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Climate Clubbing, Trade and the Natural Interest Rate*

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Abstract

In a dynamic, three-region environmental life-cycle model, we find that, when a region introduces carbon pricing, output falls initially as emissions increase production costs. Benefits from lower emissions damage materialize only later. They are smaller and output could be depressed permanently when only few/small regions participate in carbon pricing. A border adjustment mechanism mitigates but does not prevent carbon leakage. Unless compensated for, retirees living in regions that increase carbon pricing lose income and face higher consumption costs. This augments savings. As they cannot be fully invested domestically, net foreign assets increase and the world asset market-clearing interest rate falls. A higher net foreign asset position transfers income from abroad to home. This reduces (domestic) welfare costs of carbon pricing.

Keywords: Carbon Pricing, Border Adjustment, Climate Clubs, International Dynamic General Equilibrium Model, Endogenous Interest Rate, Trade

JEL classification: E32, E50, E62, H32, Q58

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1 Introduction

In recent years, over 100 countries have set or proposed ambitious climate goals involving serious greenhouse gas (GHG) emissions reductions. Countries involved cover almost 90 percent of GHG emissions. To reach the set targets, academics as well as G7/G0 policy-makers discuss economically efficient and publicly acceptable climate change mitigation policies. These measures include (regional) approaches to pricing carbon and climate clubs, the latter supposed to avoid carbon leakage. In this paper, we contribute to the discussion by analyzing the implications of different policy scenarios regarding carbon pricing, border adjustments and climate clubs on macroeconomic as well as (regional) growth developments, on international trade, on consumption/savings decisions and, thereby, on the world asset market-clearing real (natural) interest rate.

To do so, we set up a three-region environmental open-economy general equilibrium model to assess the effects. More precisely, the model contains typical environmental features along the lines of, among others, [Heutel \(2012\)](#), [Golosov, Hassler, Krusell, and Tsyvinski \(2014\)](#), [Annicchiarico and Di Dio \(2015\)](#) and [Annicchiarico, Correani, and Di Dio \(2018\)](#).¹ In addition, it includes a life-cycle population structure following, for example, [Gertler \(1999\)](#), [Carvalho, Ferrero, and Nechio \(2016\)](#), [Fujiwara and Teranishi \(2008\)](#), [Schön and Stähler \(2020\)](#) and [Ruppert and Stähler \(2022\)](#). This opens up new transmission channels for structural policy changes to spill over into the other regions because. In contrast to the standard open-economy modelling framework with an infinitely-lived representative agent, our setting generates steady-state determinacy and stationarity of net foreign assets as well as an endogenous world interest rate (see [Ghironi, 2008](#); [Ghironi, Iscan, and Rebucci, 2008](#); [Ferrero, 2010](#); [Di Giorgio and Nistico, 2013](#); [Di Giorgio, Nistico, and Traficante, 2018](#); [Di Giorgio and Traficante, 2018](#), for an in-depth discussion).² Therefore, the resulting model has many important features for our question of interest: Feedbacks between the economy and the environment, endogenous interest rates and trade, as well as a distribution between old and young within each region, to mention a few. Our simulation results can be summarized as follows.

In terms of the overall macro message, we confirm the results presented by [Ernst, Hinterlang, Mahle, and Stähler \(2022\)](#). First, the introduction of carbon pricing generates a reduction of emissions but also of production, at least in the first phase of the transmission. The latter is because production becomes more expensive. As soon as the emissions reduction decreases emissions-induced (production) damage, it eventually generates positive economic effects. However, it takes time – potentially a generation’s lifetime – before these positive effects overcompensate the adverse effects of the cost push on output and consumption, if at all. For this to be the case, the emissions reduction must be sufficiently large, i.e. the more regions participate in carbon pricing the larger the better.

However, second, there is no incremental incentive for the non-participating regions to

¹In these models, emissions occur as a by-product of production. Firms can engage in costly abatement activities. Unabated emissions increase the stock of carbon in the atmosphere, which can ultimately result in a loss of production (see also [Annicchiarico, Carattini, Fischer, and Heutel, 2022](#), for a discussion).

²In standard open-economy DSGE models ([Obstfeld and Rogoff, 1995](#)), the net foreign asset position is usually exogenous. Stationarity is reached by adding a friction to the financial market that kicks in whenever the exogenously fixed reference level is missed (see [Schmitt-Grohe and Uribe, 2003](#), [Hunt and Rebucci, 2005](#), [Lubik, 2007](#) and [Benigno, 2009](#)). This very mechanism however makes the net foreign asset position independent of structural (policy) changes.

participate. This is mainly due to the fact that they would forego trade spillovers and face a cost push implied by introducing a carbon price. Trade spillovers in non-participating regions emerge because agents substitute expensive goods that are produced in regions with a carbon price by cheaper but dirtier goods produced in non-participating regions. This is called carbon leakage.

Third, border adjustment (i.e. taxing “dirty” foreign goods and subsidizing “clean” domestic ones) dampens carbon leakage, but border adjustment alone does not provide sufficient incentives for non-participating regions to introduce carbon pricing. The resulting additional emissions reduction, compared to not having border adjustment, is also limited.

However, there exist also remarkable differences compared to the findings in [Ernst et al. \(2022\)](#). While aggregate output developments are similar, the negative impact on consumption is much shorter and less pronounced due to carbon pricing. This is caused by the life cycle structure, which makes income of workers and retirees affected differently. In particular, retirees face lower pension income as wages decrease. Additionally, consumption becomes more expansive. Taken together, this makes retirees to save more. In contrast, workers’ consumption eventually increases due to lower lump sum tax burden. However, their marginal propensity to consume also decreases since they take into account that they will potentially become retirees in the future. Since output and capital demand fall in the region introducing carbon pricing, households have to save abroad, which increases the net foreign asset position. The real exchange rates rises relative to non-participating regions such that exports fall. Imports fall by even more due to the domestic income loss. Carbon border adjustment taxes enforce these results since investment goods from abroad become relatively more expensive, implying higher rental rates for capital. There is another interesting observation. Non-participating regions benefit from positive trade/output spillovers from regions introducing carbon pricing. However, this does not hold true for consumption. Due to the fall in net foreign asset holdings in these regions, they need to pay interest to the other regions (or receive lower payments). These forgone interest payments may outweigh the increase in production, and consumption opportunities fall (see also [Ruppert and Stähler, 2022](#), discussing this mechanism related to fiscal devaluation). Last but not least, the higher world savings drive down the asset market clearing interest rate, which translates into a fall in capital interest in all regions. This fosters production. In the end, the negative macroeconomic impact of carbon pricing is smaller in our framework than it is in a standard DSGE framework, also in terms of aggregate welfare. However, retirees alive have to bear some costs due to carbon pricing.

The rest of the paper is organized as follows. We discuss related literature in [Section 2](#). The model is introduced in [Section 3](#), its calibration in [Section 4](#). General simulation results are described in [Section 5](#), and [Section 6](#) concludes.

2 Related literature

Recently, the literature on environmental macroeconomic models has started to evolve rapidly. A rather comprehensive overview of analyses in environmental DSGE models can be found in [Annicchiarico et al. \(2022\)](#). Our paper relates to this literature as we follow a common approach of that literature and assume that emissions are a direct by-

product of production (see [Heutel, 2012](#), and [Golosov et al., 2014](#)). Others, such as [Fischer and Springborn, 2011](#), [Böhringer, Fischer, and Rosendahl, 2014](#), and [Böhringer and Fischer, 2020](#), for example, analyse optimal pollution as a direct input. [Hinterlang, Martin, Röhe, Stähler, and Strobel \(2022\)](#) use a multi-sector modelling framework in which firms need inputs produced in other sectors following [Atalay \(2017\)](#) and [Bouakez, Rachedi, and Santoro \(2022\)](#) and, thereby, implicitly incorporate both modelling approaches through the input-output structure. As in [Heutel \(2012\)](#), [Golosov et al. \(2014\)](#) and [Khan, Metaxoglou, Knittel, and Papineau \(2019\)](#), we introduce a “damage function” that describes economic losses as a function of the stock of emissions. Alternative modelling approaches that include environmental aspects in the welfare function can be found in, among others, [Chang, Chen, Shieh, and Lai \(2009\)](#), [Angelopoulos, Economides, and Philippopoulos \(2013\)](#), [Cai and Lontzek \(2019\)](#) and [Cai \(2020\)](#).

The effects of carbon pricing have recently been addressed in several papers. [Annicchiarico and Di Dio \(2015\)](#) find that business cycle fluctuations are dampened by emissions taxation, and in particular by emission caps. The two-region model by [Chan \(2020\)](#) confirms this finding and adds that fluctuations are higher in case of non-cooperation between both regions. [Chan and Zhao \(2022\)](#) discuss optimal cyclicalities of carbon taxes in a model with supply chains. The effect of carbon pricing on trade spill-overs is investigated in [Annicchiarico and Diluiso \(2019\)](#) and [Duan, Ji, Lu, and Wang \(2021\)](#). Moreover, [Annicchiarico et al. \(2018\)](#) find that the environmental tax regime affects market structure and markups. In a (static) computable general equilibrium model, [Devulder and Lisack \(2020\)](#) and [Frankovic \(2022\)](#) take into account the sectoral structure and linkages of an economy when assessing carbon pricing. They find that dirty sectors tend to be affected more severely by carbon pricing, but they also benefit more from border adjustment. This is also confirmed by [Ernst et al. \(2022\)](#) in a dynamic framework. [Antosiewicz, Lewandowski, and Witajewski-Baltvilks \(2016\)](#), [Hinterlang et al. \(2022\)](#) and [Varga, Roeger, and Veld \(2022\)](#) compare different ways of energy and emissions taxation as well as recycling options of the corresponding proceeds. They find that reducing other distortions can be economically more beneficial than per-capita redistribution.

This international dimension then quickly brings us to questions related to carbon leakage, i.e. the fact that carbon emissions in abating areas may be offset (at least to some extent) by increased carbon emissions in non-abating areas. This is mainly for two reasons. First, because abating regions demand less emissions-intensive inputs, these may become cheaper on the world market, and their use in non-abating areas is likely to increase (energy market channel). Second, because emissions-intensive products become more expensive in abating regions, abating regions are likely to import more (and export less) “dirty” goods. [Yu, Zhao, and Wei \(2020\)](#) provide an overview of the most recent literature on carbon leakage. The literature that tries to quantify carbon leakage can be divided into mainly two strands. The first one relies on econometric setups that use ex post data of already implemented carbon policies (see, for example, [Aichele and Felbermayr, 2015](#), who rely on the Kyoto Protocol, and [Naegle and Zaklan, 2019](#), and [Garnadt, Grimm, and Reuter, 2020](#), relying on the European Emissions Trading System EU-ETS). The other strand uses CGE or partial equilibrium models to simulate the effects of carbon policies ex ante (see e.g. the meta study by [Branger and Quirion, 2014](#)). While the former strand typically finds no or limited carbon leakage when assessing existing carbon pricing schemes, the latter documents carbon leakage in some industries but only mixed evidence

at the aggregate level. Comprehensive reviews by, for example, [Felbermayr and Peterson \(2020\)](#), [Zachmann and McWilliams \(2020\)](#) and [Yu et al. \(2020\)](#) also discuss that the amount of leakage depends on the regions considered or on specific model assumption made, such as, for example, substitution elasticities and/or trade structures. Our carbon leakage measures fall in the range of those presented in these studies.

To prevent carbon leakage, carbon border adjustment (primarily taxing imports due to their carbon content) is discussed as a policy option. We discuss this in our model, too. On the one hand, [Branger and Quirion \(2014\)](#) and [Böhringer, Balistreri, and Rutherford \(2012\)](#); [Böhringer, Carbone, and Rutherford \(2018\)](#) find that border adjustment reduces leakage rates, especially if it is applied in emissions-intensive and trade-exposed sectors. [Weitzel, Peterson, et al. \(2012\)](#) and [Zachmann and McWilliams \(2020\)](#), on the other hand, report little gain from border adjustment. We confirm that the aggregate leakage reduction is small, but that it is beneficial for “dirty” domestic sectors. The reason is that, for these sectors, import costs increase disproportionately such that domestic demand is shifted towards domestically produced goods. [Weitzel, Hübler, and Peterson \(2012\)](#) also find this trade channel to be important (and discuss that it may also be used strategically, without any environmental intension). As long as the “dirty” domestic sectors are relatively cleaner than those abroad, the environment (mildly) benefits from border adjustment. However, according to our analysis, we should not expect too much.³

The idea of a climate club, i.e. a larger group of countries introducing (similar) carbon prices dates back to [Nordhaus \(2015\)](#). [Nachtigall, Ellis, Peterson, and Thube \(2021\)](#) review CGE and IAM modelling studies regarding international coordination on carbon pricing. They find that international cooperation has positive economic and environmental effects. Moreover, these are larger (i.) when more countries participate and (ii.) when more emissions and sectors are covered. However, regions may have different reasons not to collaborate (as discussed in [Weitzel et al., 2012](#)). Additional incentives, such as transfers or price differentiation, may be necessary to reach international agreements (see [Winkler, Peterson, and Thube, 2021](#), [Peterson and Weitzel, 2016](#), [Roelfs, Gaitan, and Edenhofer, 2021](#), and [IMF, 2022](#)). Conditions for optimal transfers are discussed in [Hillebrand and Hillebrand \(2019\)](#). Our analysis confirms results (i.) and (ii.) in the long run. However, we can show that the transition towards a less carbon-intensive economy is quite costly. This is especially true for income-poor regions (because consumption losses weigh especially heavily for households there). Aggregate welfare may fall as a result when taking into account the transition. Transfers from relatively rich to poor regions and carbon price discrimination can change this. The value of international coordination is also confirmed in [Pagliari and Ferrari \(2021\)](#). While the latter analyze optimal containment policies in a two-country model (USA and EA) with two stylized sectors (brown and green), we set up a three-region model with a life-cycle structure. First of all, this allows us to study the effect on the (endogenous) equilibrium real interest rate as well as the heterogeneous effects of emissions taxation across different types of households. Moreover, including the rest of the world is necessary to analyze carbon pricing schemes from a global perspective. Indeed, it turns out that especially low income countries may have

³Note that our border adjustment mechanism abstracts from possible incentives for foreign producers to invest in cleaner production technology in order to avoid border adjustment taxation or other technological spillovers (see also [Yu et al., 2020](#)). Such a mechanism, which should be addressed in future research, may generate more positive effects of border adjustment.

no incentive to introduce a carbon pricing scheme due to forgone positive trade spillovers and lower initial consumption levels.

To put our simulation results into perspective, we should take notice of a debate that started recently. Essentially, the climate module of our model is DICE-like (see Nordhaus, 2013, 2018). However, as argued by Dietz and Venmans (2019), Mattauch, Matthews, Millar, Rezai, Solomon, and Venmans (2020) and Dietz, van der Ploeg, Rezai, and Venmans (2021), such models may overestimate the delay between emissions and climate change, primarily because they ignore the saturation of carbon sinks. As a result, a decrease in emissions could almost immediately avoid damage. This would have substantial consequences for the analysis presented below. If this was true, the economic costs of emissions reduction would be significantly lower (if not zero) and benefits would start materializing much earlier. Incentives to participate in pricing carbon would be higher due to immediate (and potentially large) productivity gains outweighing the foregone trade spillovers. Ultimately, natural scientists must answer the question how fast lower carbon emissions improve the environment. However, the answer is important for economists because it determines optimal policies regarding, for example, the path of carbon prices or interregional transfers.

3 The model

In this section, we build a three-region environmental general equilibrium life-cycle model. Regions are indexed by $i = a, b, c$. Each region i produces differentiated goods that are tradeable across countries. They are purchased by households according to their preferences in their consumption and investment baskets. The life-cycle structure implies that net foreign asset positions and the world interest rate are determined endogenously, also in the steady state. GHG emissions are a by-product of production and (may) affect production in all regions negatively. Regions differ in size, their demographic structure, emissions intensities, abatement costs and environmental damage, as well as in other structural parameters.

3.1 Demographic structure

In the spirit of Gertler (1999), population in each region i consists of two distinct groups: workers (superscript w), $N_t^{w,i}$, and retirees (superscript r), $N_t^{r,i}$. Each individual is born as a new worker. New workers are born at rate $(1 - \omega^i)$. Conditional on being a worker in the current period, an individual faces a probability ω^i of remaining a worker in the next period. We assume no population growth in our baseline simulations, i.e. $N_{t+1}^{w,i} = N_t^{w,i} = N^{w,i} \forall t$. This is because, in the analysis that follows, we only focus on policy changes, not on changes in the demographic structure.⁴ Retirees face a survival probability γ^i . In order to facilitate aggregation within each group, we assume that the probabilities of retirement and death are independent of individual age (Blanchard, 1985; Weil, 1989). Consequently, the laws of motion for workers and retirees in region i are

$$N_{t+1}^{w,i} = (1 - \omega^i) N_t^{w,i} + \omega^i N_t^{w,i} = N^{w,i}$$

⁴A corresponding extension is possible (see, for example, Schön and Stähler, 2020).

and

$$N_{t+1}^{r,i} = (1 - \omega^i) N_t^{w,i} + \gamma^i N_t^{r,i} \Rightarrow N^{r,i} = (1 - \omega^i) / (1 - \gamma^i) \cdot N^{w,i}.$$

The old-age dependency ratio is, hence, given by $\Psi^i = N^{r,i}/N^{w,i} = (1 - \omega^i)/(1 - \gamma^i)$, while the relative size of the labor force between region i and j is defined as $rs_t^{i,j} = N^{w,i}/N^{w,j}$.

3.2 Decision problem of retirees and workers

Let $V_t^{z,i}$ denote the value function associated with the life-cycle states $z = \{w, r\}$ in region i . Households maximize their expected recursive life-time utility function from consumption, $c_t^{z,i}$, and leisure, $(1 - l_t^{z,i})$:

$$\begin{aligned} V_t^{z,i} &= \left\{ \left[(c_t^{z,i})^{v_c^i} (1 - l_t^{z,i})^{v_l^i} \right]^\rho + \beta^z E_t [V_{t+1}^i | z]^\rho \right\}^{\frac{1}{\rho}}, \\ \beta^w &= \beta, \quad \beta^r = \beta \cdot \gamma^i, \\ E_t [V_{t+1}^i | w] &= \omega^i \cdot V_{t+1}^{w,i} + (1 - \omega^i) \cdot V_{t+1}^{r,i}, \\ E_t [V_{t+1}^i | r] &= V_{t+1}^{r,i}, \end{aligned}$$

where ρ determines the intertemporal elasticity of substitution and v_c^i and v_l^i , with $v_c^i + v_l^i = 1$, define the marginal rate of transformation between consumption and leisure. The conditional expectations operator E_t depends on the states $z = \{w, r\}$, and workers and retirees have different discount factors to account for the probability of death.

The model is analytically tractable because the transition probabilities from working age to retirement and, then, to death are independent of age, as discussed by [Gertler \(1999\)](#), [Ferrero \(2010\)](#) and [Carvalho et al. \(2016\)](#). To avoid a strong precautionary saving motive for young agents, which is at odds with data, however, this requires assuming a utility function similar to [Epstein and Zin \(1989\)](#). As discussed in the literature, separating the coefficient of intertemporal substitution, $\sigma = 1/(1 - \rho)$, from risk aversion, as done in the utility function, helps to reproduce reasonable responses of consumption and savings to interest rate variations.

Retirees: In period t , the representative retiree, indexed by j , maximizes

$$V_t^{r,i,j} = \left\{ \left[(c_t^{r,i,j})^{v_c^i} (1 - l_t^{r,i,j})^{v_l^i} \right]^\rho + \beta \gamma^i (V_{t+1}^{r,i,j})^\rho \right\}^{\frac{1}{\rho}},$$

with respect to real consumption, $c_t^{r,i,j}$, labor supply $l_t^{r,i,j}$, and real assets $a_t^{r,i,j}$, subject to the real flow budget constraint

$$(1 + \tau_t^{b,i}) \cdot c_t^{r,i,j} + a_t^{r,i,j} = \frac{1 + r_{t-1}}{\gamma^i} \cdot a_{t-1}^{r,i,j} + \xi^i \cdot w_t^i \cdot l_t^{r,i,j} + e_t^{i,j}.$$

The retiree receives real old-age benefits $e_t^{i,j}$ and faces an effective real wage rate $\xi^i w_t^i$ when working. The parameter $\xi^i \in (0, 1)$ captures the productivity difference between the old and the young. As is standard in the literature, we will choose ξ^i such that $l_t^{r,i,j}$ is close to zero (i.e. little to no work after retirement).

Defining r_t as the real world interest rate that clears international capital markets (therefore the lack of the superscript), the real return on asset investments for a retiree who

has survived from period $t-1$ to t is $(1+r_{t-1})/\gamma^i$. This implies that, for retirees, a perfectly competitive mutual fund industry invests the proceeds and pays back a premium over the market return to compensate for the probability of death (see [Yaari, 1965](#); [Blanchard, 1985](#)).⁵ $\tau_t^{b,i}$ is the border adjustment mechanism-implied tax rate on consumption in region i . We will discuss it in more detail below.

The first-order condition with respect to labor is given by

$$(1 - l_t^{r,i,j}) = \frac{v_l^i}{v_c^i} \cdot \frac{(1 + \tau_t^{b,i}) \cdot c_t^{r,i,j}}{\xi^i w_t^i},$$

while the consumption-Euler equation of the retiree's maximization problem turns out to be

$$c_{t+1}^{r,i,j} = \left[\left(\frac{w_t^i}{w_{t+1}^i} \right)^{v_l^i \rho} \cdot \beta \frac{1 + \tau_t^{b,i}}{1 + \tau_{t+1}^{b,i}} (1 + r_t) \right]^\sigma c_t^{r,i,j},$$

where $\sigma = 1/(1 - \rho)$. If we define $\zeta_t^{r,i}$ as the marginal propensity of retirees to consume out of wealth in region i , we can derive the consumption function and the law of motion of the retiree's marginal propensity to consume as

$$(1 + \tau_t^{b,i}) \cdot c_t^{r,i,j} = \zeta_t^{r,i} \cdot \left(\frac{1 + r_{t-1}}{\gamma^i} \cdot a_{t-1}^{r,i,j} + h_t^{r,i,j} \right),$$

and

$$\zeta_t^{r,i} = 1 - \left[\beta \cdot \frac{1 + \tau_t^{b,i}}{1 + \tau_{t+1}^{b,i}} \cdot \left(\frac{w_t^i}{w_{t+1}^i} \right)^{v_l^i \rho} \right]^\sigma \cdot [(1 + r_t)]^{\sigma-1} \cdot \gamma^i \cdot \frac{\zeta_t^{r,i}}{\zeta_{t+1}^{r,i}}, \quad (1)$$

where

$$h_t^{r,i,j} = \xi^i \cdot w_t^i \cdot l_t^{r,i,j} + e_t^{i,j} + \frac{\gamma^i}{1 + r_t} h_{t+1}^{r,i,j}$$

is the recursive law of motion of human capital (i.e. life-time income from wages and pension benefits at time t). These expressions allow us to derive an analytical expression for the value function $V_t^{r,i,j}$, which will be a key input for the decision problem of the representative worker (see technical appendix in [Schön and Stähler, 2020](#), for the formal derivation).

Workers: In period t , the representative worker, again indexed by j , maximizes

$$V_t^{w,i,j} = \left\{ \left[(c_t^{w,i,j})^{v_c^i} (1 - l_t^{w,i,j})^{v_l^i} \right]^\rho + \beta (\omega^i V_{t+1}^{w,i,j} + (1 - \omega^i) V_{t+1}^{r,i,j})^\rho \right\}^{\frac{1}{\rho}},$$

⁵In our model, national funds of region i only operate in their home region. This prevents equalization of returns in the insurance market, which would otherwise dampen the effects of life expectancy differences across regions significantly (see [Ferrero, 2010](#)).

with respect to real consumption, $c_t^{w,i,j}$, labor supply $l_t^{w,i,j}$, and real assets, $a_t^{w,i,j}$, subject to the flow budget constraint

$$(1 + \tau_t^{b,i}) \cdot c_t^{w,i,j} + a_t^{w,i,j} = (1 + r_{t-1}) \cdot a_{t-1}^{w,i,j} + w_t^i \cdot l_t^{w,i,j} + f_t^{i,j} - \tau_t^{i,j}.$$

In contrast to the retiree, the worker has a different discount factor (because she cannot die) and takes into account the fact that he may stay a worker or become a retiree next period. Furthermore, the return on assets is different from retirees as there is no mutual fund operated for workers (i.e. gross interest on asset investments are no longer divided by the probability of death), and workers do not receive pension benefits but obtain firm profits, $f_t^{i,j}$, and have to pay lump-sum taxes, $\tau_t^{i,j}$.⁶ They also receive the full wage w_t^i . The solution of the worker's decision problem is:

$$\omega^i c_{t+1}^{w,i,j} + (1 - \omega^i) \left(\frac{\zeta_{t+1}^{r,i}}{\zeta_{t+1}^{w,i}} \right)^{\frac{\sigma}{1-\sigma}} \left(\frac{1}{\xi^i} \right)^{v_i^i} c_{t+1}^{r,i,j} = \left[\beta \frac{1 + \tau_t^{b,i}}{1 + \tau_{t+1}^{b,i}} (1 + r_t) \Omega_{t+1}^i \cdot \left(\frac{w_t^i}{w_{t+1}^i} \right)^{v_i^i \rho} \right]^\sigma c_t^{w,i,j},$$

as the consumption-Euler equation, with

$$\Omega_t^i = \omega^i + (1 - \omega^i) \left(\zeta_t^{r,i} / \zeta_t^{w,i} \right)^{1/(1-\sigma)} \left(1 / \xi^i \right)^{v_i^i}, \quad (2)$$

and the first-order condition with respect to leisure:

$$(1 - l_t^{w,i,j}) = \frac{v_l^i}{v_c^i} \cdot \frac{(1 + \tau_t^{b,i}) \cdot c_t^{w,i,j}}{w_t^i}.$$

Here, $\zeta_t^{w,i}$ is the marginal propensity of workers to consume out of wealth. We can show that retirees have a higher marginal propensity to consume than workers, $\zeta_t^{r,i} / \zeta_t^{w,i} > 1 \forall t$. This implies $\Omega_t^i > 1 \forall t$ which, in turn, indicates that workers discount future income streams at an effective rate $(1 + r_t) \Omega_{t+1}^i > (1 + r_t)$. It makes the future less valuable relative to a conventional New Keynesian setting with infinite lives and reflects the expected finiteness of their life (see, among others, [Gertler, 1999](#), and [Kara and von Thadden, 2016](#), for a discussion). In more detail, the worker's consumption function and the law of motion of the worker's marginal propensity to consume are

$$(1 + \tau_t^{b,i}) \cdot c_t^{w,i,j} = \zeta_t^{w,i} \cdot ((1 + r_{t-1}) \cdot a_t^{w,i,j} + h_t^{w,i,j}),$$

and

$$\zeta_t^{w,i} = 1 - \left[\beta \cdot \frac{1 + \tau_t^{b,i}}{1 + \tau_{t+1}^{b,i}} \cdot \left(\frac{w_t^i}{w_{t+1}^i} \right)^{v_i^i \rho} \right]^\sigma \cdot [(1 + r_t) \cdot \Omega_{t+1}^i]^{\sigma-1} \frac{\zeta_t^{w,i}}{\zeta_{t+1}^{w,i}}, \quad (3)$$

⁶If we allowed retirees to also own firms, this would not affect our results much, as discussed by [Fujiwara and Teranishi \(2008\)](#). However, making them pay lump-sum taxes may have effects, as we will discuss in Section ??.

where

$$h_t^{w,i,j} = w_t^i \cdot l_t^{w,i,j} + f_t^{i,j} - \tau_t^{i,j} + \frac{\omega^i}{[1+r_t]\Omega_{t+1}^i} h_{t+1}^{w,i,j} + \left(1 - \frac{\omega_t}{\Omega_{t+1}^i}\right) \frac{h_{t+1}^{r,i,j}}{1+r_t}.$$

3.3 Aggregation of households' decisions

To characterize aggregate variables, we drop the index j and carry on using the previous notation. Given the numbers of retirees and workers in each period t , $N_t^{r,i}$ and $N_t^{w,i}$, the aggregate labor supply schedule can be derived from the individual ones as

$$l_t^{w,i} = N_t^{w,i} l_t^{w,i,j} = N_t^{w,i} - \frac{v_l^i}{v_c^i} \cdot \frac{(1 + \tau_t^{b,i}) \cdot c_t^{w,i}}{w_t^i}, \quad (4)$$

$$l_t^{r,i} = N_t^{r,i} l_t^{r,i,j} = N_t^{r,i} - \frac{v_l^i}{v_c^i} \cdot \frac{(1 + \tau_t^{b,i}) \cdot c_t^{r,i}}{\xi^i w_t^i}, \quad (5)$$

$$l_t^i = l_t^{w,i} + l_t^{r,i}, \quad (6)$$

where $c_t^{z,i} = N_t^{z,i} c_t^{z,i,j}$ with $z = \{w, r\}$ denotes aggregate consumption of workers and retirees, respectively. Using the respective equations for retirees and workers, these are given by

$$(1 + \tau_t^{b,i}) \cdot c_t^{w,i} = \zeta_t^{w,i} [(1 + r_{t-1})(1 - \lambda_{t-1}^i) a_{t-1}^i + h_t^{w,i}], \quad (7)$$

$$(1 + \tau_t^{b,i}) \cdot c_t^{r,i} = \zeta_t^{r,i} [(1 + r_{t-1}) \lambda_{t-1}^i a_{t-1}^i + h_t^{r,i}]. \quad (8)$$

We define aggregate consumption as $c_t^i = c_t^{w,i} + c_t^{r,i}$. In equations (7) and (8), we have used $a_t^i = a_t^{w,i} + a_t^{r,i}$ and the definition $\lambda_t^i = a_t^{r,i}/a_t^i$, which is the share of (financial) wealth held by retirees over total wealth.

To determine the aggregate stocks of human capital, $h_t^{r,i} = N_t^{r,i} h_t^{r,i,j}$ and $h_t^{w,i} = N_t^{w,i} h_t^{w,i,j}$, we have to take into account population dynamics described in section 3.1. This yields

$$h_t^{r,i} = \xi^i \cdot w_t^i \cdot l_t^{r,i} + e_t^i + \frac{\gamma^i}{(1+r_t)} h_{t+1}^{r,i}, \quad (9)$$

$$h_t^{w,i} = w_t^i \cdot l_t^{w,i} + f_t^i - \tau_t^i + \frac{\omega^i \cdot h_{t+1}^{w,i,j}}{(1+r_t)\Omega_{t+1}^i} - \left(1 - \frac{\omega^i}{\Omega_{t+1}^i}\right) \frac{h_{t+1}^{r,i}}{(1+r_t)\Psi^i}, \quad (10)$$

where $e_t^i = N_t^{r,i} e_t^{i,j}$ and $f_t^i = N_t^{w,i} f_t^{i,j}$. The absence of γ^i in equation (8) relative to individual human wealth for retirees reflects the competitive insurance/annuity market. As discussed in Blanchard (1985), the probability of death is relevant for the individual household j , but it does not affect the aggregate consumption of retirees.

It remains to characterize the law of motion for λ_t^i , i.e. the fraction of wealth over total wealth held by retirees. In doing so, we realize that the fraction of total wealth held by the working-age population evolves according to $(1 - \lambda_t^i) a_t^i = \omega^i [(1 - \lambda_{t-1}^i)(1 + r_{t-1}) a_{t-1}^i + w_t^i \cdot l_t^{w,i} + f_t^i - \tau_t^i - (1 + \tau_t^{b,i}) \cdot c_t^{w,i}]$. It increases by the savings of those workers who remain workers in the next period. Analogously, the fraction of total wealth held by

retirees increases by the savings of those retirees who do not die (bearing in mind that savings of those who die are redistributed through the competitive annuity market) plus the savings of those workers who become retirees: $\lambda_t^i a_t^i = \lambda_{t-1}^i (1 + r_{t-1}) a_{t-1}^i + \xi^i \cdot w_t^i \cdot l_t^{r,i} + e_t^i - (1 + \tau_t^{b,i}) \cdot c_t^{r,i} + (1 - \omega^i) \left[(1 - \lambda_{t-1}^i) (1 + r_{t-1}) a_{t-1}^i + w_t^i \cdot l_t^{w,i} + f_t^i - \tau_t^i - (1 + \tau_t^{b,i}) \cdot c_t^{w,i} \right]$. Combining these expressions and using equations (7) and (8), we get

$$\lambda_t^i a_t^i = \omega^i \left\{ (1 - \zeta_t^{r,i}) \left[(1 + r_{t-1}) \lambda_{t-1}^i a_{t-1}^i + h_t^{r,i} \right] - (h_t^{r,i} - \xi^i w_t^i l_t^{r,i} - e_t^i) \right\} + (1 - \omega^i) a_t^i. \quad (11)$$

3.4 Production

The representative producer in region i operates with production technology

$$y_t^i = [1 - D_i(M_t)] \cdot \varepsilon_i \cdot [l_t^i]^{\alpha^i} \cdot [k_{t-1}^i]^{1-\alpha^i}.$$

Here, α^i is the Cobb-Douglas share of labor in production and l_t^i and k_{t-1}^i are the inputs of labor and capital in production. ε_i is total factor productivity. $D_i(M_t)$ is a region-specific damage function that positively depends on the world emission stock M_t . As in [Heutel \(2012\)](#), we assume that emission-induced damage is given by $D_i(M_t) = \gamma_{0,i} + \gamma_{1,i} \cdot M_t + \gamma_{2,i} \cdot M_t^2$ (alternative damage functions are discussed in the appendix). It is taken as given from the firm's perspective. The firm's cost minimization problem with respect to labor and capital yields the following capital-to-labor ratio

$$\frac{l_t^i}{k_{t-1}^i} = \frac{\alpha^i}{1 - \alpha^i} \cdot \frac{r_t^{k,i}}{w_t^i}. \quad (12)$$

Hence, real marginal costs are given by

$$mc_t^i = \left(\frac{w_t^i}{\alpha^i} \right)^{\alpha^i} \cdot \left(\frac{r_t^{k,i}}{1 - \alpha^i} \right)^{1-\alpha^i}. \quad (13)$$

Following [Annicchiarico and Di Dio \(2015\)](#), emissions are a by-product of production taking the form $Z_{i,t} = \kappa_i \cdot (1 - U_{i,t}) \cdot y_{i,t}$, where emissions intensity $\kappa_i \in [0, \infty)$. Abatement $U_{i,t} \in [0, 1)$ is costly as given by the cost function $C(U_{i,t}) = \phi_{1,i} \cdot U_{i,t}^{\phi_{2,i}} \cdot y_{i,t}$, where $\phi_{1,i} > 0$ and $\phi_{2,i} > 1$ (see [Annicchiarico and Di Dio, 2015](#), [Annicchiarico et al., 2018](#), and [Annicchiarico and Diluiso, 2019](#), for a discussion). If emissions are priced at a (potentially region-specific) price $P_{i,t}^{em}$, abatement is determined by

$$\phi_{1,i} \cdot \phi_{2,i} \cdot U_{i,t}^{\phi_{2,i}-1} = P_{i,t}^{em} \cdot \left(1 - \sum_{i \neq j} \tilde{I}_t^{i,j} \cdot \frac{Exp_t^{j,i}}{y_t^i} \right) \cdot \kappa_i. \quad (14)$$

For $P_{i,t}^{em} = 0$, it holds that $U_{i,t} = 0$ because firms do not take into account the pollution externality as it is costless from the individual firm perspective. $\tilde{I}_t^{i,j}$ is an indicator function that take the value one if exports from region i to j , $Exp_t^{j,i}$, are subsidized (i.e. whenever there is a border adjustment mechanism with export subsidies) and zero otherwise.

Firms are price setters and may charge a markup $\theta_i^P/(\theta_i^P - 1)$ on their marginal production costs. Under flexible prices, it holds that

$$P_{i,t} = \frac{\theta_i^P}{\theta_i^P - 1} \cdot \tilde{m}c_{i,t}, \quad (15)$$

which is the standard pricing equations with one exception: For factor demand, the relevant marginal costs are $mc_{i,t}$, whereas they are

$$\tilde{m}c_{i,t} = mc_{i,t} + \phi_{1,i} \cdot U_{i,t}^{\phi_{2,i}} + P_{i,t}^{em} \cdot \left(1 - \sum_{i \neq j} \tilde{I}_t^{i,j} \cdot \frac{Exp_t^{j,i}}{y_t^i} \right) \cdot \kappa_i \cdot (1 - U_{i,t}) \quad (16)$$

in the pricing equation. Marginal costs relevant for pricing also include abatement costs and emission taxes. They only equal marginal factor input costs whenever the price per emission is zero (and, thus, firms ignore these “extra costs”; see [Annicchiarico and Di Dio, 2015](#), for details). Also note that, as $\theta_i^P \rightarrow \infty$, $P_{i,t} = \tilde{m}c_{i,t}$.

3.5 Investment funds and financial market clearing

Following [Fujiwara and Teranishi \(2008\)](#), an investment fund in each region i collects deposits from households, a_t^i , and invests these into physical capital, domestic government bonds and international assets. Government bonds and international assets are assumed to pay an interest $i_t^{G,i}$ and $i_t^{d,i}$ next period, respectively. The financial investor pays the households a real interest r_t on the deposited assets. The investment fund hence aims to maximize its profits

$$f_t^{fund,i} = r_{t+1}^{k,i} \cdot k_t^i + (1 + i_t^{G,i}) \cdot b_t^i + (1 + i_t^{d,i}) \cdot d_t^i - (1 + \tau_t^{b,i}) inv_t^i + a_{t+1}^i - (1 + r_t) a_t^i,$$

where b_t^i and d_t^i are real government bonds and net foreign assets, respectively, and $r_{t+1}^{k,i}$ is the ex-ante uncertain rate of return on capital. Physical capital investments are denoted by inv_t^i (and may potentially be also subject to the border adjustment tax). Capital follows the conventional law of motion:

$$k_{t+1}^i = (1 - \delta^i) k_t^i + inv_t^i, \quad (17)$$

where δ^i denotes capital depreciation. This implies that the conventional no-arbitrage condition must hold:

$$(1 + r_t) = (1 + i_t^{G,i}) = (1 + i_t^{d,i}) = \frac{r_{t+1}^{k,i} + (1 - \delta^i)(1 + \tau_t^{b,i})}{1 + \tau_t^{b,i}}. \quad (18)$$

Financial markets must clear, which implies that

$$a_t^i = k_t^i + b_t^i + d_t^i \quad (19)$$

and, because international assets traded between regions are in zero net supply, $P_t^a d_t^a + P_t^b d_t^b + P_t^c d_t^c = 0$, where P_t^i is region i 's consumer price index. We will discuss this in more detail in the international linkages section below.

3.6 Fiscal policy

The government's budget constraint in region i in CPI-deflated real terms is given by

$$b_t^i + \tau_t^i + P_{i,t}^{em} \cdot \left(1 - \sum_{i \neq j} \tilde{I}_t^{i,j} \cdot \frac{Exp_t^{j,i}}{y_t^i} \right) \cdot Z_{i,t} + \tau_t^{b,i} \cdot c_t^i = (1 + r_{t-1}) b_{t-1}^i + \frac{P_t^{i,i}}{P_t^i} \cdot g_t^i + e_t^i, \quad (20)$$

where use has been made of equation (18). Hence, the government must finance real government expenditures, g_t^i , aggregate real pension benefits, e_t^i , and interest payments on outstanding debt, $(1 + r_{t-1}) b_{t-1}^i$, by lump-sum taxes, τ_t^i , income from carbon pricing net of export subsidies, $P_{i,t}^{em} \cdot \left(1 - \sum_{i \neq j} \tilde{I}_t^{i,j} \cdot \frac{Exp_t^{j,i}}{y_t^i} \right) \cdot Z_{i,t}$, border adjustment taxation-implied consumption taxes, $\tau_t^{b,i} \cdot c_t^i$, and issuance of new debt, b_t^i .

We assume full home bias in government consumption, which requires the price correction $\frac{P_t^{i,i}}{P_t^i}$, where $P_t^{i,i}$ (P_t^i) is the producer (consumer) price index in region i . The assumption is based on the observation that the import share in government consumption is, in general, significantly lower than in private consumption or investment (see Schön and Stähler, 2020, for a discussion). The path of aggregate real pension benefits is determined by the replacement rate μ_t^i between individual benefits and real wages, that is $\mu_t^i = e_t^{i,j} / w_t^i \Rightarrow e_t^i = e_t^{i,j} \cdot N_t^{r,i} = \mu_t^i \cdot w_t^i \cdot N_t^{r,i}$.

3.7 International linkages and market clearing

We assume that households in region i consume goods produced in any of the three regions. The corresponding consumption bundle is given by

$$c_t^i = \left[(\vartheta_a^i)^{1-\eta^i} (c_{a,t}^i)^{\eta^i} + (\vartheta_b^i)^{1-\eta^i} (c_{b,t}^i)^{\eta^i} + (\vartheta_c^i)^{1-\eta^i} (c_{c,t}^i)^{\eta^i} \right]^{\frac{1}{\eta^i}}.$$

Here, $c_{j,t}^i$ denotes goods produced in j and consumed in i and $\eta^i \in (-\infty, 1)$ governs the elasticity of substitution between these goods, which equals $1/(1 - \eta^i)$. As $\eta^i \rightarrow 0$, the function boils down to a Cobb Douglas aggregator. ϑ_j^i denotes the consumption bias of region i -households towards goods produced in j . Hence, ϑ_i^i can be interpreted as the home bias of region i . We assume that $\vartheta_a^i + \vartheta_b^i + \vartheta_c^i = 1$. Given a border adjustment tax rate $\tau_t^{b,i,j}$ potentially different from zero, cost minimization of consumption expenditures, $(1 + \tau_t^{b,i}) P_t^i c_t^i = (1 + \tau_t^{b,i,a}) P_t^{i,a} c_{a,t}^i + (1 + \tau_t^{b,i,b}) P_t^{i,b} c_{b,t}^i + (1 + \tau_t^{b,i,c}) P_t^{i,c} c_{c,t}^i$, implies

$$c_{j,t}^i = \vartheta_j^i \left(\frac{(1 + \tau_t^{b,i,j}) P_t^{i,j}}{(1 + \tau_t^{b,i}) P_t^i} \right)^{-\frac{1}{1-\eta^i}} \cdot c_t^i. \quad (21)$$

The consumer price index (CPI) results to be

$$P_t^i = \left[\vartheta_a^i \cdot (P_t^{a,i})^{-\eta^i/(1-\eta^i)} + \vartheta_b^i \cdot (P_t^{b,i})^{-\eta^i/(1-\eta^i)} + \vartheta_c^i \cdot (P_t^{c,i})^{-\eta^i/(1-\eta^i)} \right]^{-\frac{1-\eta^i}{\eta^i}}, \quad (22)$$

which we can use to derive the border adjustment tax-implied consumption tax rate, see also [Ernst et al. \(2022\)](#). We assume that an analogous aggregator holds for investment goods such that we can derive analogous equations for inv_t^i and $inv_{j,t}^i$. CPI-deflated net exports in region i , nx_t^i , are hence given by

$$nx_t^i = \underbrace{\frac{P_t^{j,i}}{P_t^i} \cdot (c_{i,t}^j + inv_{i,t}^j)}_{=Exp^{j,i}} + \underbrace{\frac{P_t^{\tilde{j},i}}{P_t^i} \cdot (c_{i,t}^{\tilde{j}} + inv_{i,t}^{\tilde{j}})}_{=Exp^{\tilde{j},i}} - \frac{P_t^{i,j}}{P_t^i} \cdot (c_{j,t}^i + inv_{j,t}^i) - \frac{P_t^{i,\tilde{j}}}{P_t^i} \cdot (c_{\tilde{j},t}^i + inv_{\tilde{j},t}^i), \quad (23)$$

where $i, j, \tilde{j} = a, b, c$, and $i \neq j \neq \tilde{j}$. Given net exports and using the no-arbitrage conditions (18), we get that net foreign assets in region i evolve according to

$$d_t^i = (1 + r_{t-1}) d_{t-1}^i + nx_t^i. \quad (24)$$

As stressed above, it must hold that $P_t^a d_t^a + P_t^b d_t^b + P_t^c d_t^c = 0$ because international assets traded between regions are in zero net supply.⁷

Product market clearing implies that whatever is produced in region i must be consumed/used somewhere around the world. Formally, we get

$$y_t^i = (c_{i,t}^i + inv_{i,t}^i) + (c_{i,t}^j + inv_{i,t}^j) + (c_{i,t}^{\tilde{j}} + inv_{i,t}^{\tilde{j}}) + g_t^i + C(U_{i,t}). \quad (25)$$

This completes the model description. At equilibrium, government actions and optimizing decisions of workers, retirees, investment funds and firms must be mutually consistent at the aggregate level, i.e. the above equations hold. We now turn to the model calibration.

4 Calibration

We calibrate our model to annual frequency. Individuals become economically active at the age of 20, stay on average $1/(1 - \omega^i)$ years in the labor force and live on average $1/(1 - \gamma^i)$ years after retirement. We choose ω^i such that, in steady state, individuals retire at the age of 65.

We follow [Ernst et al., 2022](#) by grouping countries according to attitudes towards

⁷At this juncture, it may be noteworthy that the standard (multi-country) representative agent model, in general, entails steady-state indeterminacy and non-stationary dynamics of net foreign assets. To overcome this problem, modelers assume additional frictions in the international financial markets (for example, a risk premium on international asset holdings or some asset adjustment costs) whenever holdings of net foreign assets exceed some exogenously fixed reference level. That introduces a link between consumption and the net foreign asset position and pins down the steady-state level of international financial assets uniquely. However, it does so independent of policy or structural economic changes. An in-depth discussion of this issue can be found in [Schmitt-Grohe and Uribe \(2003\)](#), [Hunt and Rebucci \(2005\)](#), [Lubik \(2007\)](#) and [Benigno \(2009\)](#). As discussed by, for example, [Ghironi \(2008\)](#), [Ghironi et al. \(2008\)](#) and [Di Giorgio and Nistico \(2013\)](#), such an “extra” assumption is not needed in our framework. OLG models entail an elastic asset demand curve resulting from the old-age savings motive discussed in section 3.2.

climate protection. The first region a represents the EU27 countries, Norway, Switzerland and the United Kingdom. We label it “Europe”. The United States (US), Canada, Mexico, Australia, Japan and South Korea form the second region b . We label it “North America (and friends)”. The rationale behind this group is twofold. First, if the US introduces carbon pricing, the concept would probably spill over to other countries with similar economic well-being and environmental preferences. Second, Mexico would presumably follow the US and Canada in order to maintain their free trade agreement. The remaining countries form the third region c , including, for example, China and India. It is labelled “Rest of World”.

Table 1: Initial steady-state population dynamics

Variable/Parameter	Symbol	Value		
		Europe	North America	Rest of world
Old age dependency ratio ^{T}	Ψ	0.35	0.30	0.19
Retirement probabilities	$1 - \omega$	0.0222	0.0222	0.0222
Survival probabilities ^{e}	γ	0.9365	0.9259	0.8947
Relative size Europe/North America ^{T}	$rs^{a,b}$		0.7507	
Relative size Europe/Rest of World ^{T}	$rs^{a,c}$		0.1478	
Relative size North America/Rest of World ^{T}	$rs^{b,c}$		0.1968	

Source: [OECD \(2017\)](#). The superscript T marks targets, e endogenously derived values to meet targets. Parameters without a mark are set exogenously as described in the main text. We omit the country index i for convenience.

According to UN World Population data, relative working-age population size is thus given by $rs^{a,b} = 0.7507$, $rs^{a,c} = 0.1478$ and $rs^{b,c} = 0.1968$. Given ω^i , the survival probabilities γ^i are used to match all region- i old-age dependency ratios of the year 2020, which we take as the base year for our steady-state derivation. They are $\Psi^a = 0.35$, $\Psi^b = 0.30$ and $\Psi^c = 0.19$ (see also [OECD, 2017](#), and the related data appendices). Table 1 summarizes our assumptions determining the demographic situation in the initial steady state.

For the general model calibration, we follow [Ferrero \(2010\)](#) and set standard values from the business cycle literature (see also [Cooley and Prescott, 1995](#)). We target a world asset market-clearing real interest rate of 4%. Together with the demographic structure described above, this implies $\beta = 0.962$. We choose a labor share in production of $2/3$, assume that capital depreciates at an annual rate of 10% and set the elasticity of intertemporal substitution to $\sigma = 0.5$. As discussed in [Ferrero \(2010\)](#), the latter somewhat low value has become standard in this class of models since [Auerbach and Kotlikoff \(1987\)](#). Following [Kara and von Thadden \(2016\)](#), the choice of the relative productivity parameter ξ^i as well as v_c^i ensures that the participation rate of workers is $\bar{l}^{w,i} = 0.7$, and that the one of retirees is $\bar{l}^{r,i} = 0.01$ (remember that $v_l^i = 1 - v_c^i$). We follow [Ernst et al. \(2022\)](#) and target per-capita output levels of 1, 0.985 and 0.3885 in regions a , b and c , respectively. Given environmental damage, which we describe below, this allows us to derive ε_i . The

markup is assumed to be zero in our baseline simulation. Hence, $\theta_i^P \rightarrow \infty$. Structural parameters are summarized in Table 2.

The replacement rate for pension benefits μ^i is set to 0.48 in all regions. Admittedly, it may be somewhat lower in the rest of the world. However, changing it does not make a qualitative difference. This also holds for the government spending-to-GDP ratio, which is set to 0.18, and the debt-to-GDP ratios, set to 60%. These are standard values, summarized in Table 3. The initial carbon price is assumed set at a very low value, $P_i^{em} = 0.01$, reflecting 30 USD of 2020. Border adjustment taxes and subsidies are zero in our initial steady state. In our baseline simulation, we assume a balance budget rule, in which the government budget is closed by lump-sum taxes τ^i .

Table 2: Structural parameters

Variable/Parameter	Symbol	Value		
		Europe	North America	Rest of world
Discount rate	β	0.962	0.962	0.962
Intertemporal elasticity of substitution	σ	0.5	0.5	0.5
Preference for consumption	v_c	0.6397 ^e	0.6382 ^e	0.6436 ^e
Substitution elasticity home/foreign	$1/(1 - \eta)$	1.5	1.5	1.5
Bias for goods produced in Europe	ϑ_a	0.8	0.1	0.0209 ^e
Bias for goods produced in North America	ϑ_b	0.1	0.8	0.0628 ^e
Bias for goods produced in Rest of World	ϑ_c	0.1 ^e	0.1 ^e	0.9161 ^e
Cobb-Douglas share of labor	σ	2/3	2/3	2/3
Productivity parameter	ϵ	1.4505 ^e	1.5136 ^e	1.7304 ^e
Capital depreciation	δ	0.1	0.1	0.1
Relative productivity of retirees	ξ	0.1718 ^e	0.1678 ^e	0.1629 ^e
Demand elasticity to determine markup	θ_p	∞	∞	∞

Source: The superscript T marks targets, e endogenously derived values to meet targets. Parameters without a mark are set exogenously as described in the main text. We omit the country index i for convenience.

As regards international trade, we assume a substitution elasticity between home and foreign goods of 1.5, which is a standard value in the literature. This implies $\eta^i = 0.33$. In the initial steady state, relative prices between all regions equal one. Given this assumption and the other calibration choices made so far, we can then endogenously solve for each region's net foreign asset-to-GDP ratio (see Schön and Stähler, 2020 and Ruppert and Stähler, 2022, for formal details). We set the home bias for goods in a typical European and North American country to 80%, and the import content from each other to 10%. This roughly corresponds to the values set in Ernst et al. (2022) and allows us to derive the biases towards the different regional consumption/investment goods in the rest of the world that meet the net foreign asset positions which we just calculated.

Table 3: Policy parameters

Variable/Parameter	Symbol	Value		
		Europe	North America	Rest of world
Replacement rate for pension benefits ^T	μ	0.48	0.48	0.48
Government spending share ^T	$\bar{g}y$	0.18	0.18	0.18
Debt-to-GDP ratio ^T	ω^b	0.60	0.60	0.60
Carbon price ^T	P^{em}	0.01	0.01	0.01
Lump-sum tax ^e	τ	0.3635	0.3389	0.1112

Source: The superscript T marks targets, e endogenously derived values to meet targets. Parameters without a mark are set exogenously as described in the main text. We omit the country index i for convenience.

To calibrate region-specific CO2 emissions per unit of output κ_i , we follow [Ernst et al. \(2022\)](#) and use environmental accounts provided by the European Commission that are consistent with WIOD (see [Corsatea, Lindner, Arto, Roman, Rueda-Cantuche, Afonso, Amores, Neuwahl, et al., 2019](#)). Information on emissions is available from 2000-2016. However, we are restricted to take values from 2014, since the WIOD series end in this period and carbon intensities are approximated by dividing emissions by gross output. Since we can only observe emissions after abatement in the data, we match $(1 - U_{i,t})\kappa_i$ with the 2014 values in steady state as is done by [Hinterlang et al. \(2022\)](#). We assume a linear decay rate for the stock of pollution of $1 - \rho^{EM} = 0.9916264$ following [Heutel \(2012\)](#) and [Annicchiarico and Di Dio \(2015\)](#), whose values are given in quarterly frequency. Following the recent E-DSGE literature, the parameters of the abatement cost function are $\phi_{1,i} = 0.185$ and $\phi_{2,i} = 2.8 \forall i$ as in [Nordhaus \(2008\)](#) and [Annicchiarico and Di Dio \(2015\)](#). A critical discussion about different abatement cost functions and their parameterizations can be found in [Cline \(2011\)](#).

Our parametrization for the damage function follows [Nordhaus \(2007\)](#) and accounts for the fact that the economic impact of climate change differs between regions. More specifically, we translate the emission stocks into temperature increases and use the region-specific total damage estimates at 2.5°C warming. The targeted steady-state damage is 1.94%, 1.56% and 4.17% in regions a , b and c , respectively. The way we translate all this into our damage function follows [Barrage \(2020\)](#). We assume that a 10% increase in the emissions stock doubles damage roughly following [Kalkuhl and Wenz \(2020\)](#). This is also in line with [Ernst et al. \(2022\)](#). It should be noted, however, that uncertainty regarding economic damage of emissions is high (see [Gillingham, Nordhaus, Anthoff, Blanford, Bosetti, Christensen, McJeon, and Reilly, 2018](#), and [Nordhaus, 2019](#)). For example, damages used by the Network for Greening the Financial System (NGFS; see [NGFS, 2020, 2021a](#)), which are slightly higher than ours, are said to underestimate the full impact from physical climate risks. Furthermore, [Dietz and Venmans \(2019\)](#), [Mattauch et al. \(2020\)](#) and [Dietz et al. \(2021\)](#) claim that standard damage function, as we have here, overestimate the delay between emissions and climate change, primarily because they ignore the saturation of carbon sinks. As a result, a decrease in emissions could

almost immediately avoid damage. All this would have substantial consequences for the analysis presented below. We will therefore present analyses with alternative damage functions in the appendix.

Table 4: Environmental parameters

Variable/Parameter	Symbol	Value		
		Europe	North America	Rest of world
Decay rate of pollution stock	$1 - \rho^{EM}$		0.9916264	
Emissions intensity ^e	κ	0.1937	0.3424	0.6617
Abatement costs (linear parameter)	ϕ_1	0.185	0.185	0.185
Abatement costs (exponential parameter)	ϕ_2	2.8	2.8	2.8
Independent damage term ^e	γ_0	0.3414	0.2745	0.7339
Linear damage term ^e	γ_1	-0.0210	-0.0169	-0.0452
Quadratic damage term ^e	γ_2	3.3233e-4	2.6724e-4	7.1435e-04

Source: The superscript T marks targets, e endogenously derived values to meet targets. Parameters without a mark are set exogenously as described in the main text. We omit the country index i for convenience.

5 Baseline simulations

In this section, we describe the simulation design and the simulation results. We follow [Ernst et al. \(2022\)](#) in simulating carbon pricing, border adjustment and climate clubs. A detailed discussion can be found therein.

Simulation design We distinguish between five policy scenarios. First, we increase carbon pricing in Europe (region a) only. Second, we assume that Europe introduces the carbon price and, at the same time, implements a carbon border adjustment mechanism. Third, we assume that Europe and North America (regions a and b) introduce the same carbon price simultaneously. In a fourth step, we assume that both regions additionally implement a carbon border adjustment mechanism vis-a-vis the rest of the world (region c). Following [Nordhaus \(2015\)](#), we call this a climate club. In a last simulation, we assume that the carbon price is introduced in all regions. We conduct deterministic simulations of the fully non-linear system under perfect foresight in all scenarios. Hence, the price path and mitigation plans are credible and the agents anticipate them.

As regards the carbon price path that we feed into the model, we assume that it is the same across regions for all those that increase carbon pricing. As prices are expressed relative to CPI in our model, price changes fed into our model are scaled by this factor. It is given exogenously and comes from calculations of the Network of Central Banks and Supervisors for Greening the Financial System (NGFS). We assume a steadily increasing price on carbon emissions for those regions that introduce it from now until 2100. After

2100, it will stay constant at the higher level (see Figure 1).⁸ Formally, $P_{i,t}^{em}$ is hence exogenously fed into the model, depicting the price increase suggested by the NGFS for those regions $i = a, b, c$ introducing carbon pricing according to the simulated policy scenario described above.

As regards carbon border adjustment, we assume the following: Regions that introduce carbon border adjustment tax the imported goods with a base tax rate equal to the carbon price $P_{i,t}^{em}$. In addition, they subsidize exports to protect their domestic industries by setting the indicator function to one. The tax rate is formally given by $\tau_t^{b,i,j} = P_{i,t}^{em} \cdot \kappa_j$ as it applies to quantities produced in the foreign regions.⁹

Results The policy variables for the different experiments are shown in Figure 1. The evolution of selected endogenous variables are shown in Figures 2 to 7. The new steady state (relative to the initial one) is depicted in Table 5. To better visualize the differences of the first four policy scenarios, we only show these in the main text. To save space, we put figures including the fifth policy scenario in the appendix.

As Figure 2 reveals, the increase of carbon pricing leads to a reduction in domestic production, at least on impact. The reason is simple: As pollution becomes costly, marginal production costs increase, which augments prices and dampens demand for these goods. The fall in production leads to a reduction in employment and capital input. In addition, the higher price for emissions generates an incentive for firms to invest in mitigation efforts which, in the end, reduces the emissions stock (together with lower production; see Figure 3). A reduced emissions stock decreases economic damage and improves productivity which, in turn, generates positive economic effects. Whether or not these effects compensate the initially negative ones depends on how much the emissions stock is reduced, and on how much this reduces damage. In Figure 2, we see that, for region a , the positive effects do not outweigh the negative ones if only region a augments the carbon price. If, however, region b does so, too, the damage reduction is sufficient for region a to eventually overcompensate the cost increase (in terms of production output). This is given even more if region c also participates in carbon pricing.

The introduction of carbon pricing in some regions only also fosters carbon leakage (see Figure 3). As goods in regions with carbon pricing become more expensive, (not only domestic) demand is tilted towards products produced in regions without carbon pricing, potentially produced with a dirtier production technology. This effect is mitigated somewhat by a carbon border adjustment mechanism, but carbon border adjustment definitely does not seem to be the game changer.

These findings confirm the results of Ernst et al. (2022). However, some interesting

⁸Based on calculations using the integrated assessment model REMIND (see <https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind> for details), the NGFS assumes a continuing price increase from a bit more than 30 USD per tonne of emitted carbon dioxide today to around 400 USD per tonne in 2100. Under this path, the global temperature increase is calculated to remain below 2 degrees Celsius (see NGFS, 2020, 2021a,b,c, for details). Recent discussions among climate scientists suggest that this may not be sufficient.

⁹We could also assume $\tau_t^{b,i,j} = P_{i,t}^{em} \cdot (1 - U_{j,t}) \cdot \kappa_j$, where abatement efforts are taken into account. In this case, the border adjustment tax would be a little smaller relative to the one in the simulations shown below. However, the resulting differences are very small quantitatively, and non-existent qualitatively. As carbon subsidies may not comply with WTO rules, we show in the appendix that there is no large difference to taxing carbon imports only in terms of macroeconomic implications.

differences exist in our framework. The negative impact on consumption is much shorter and less aligned relative to the one emerging in a standard DSGE model. Why is this the case? Higher carbon pricing affects the income of workers and retirees differently in our framework. As we will discuss in the next section, this also depends on how tax proceeds are distributed between workers and retirees. For now, however, we will describe the baseline case in which lump-sum taxes are paid by workers only.

Because employment and wages fall, labor income is reduced. As pensions are tied to wages, pension income falls, too. Retirees therefore face an income loss. At the same time, consumption becomes relatively more expensive. Workers, who benefit from reduced lump-sum taxes, manage to increase their per-period income (see Figure 4).¹⁰ This eventually allows workers to increase consumption, while it falls for retirees (see Figure 5). Because of the permanent consumption loss for retirees, the incentive to save more increases (depicted by the falling marginal propensity to consume for workers *and* retirees in Figure 5). This not only holds for retirees but also for workers, as they will eventually become a retiree, too.

Savings in the region that introduces carbon prices therefore increase, despite the potential aggregate output loss (see Figure 6). Because of the fall in capital needed for production (and constant government debt), these additional savings cannot be invested domestically. Therefore, households save abroad and the net foreign asset position increases (see Figure 7). In regions that introduce/increase carbon pricing, the real exchange rate increases relative to those regions that do not introduce carbon pricing. Exports fall. Imports do so even more because of the domestic income loss. Carbon border adjustment drives down imports further and, thereby, increases the net foreign asset position further.

The stronger fall in exports (relative to not having border adjustment) comes from the fact that consumption in regions with carbon pricing *and* border adjustment increase disproportionately. The reason is that border adjustment taxation makes investment goods from abroad more costly, implying relatively higher rental rates for capital (when only region *a* introduces carbon pricing and border adjustment, capital interest in *a* even increases; see Figure 6).¹¹ Higher consumption further increases domestic prices and, thereby, makes exports less attractive (even though the export subsidy mildly lowers the effective carbon price for firms; see Figure 1).

There is another interesting observation. Although introducing carbon pricing generates positive trade/output spillovers to those regions not introducing it (carbon leakage), this may not be true for consumption (see Figure 2). As net foreign asset holdings in these regions fall, they need to “pay” interest to the regions in which they increase (or receive lower interest payments from abroad). It may be the case that these forgone interest payments outweigh the increase in production, and consumption opportunities fall (see also Ruppert and Stähler, 2022, discussing this mechanism related to fiscal devaluation). This is true for region *b* when region *a* introduces carbon pricing (Figure 2).

In terms of output developments, we confirm the results of Ernst et al. (2022) and find

¹⁰In case firms have positive profits (whenever θ_i^P does not approach infinity), workers forego some of these, but are still able to increase their per-period income.

¹¹Higher savings decrease the world asset market-clearing interest rate (Figure 6), which translates in to falling capital rates *ceteris paribus*. However, due to the tax rate on investment goods from abroad, capital investment becomes less attractive relative to investing in, for example, net foreign assets. Households want to be compensated for this by higher capital rental rates (see equation (18)).

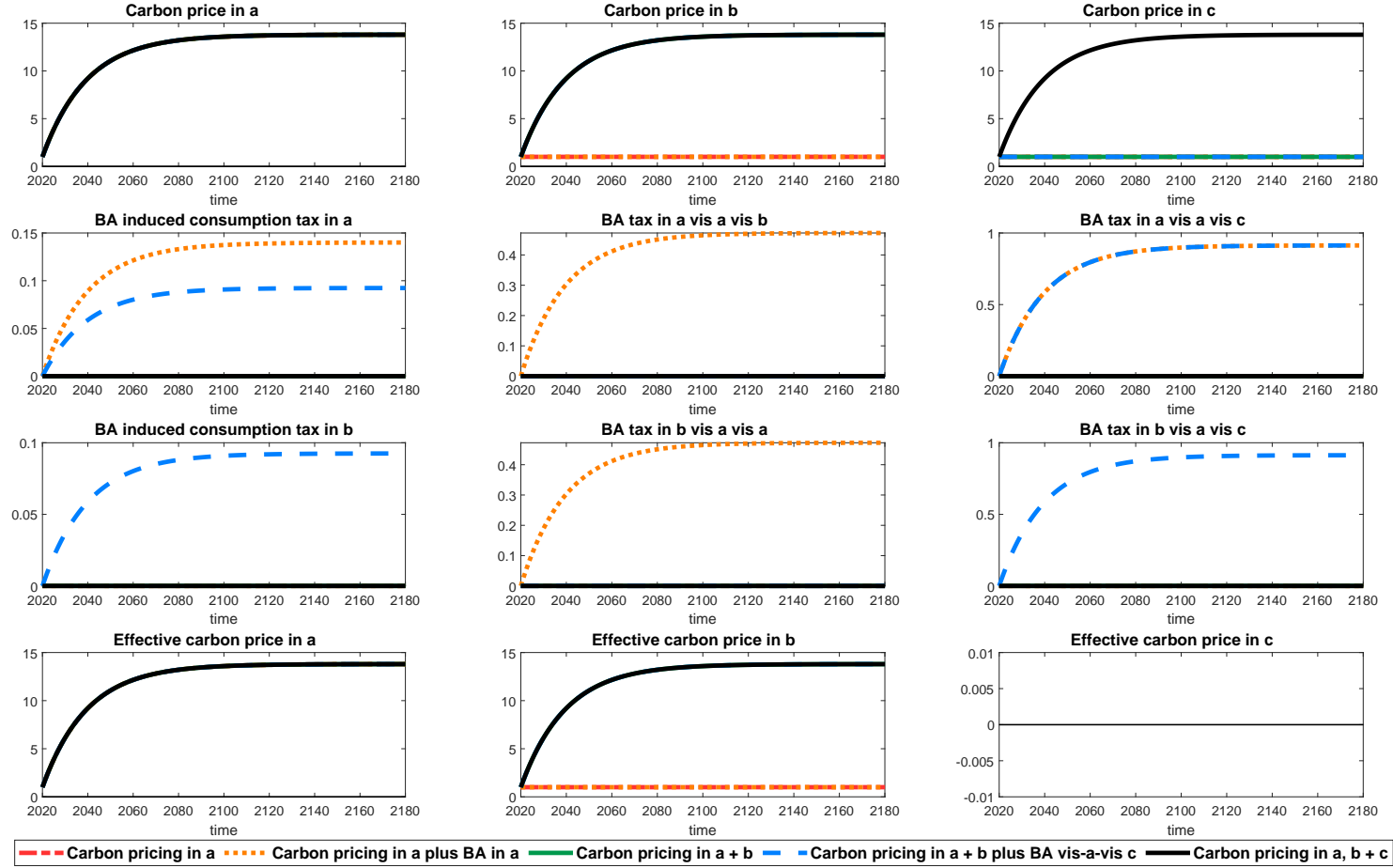
that, if one regions introduces carbon pricing, it benefits from others joining. However, these other regions will face initial output losses. Still, the linkages between output and consumption (utility, which we discuss below) are not as tight as they are in a standard DSGE framework. If all regions introduce carbon pricing, region c experiences aggregate output gains after roughly 10 years already. The reason is, in this situation, the relatively sharp savings increase in region c makes it a capital exporter. The additional interest income compensates for initial output losses. Furthermore, higher world savings drive down the asset market clearing interest rate, which translates into a fall in capital interest in all regions. This fosters production. In the end, the negative macroeconomic impact of carbon pricing is smaller in our framework than it is in a standard DSGE framework, also in terms of aggregate welfare. However, as we will discuss below, retirees alive have to bear some costs due to carbon pricing.

Table 5: Long-run effects

Scenario:	$P_a^{em} \uparrow$	$P_a^{em}, \tau_{a,i}^X \uparrow$	$P_i^{em} \uparrow$ for $i = a, b$	$P_i^{em}, \tau_{i,i}^X \uparrow$ for $i = a, b$	$P_i^{em} \uparrow$ for $i = a, b, c$
Output in a	-0.14	-0.13	0.01	0.06	0.76
Consumption in a	-0.11	0.06	0.13	0.24	1.18
Investment in a	-0.38	-0.33	-0.27	-0.13	0.47
Hours in a	-0.08	-0.09	-0.12	-0.10	-0.20
Wages in a	-0.28	-0.13	-0.11	0.03	0.75
Capital interest in a	0.02	0.11	0.04	0.07	0.07
Emissions in a	-4.30	-4.29	-4.16	-4.11	-3.44
Output in b	0.03	0.05	-0.16	-0.13	0.47
Consumption in b	0.07	-0.01	-0.04	0.03	0.83
Investment in b	0.02	0.03	-0.58	-0.51	0.05
Hours in b	-0.01	0.01	-0.16	-0.14	-0.21
Wages in b	0.05	-0.00	-0.38	-0.30	0.33
Capital interest in b	0.02	-0.03	0.04	0.07	0.07
Emissions in b	0.03	0.05	-5.90	-5.87	-5.31
Output in c	0.12	0.14	0.47	0.49	1.50
Consumption in c	0.17	0.16	0.68	0.63	2.32
Investment in c	0.10	0.15	0.42	0.48	0.60
Hours in c	-0.02	-0.01	-0.07	-0.06	-0.48
Wages in c	0.13	0.14	0.53	0.51	1.16
Capital interest in c	0.02	-0.03	0.04	-0.03	0.07
Emissions in c	0.12	0.14	0.47	0.49	-6.98
World emission stock	-0.30	-0.28	-1.23	-1.20	-6.32

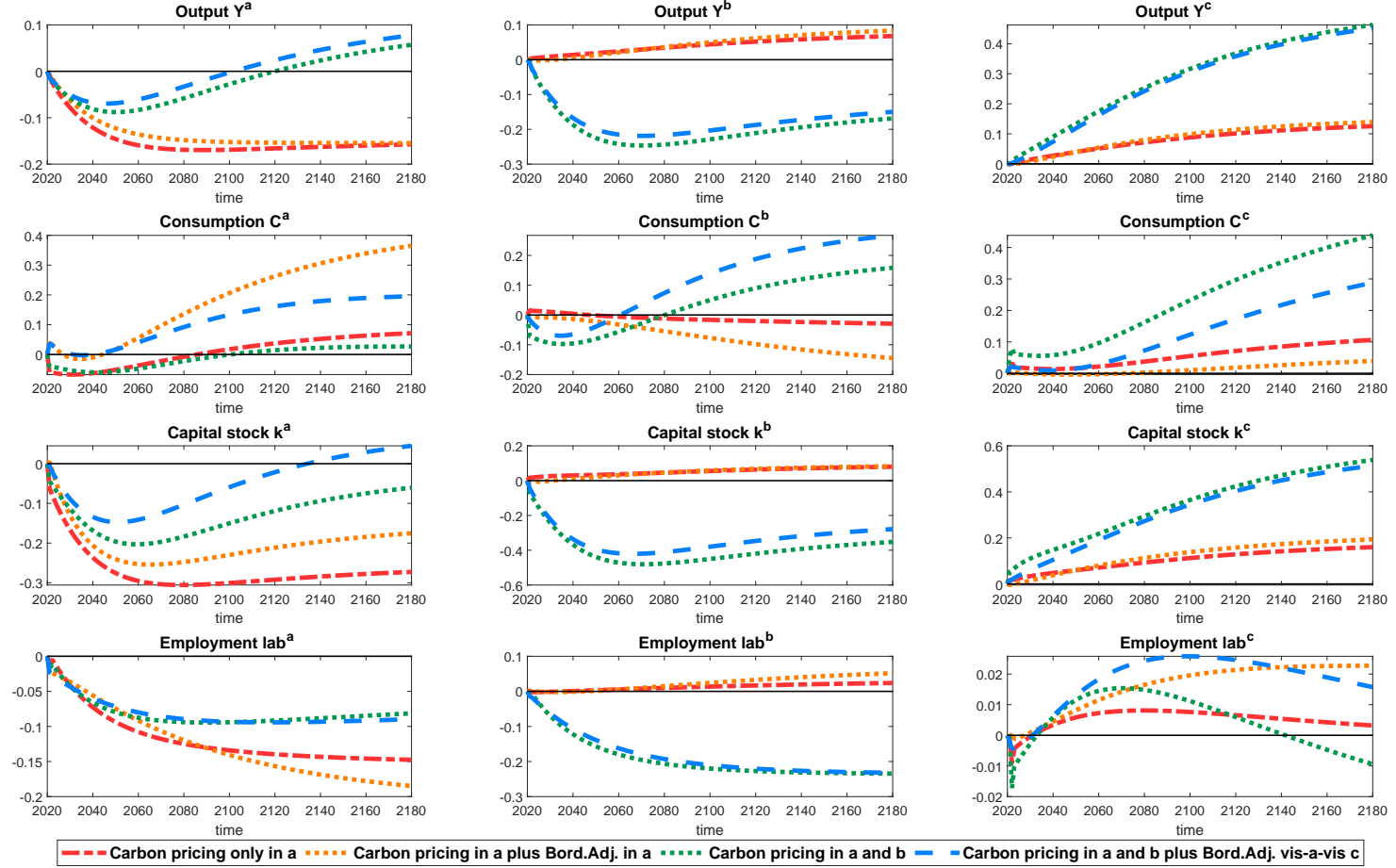
Notes: Table shows long-run effects on selected aggregate macro variables of different carbon pricing scenarios for regions a , b and c as well as for the world emissions stock, in percent deviations from initial steady state.

Figure 1: Policy variables



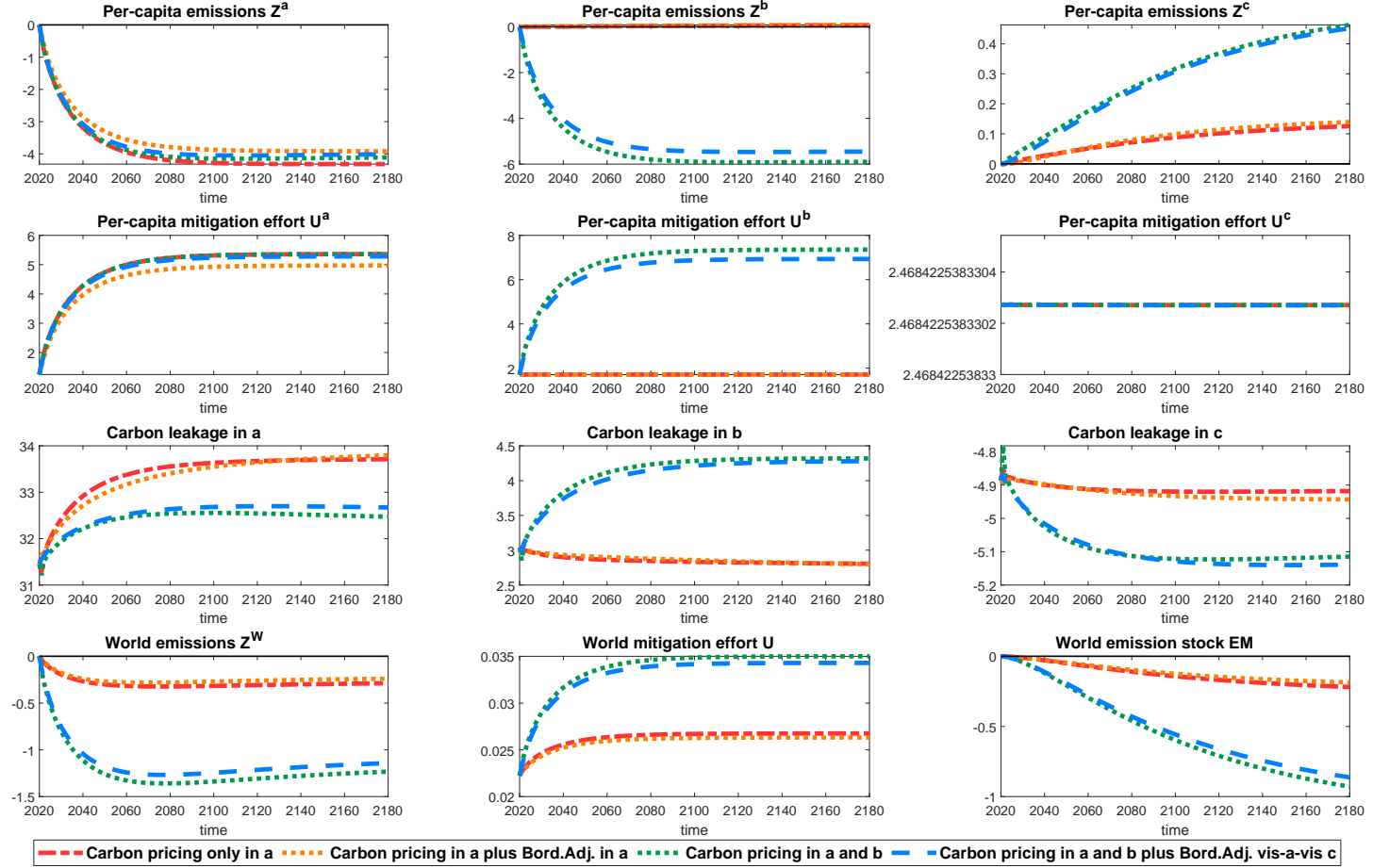
Notes: Figure plots exogenously given policy variables in percentage(point)/relative deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region *a* only. Carbon prices in *a* with border adjustment in *a* is depicted by the orange dotted line, carbon prices in *a* and *b* by the green straight line, and a climate club of regions *a* and *b* by the dashed blue line. The effective carbon price and the border adjustment mechanism-induce consumption tax rate are derived as described in the main text. BA stands for border adjustment.

Figure 2: Implications of carbon pricing for selected key macroeconomic variables



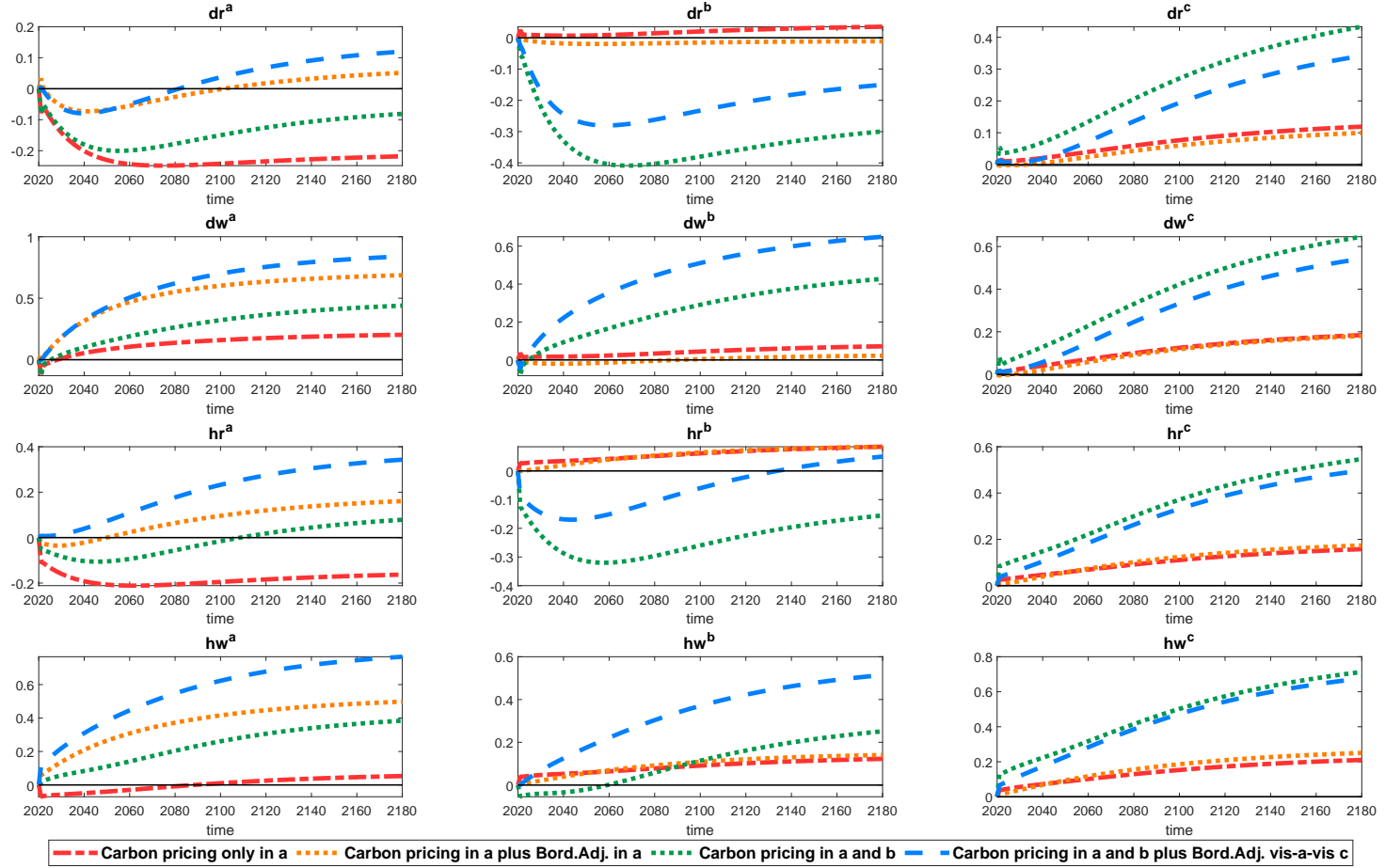
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the orange dotted line, carbon prices in a and b by the green straight line, and a climate club of regions a and b by the dashed blue line.

Figure 3: Implications of carbon pricing for selected key environmental variables



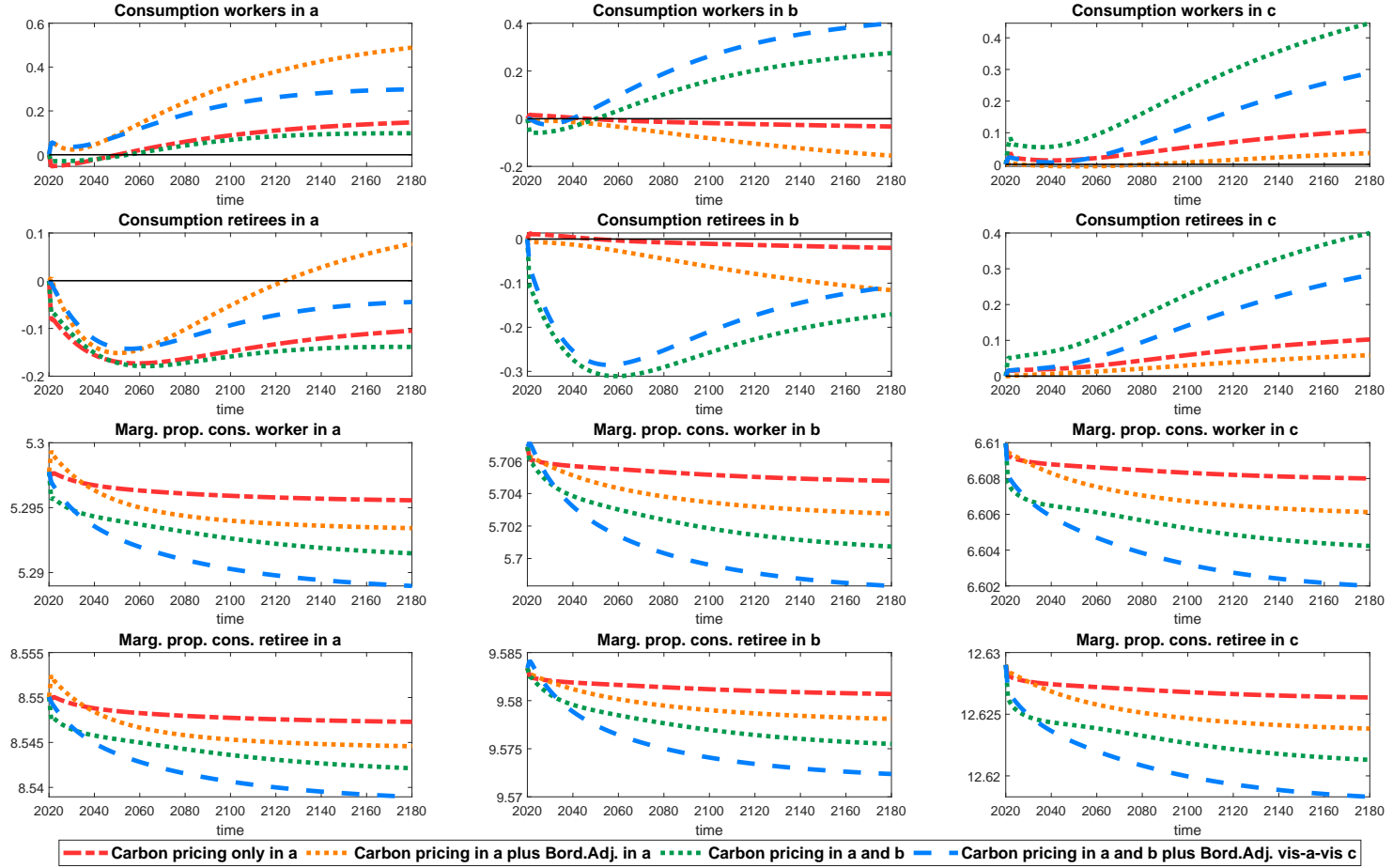
Notes: Figure plots (projected) implications of carbon pricing for selected key environmental variables in percentage(point) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the orange dotted line, carbon prices in a and b by the green straight line, and a climate club of regions a and b by the dashed blue line.

Figure 4: Implications of carbon pricing for income of workers and retirees



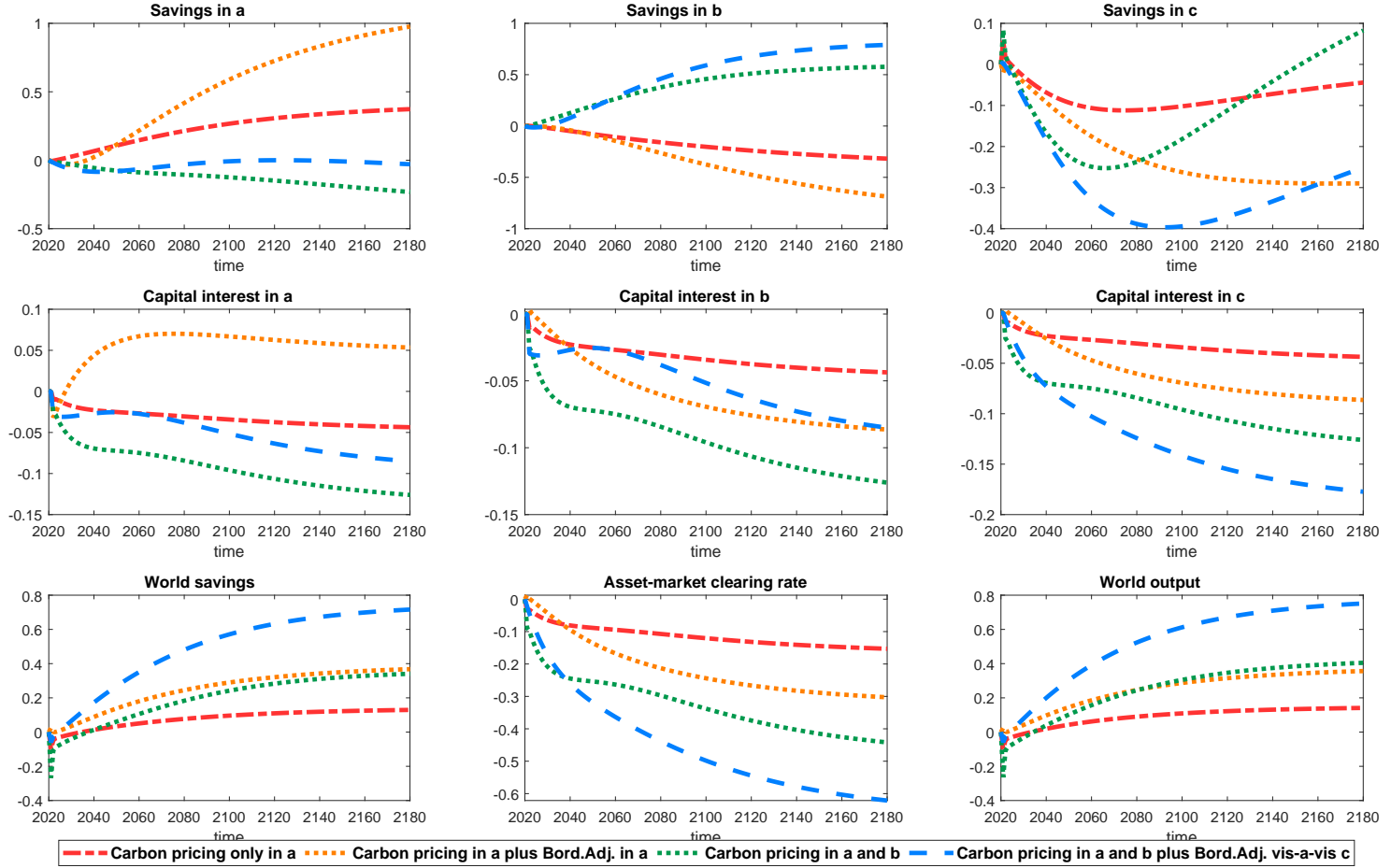
Notes: Figure plots (projected) implications of carbon pricing for income of workers and retirees in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the orange dotted line, carbon prices in a and b by the green straight line, and a climate club of regions a and b by the dashed blue line.

Figure 5: Implications of carbon pricing for consumption of workers and retirees



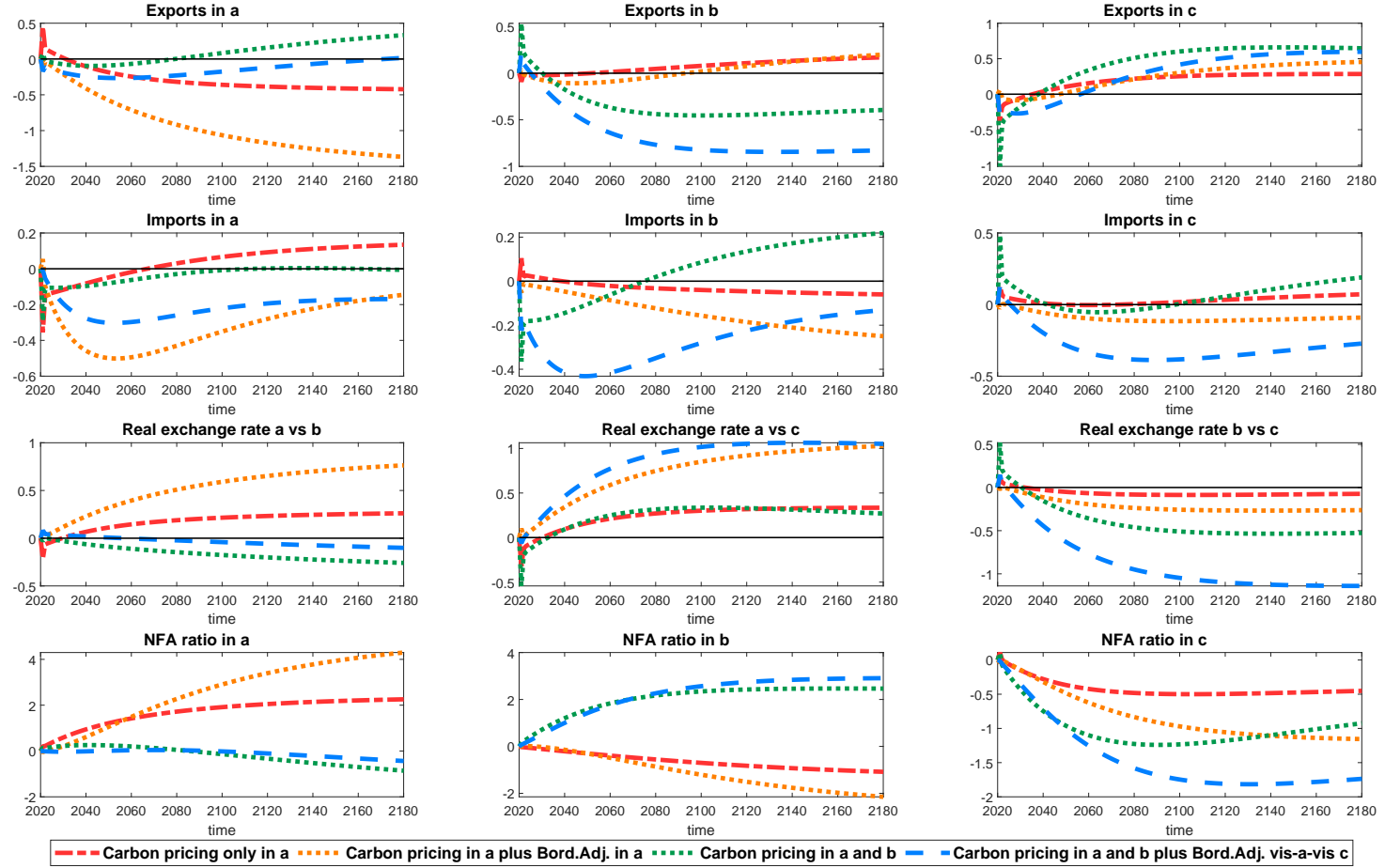
Notes: Figure plots (projected) implications of carbon pricing for consumption of workers and retirees in percentage (levels for marginal propensities to consume) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region *a* only. Carbon prices in *a* with border adjustment in *a* is depicted by the orange dotted line, carbon prices in *a* and *b* by the green straight line, and a climate club of regions *a* and *b* by the dashed blue line.

Figure 6: Implications of carbon pricing for savings, interest rates and world output



Notes: Figure plots (projected) implications of carbon pricing for savings, interest rates and world output in percentage(point) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region *a* only. Carbon prices in *a* with border adjustment in *a* is depicted by the orange dotted line, carbon prices in *a* and *b* by the green straight line, and a climate club of regions *a* and *b* by the dashed blue line.

Figure 7: Implications of carbon pricing for selected key trade-related variables



Notes: Figure plots (projected) implications of carbon pricing for selected key trade-related variables in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region *a* only. Carbon prices in *a* with border adjustment in *a* is depicted by the orange dotted line, carbon prices in *a* and *b* by the green straight line, and a climate club of regions *a* and *b* by the dashed blue line.

6 Conclusions

In a dynamic, three-region environmental life-cycle model, we find that the introduction of carbon pricing reduces output initially as emissions increase production costs. Benefits from lower emissions damage materialize only later. A border adjustment mechanism mitigates but does not prevent carbon leakage. Unless compensated for, retirees living in regions that increase carbon pricing tend to lose income and, at the same time, face higher consumption costs. This augments savings (also of the young), which cannot be fully invested domestically, however. Net foreign assets increase and the world asset market-clearing interest rate tends to fall. The latter feeds into capital interest rates and boosts production, also domestically. The former transfers income from abroad to home. This reduces welfare costs of carbon pricing.

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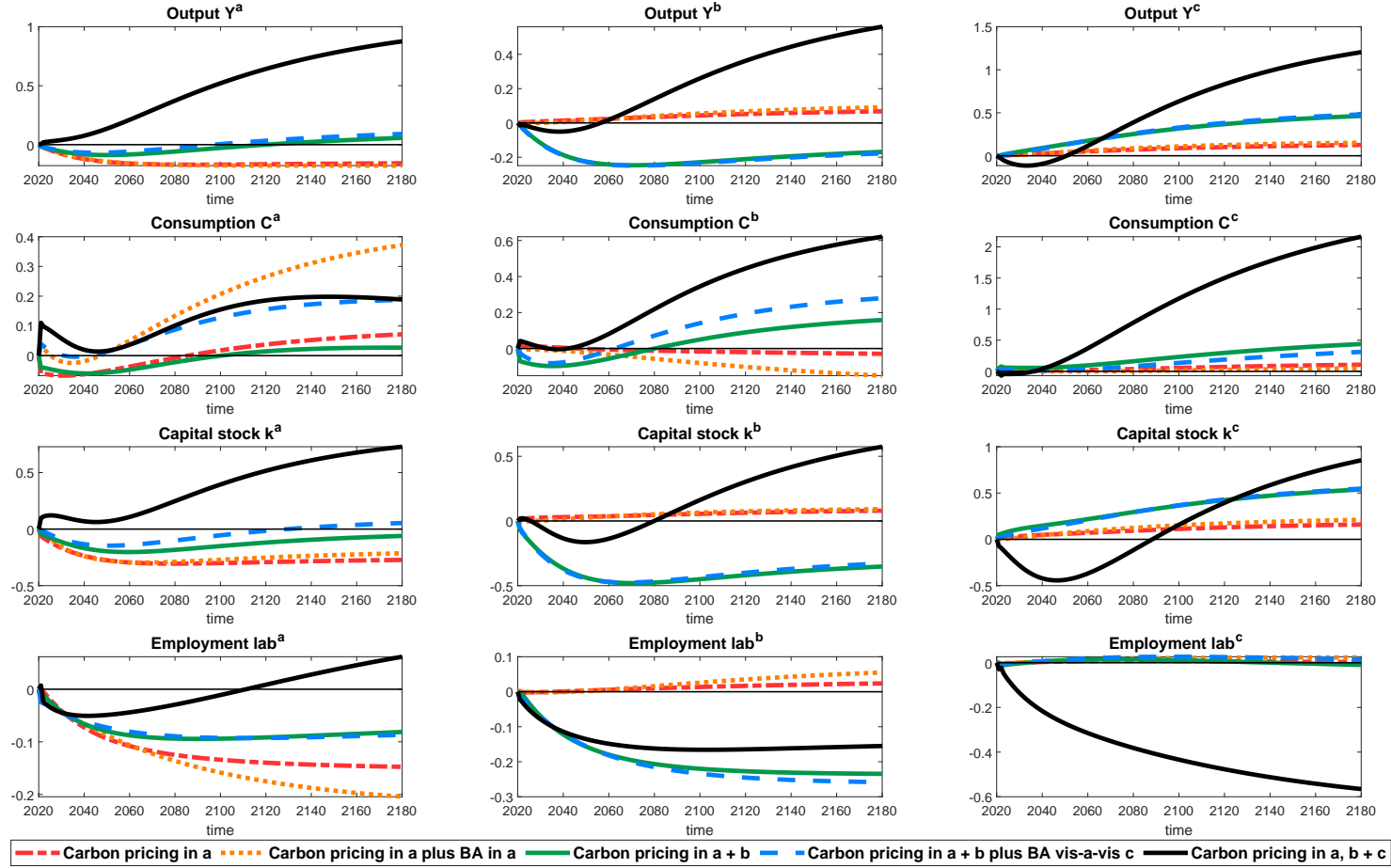
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Appendix

Appendix A: Additional results

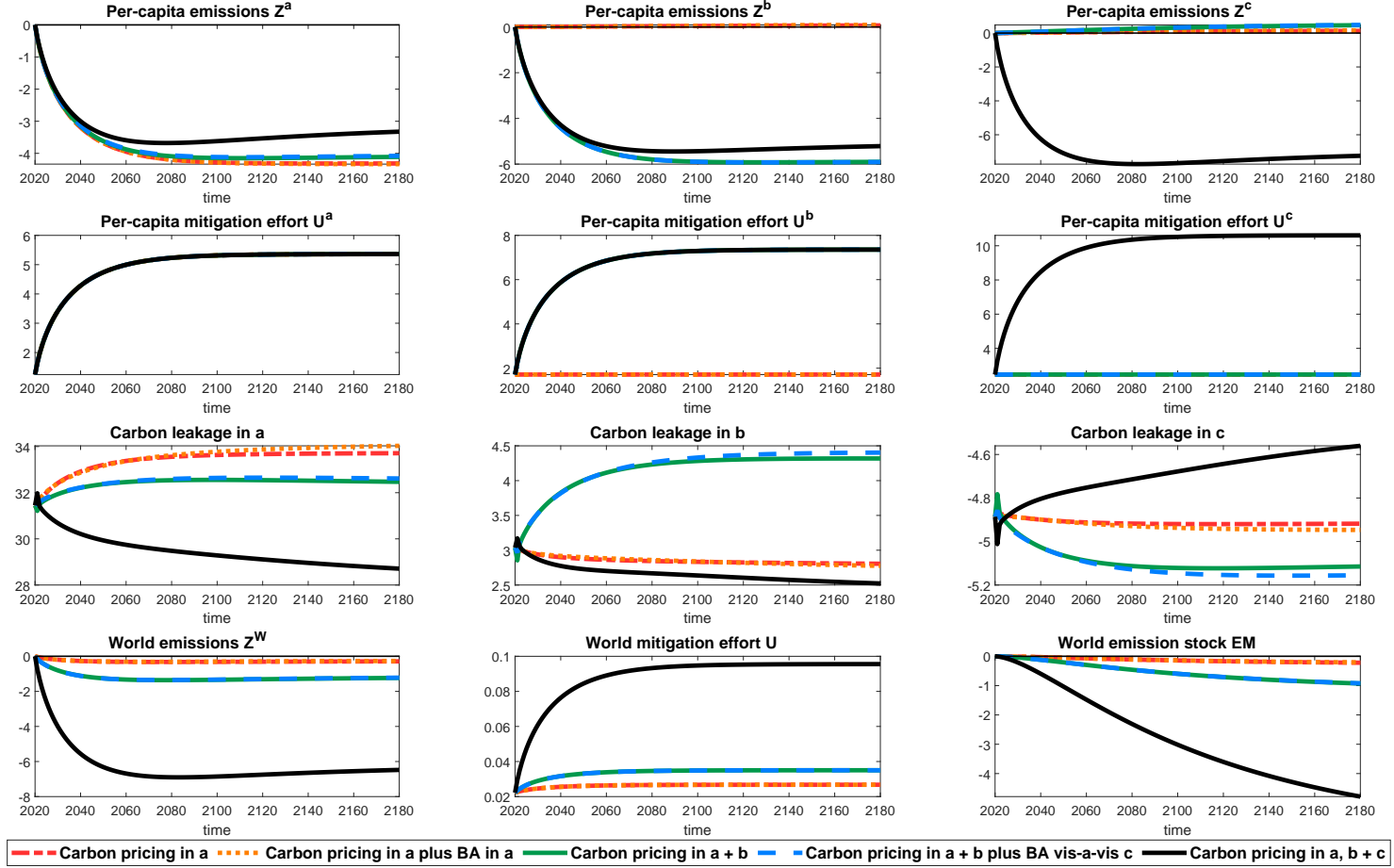
In this appendix, we repeat the graphs of the main text, now including the fifth scenario. In addition, we show how macro developments differ when only introducing border adjustment taxation relative to the full border adjustment mechanism (with subsidies).

Figure 8: Implications of carbon pricing for selected key macroeconomic variables



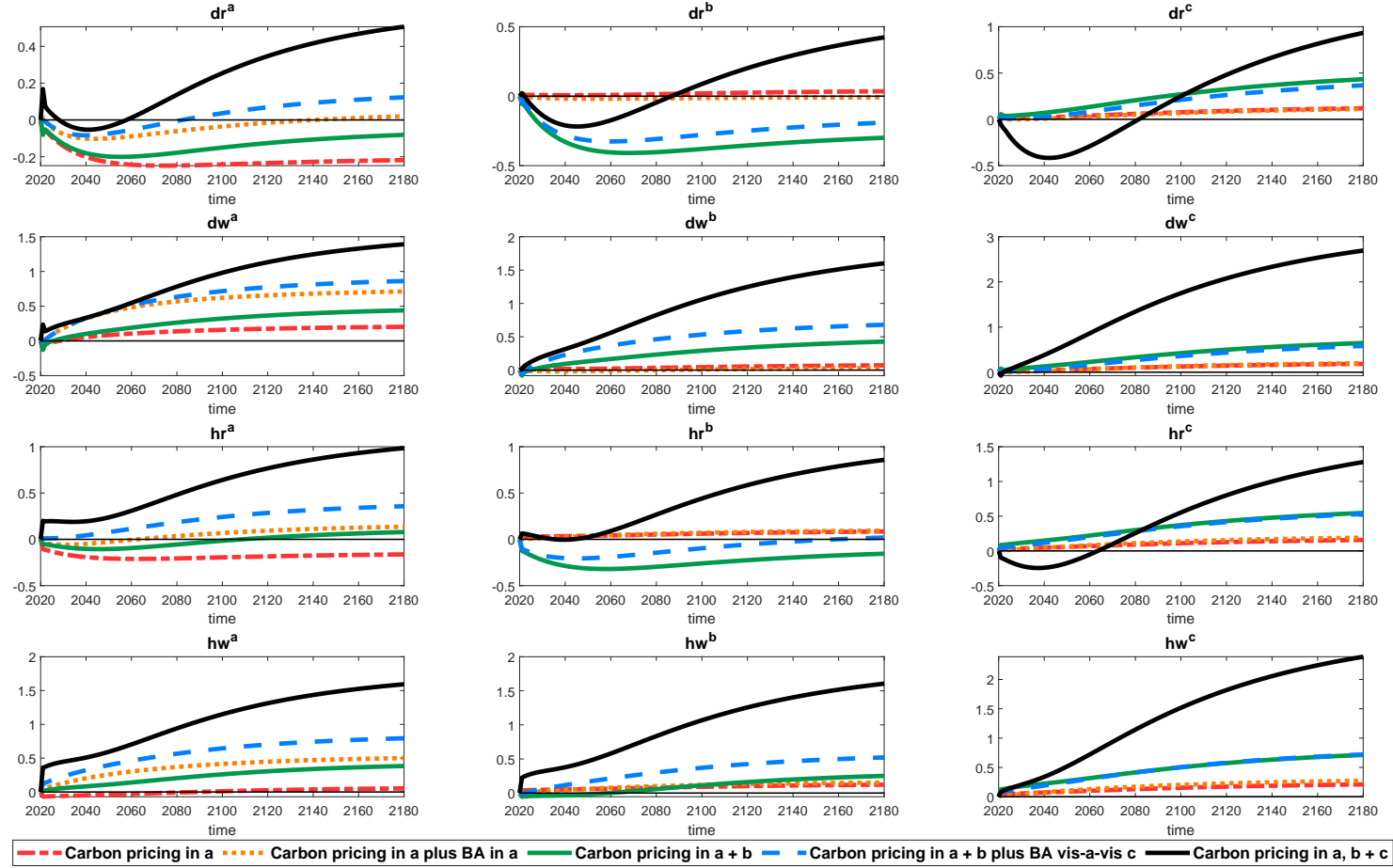
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the orange dotted line, carbon prices in a and b by the green straight line, a climate club of regions a and b by the dashed blue line, and carbon pricing in all regions by the black solid line.

Figure 9: Implications of carbon pricing for selected key environmental variables



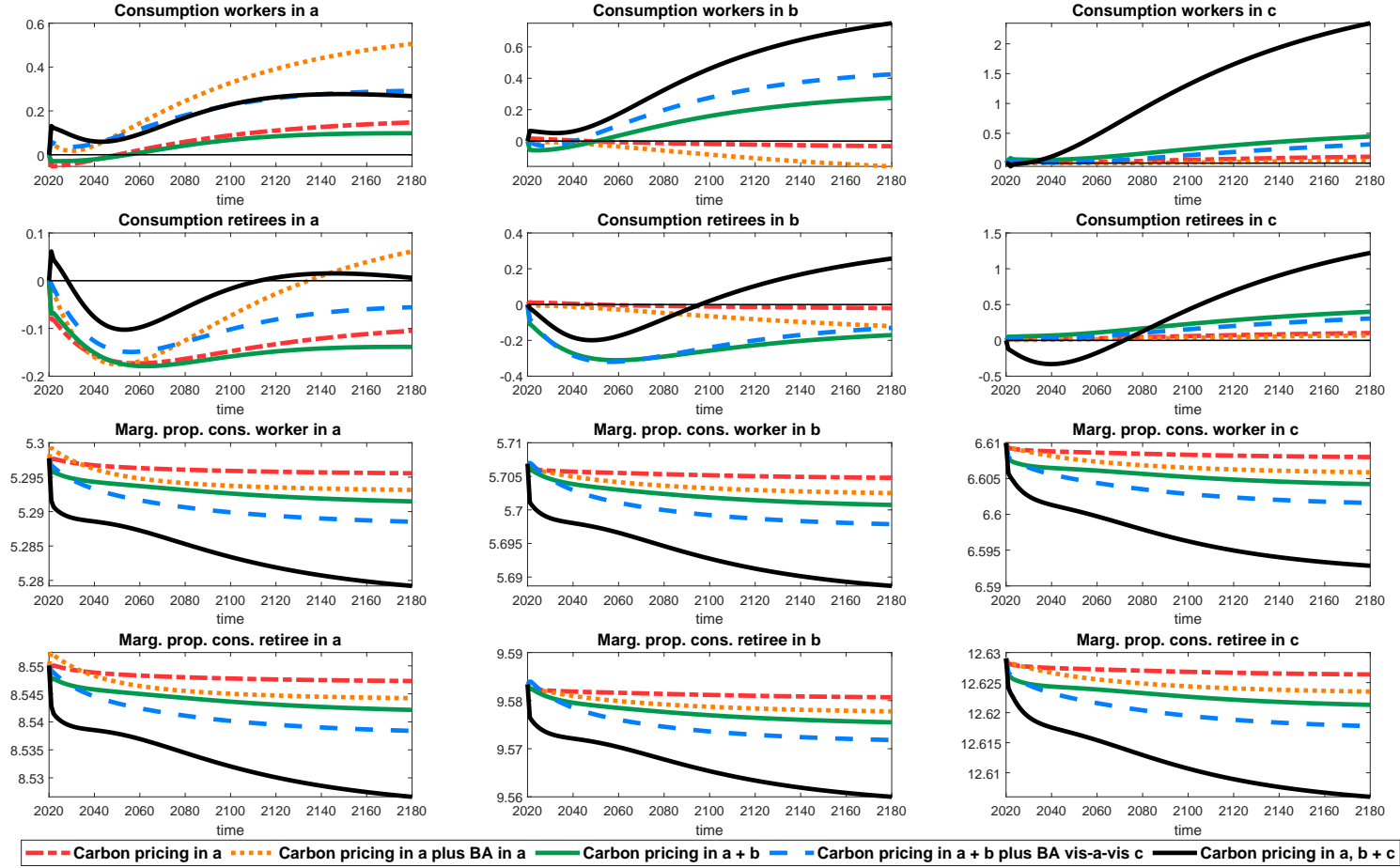
Notes: Figure plots (projected) implications of carbon pricing for selected key environmental variables in percentage(point) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the orange dotted line, carbon prices in a and b by the green straight line, a climate club of regions a and b by the dashed blue line, and carbon pricing in all regions by the black solid line.

Figure 10: Implications of carbon pricing for income of workers and retirees



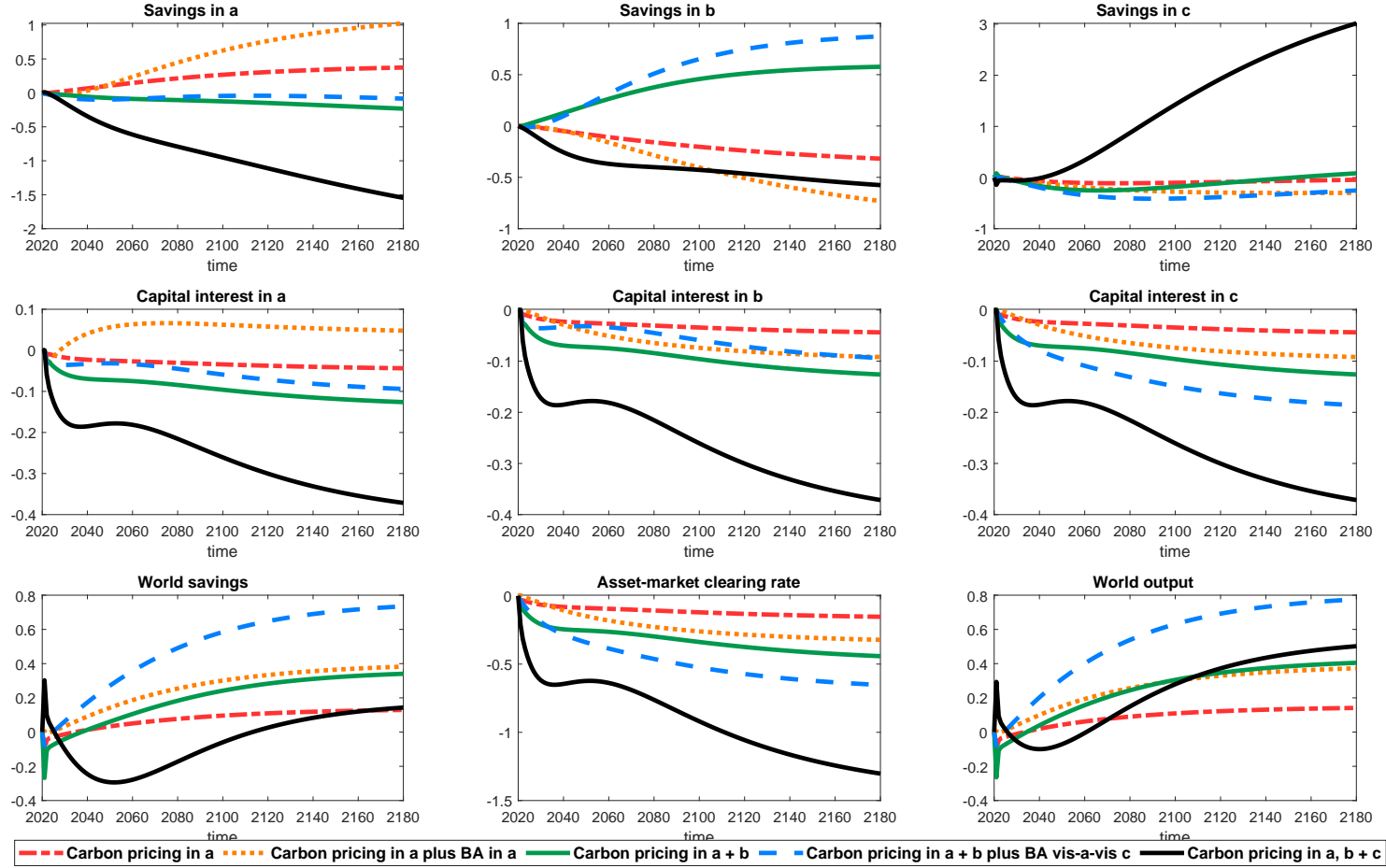
Notes: Figure plots (projected) implications of carbon pricing for income of workers and retirees in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the orange dotted line, carbon prices in a and b by the green straight line, a climate club of regions a and b by the dashed blue line, and carbon pricing in all regions by the black solid line.

Figure 11: Implications of carbon pricing for consumption of workers and retirees



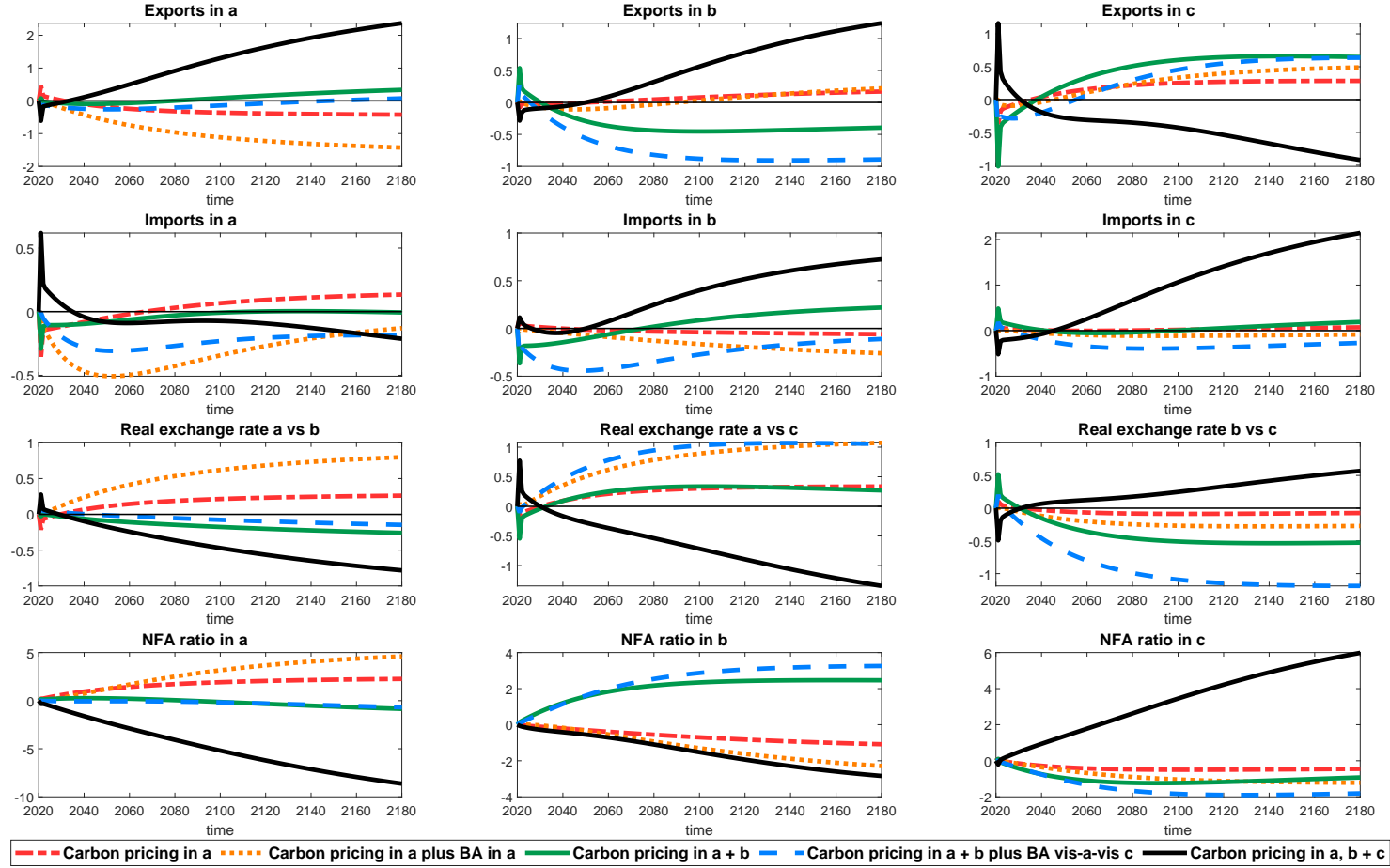
Notes: Figure plots (projected) implications of carbon pricing for consumption of workers and retirees in percentage (levels for marginal propensities to consume) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region *a* only. Carbon prices in *a* with border adjustment in *a* is depicted by the orange dotted line, carbon prices in *a* and *b* by the green straight line, a climate club of regions *a* and *b* by the dashed blue line, and carbon pricing in all regions by the black solid line.

Figure 12: Implications of carbon pricing for savings, interest rates and world output



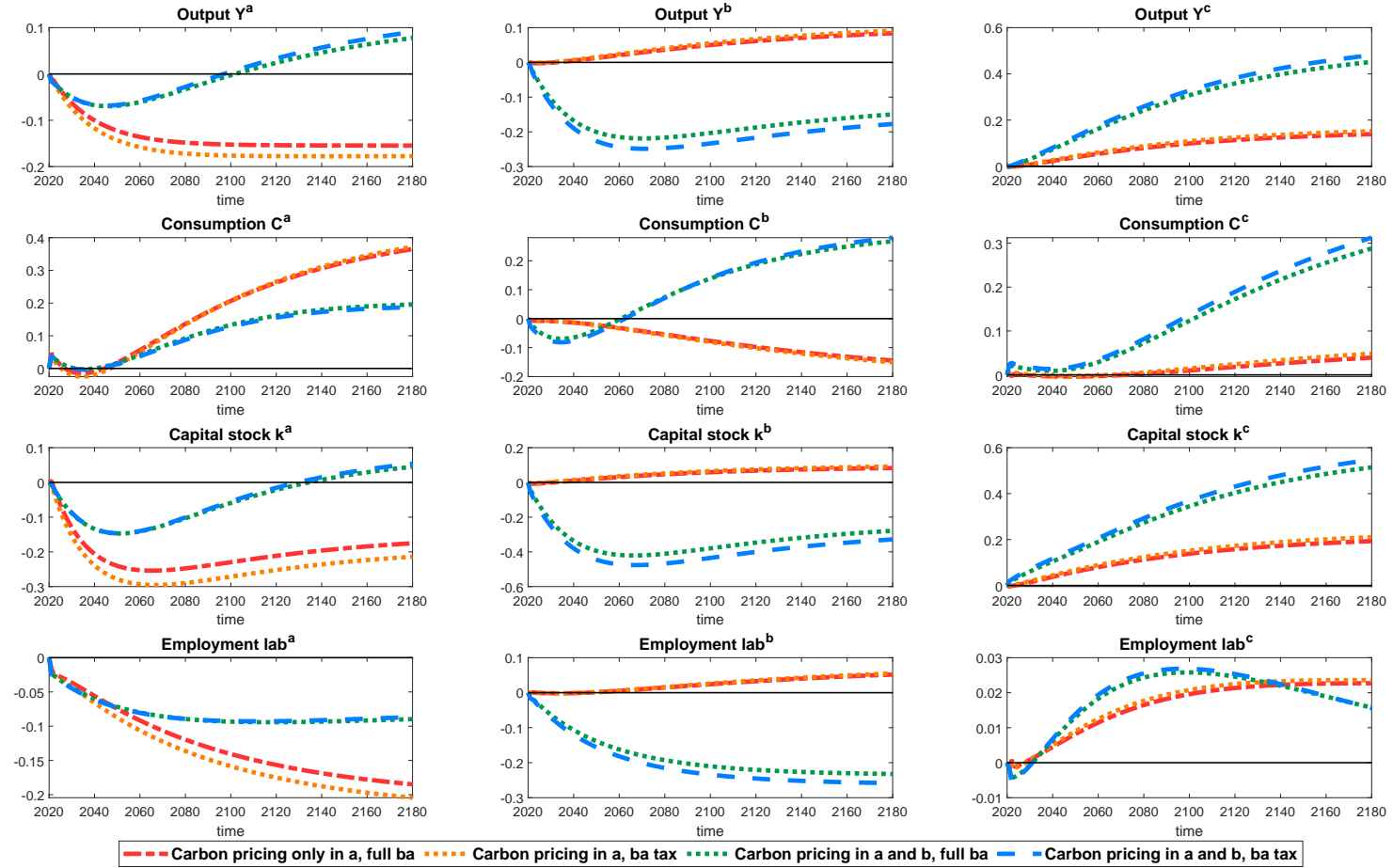
Notes: Figure plots (projected) implications of carbon pricing for savings, interest rates and world output in percentage(point) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region *a* only. Carbon prices in *a* with border adjustment in *a* is depicted by the orange dotted line, carbon prices in *a* and *b* by the green straight line, a climate club of regions *a* and *b* by the dashed blue line, and carbon pricing in all regions by the black solid line.

Figure 13: Implications of carbon pricing for selected key trade-related variables



Notes: Figure plots (projected) implications of carbon pricing for selected key trade-related variables in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region *a* only. Carbon prices in *a* with border adjustment in *a* is depicted by the orange dotted line, carbon prices in *a* and *b* by the green straight line, a climate club of regions *a* and *b* by the dashed blue line, and carbon pricing in all regions by the black solid line.

Figure 14: Comparing effects of border adjustment tax and subsidies for selected key macroeconomic variables



Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices and full border adjustment (including subsidies) in region a . Carbon border taxation in a only is depicted by the orange dotted line. The green straight line shows the climate club scenario with full border adjustment, the dashed blue line with border adjustment taxation only.