regional output  $Y_0^\ell$  and emissions  $X_0^\ell$  one can explicitly solve the second condition in (84) to obtain the values  $\eta_{X,0}^\ell = 1 - \eta_{K,0}^\ell$  for all  $\ell \in \mathbb{L}$ . This also determines  $\eta_{K,0}^\ell$  for each  $\ell$ , which can be used in (84) together with the given output levels  $(Y_0^\ell)_{\ell \in \mathbb{L}}$  to infer the initial capital allocation  $(K_0^\ell)_{\ell \in \mathbb{L}}$ . Further, one obtains from (81) the values  $F_0^\ell(K_0^\ell, X_0^\ell)$  as

$$F_0^\ell(K_0^\ell, X_0^\ell) = Y_0^\ell \cdot \exp \left( \gamma^\ell \left( S_{-1} + \sum_{k \in \mathbb{L}} X_0^k \right) \right). \quad (85)$$

Using the values  $\eta_{X,0}^\ell$ ,  $X_0^\ell$ , and  $F_0^\ell(K_0^\ell, X_0^\ell)$  one can solve the second condition in (79) explicitly for  $e_0^\ell$ . Analogously, one can use  $\eta_{K,0}^\ell$ ,  $K_0^\ell$ ,  $F_0^\ell(K_0^\ell, X_0^\ell)$  and the given value  $N_0^\ell$  to solve the first condition in (79) explicitly for  $h_0^\ell$ .

## B.3 Data

### *Regions*

Based on the 'World Development Indicators' of the World Bank (2022), countries are classified as 'high income', 'upper-middle income', 'lower-middle income', and 'low income'. These form the basis of the set of regions in Table 1 where 'Developing countries' (region  $\ell = 9$ ) consist of 'upper-middle income' countries while low-income countries (region  $\ell = 10$ ) consist of 'lower-middle income' and 'low income' countries.

### *Population data*

Population data are from United Nations (2024). Current population data of individual countries are obtained from the series Estimates, 1950 - 2023. Future population

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projections employ the Medium fertility variant, 2024 - 2100. Annual data are aggregated over countries forming the region and years of the respective decade.

#### *Regional GDP and emissions*

GDP-data are from the World Bank (2022) measuring annual PPP-adjusted GDP at the country level in constant 2017 international dollars. Data on CO<sub>2</sub>-emissions at the country level were obtained from Friedlingstein et al. (2023) and converted to GtC using a conversion factor of 12/44. In all cases, regional values were obtained by aggregating over all countries forming the region and years of the respective decade.

#### *Atmospheric carbon and global temperature*

Atmospheric carbon levels for 2011 in ppm from the United States Environmental Protection Agency (2024) were converted to GtC using a conversion factor of 2.124. Temperature data from NASA (2018) using the 'Smoothed Temperature Anomaly' gives the value  $TEMP_{-1} = 0.66$  °C at the beginning of  $t = 0$  corresponding to the year 2011.

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