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Abstract

Introducing carbon pricing increases production costs and reduces output, at least initially. Benefits from reduced emissions damage materialize only later. This affects households' saving behavior and, thereby, the natural interest rate r^*. Using a dynamic, three-region environmental life-cycle model, we find that the effects on the natural interest rate and net foreign asset positions crucially depend on how governments recycle carbon revenues. If carbon revenues are paid back to all households in a lump-sum manner, saving declines, the natural rate increases permanently and the net foreign asset position of the carbon pricing-increasing country falls. The opposite holds if only the working-age population benefits from carbon revenues. The impact on exchange rates and trade flows depends on which regions introduce carbon pricing (and potential border adjustment mechanisms) as this ultimately drives relative price changes across the regions.

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

JEL classification: E32, E50, E62, F18, H32, Q58

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1 Introduction

In recent years, more than 100 countries have set or proposed ambitious climate goals involving substantial reductions in greenhouse gas (GHG) emissions. These countries account for almost 90 percent of GHG emissions. To reach the targets, both academics and policymakers discuss economically efficient and publicly acceptable climate change mitigation policies. The recent COP30 underscores the importance of the latter. The measures discussed include (regional) approaches to pricing carbon, border adjustment mechanisms and climate clubs. The latter two policies are intended to avoid carbon leakage. We contribute to the discussion by analyzing the effects of different carbon pricing schemes on the macroeconomy. We put special emphasis on international trade, (regional) growth developments and the asset market clearing world interest rate. The latter is often called the natural interest rate r^* and plays an important role in economic and monetary policy analysis. The real interest also plays a role for debt sustainability, as reviewed in Seghini (2026).

To assess these effects, we set up a three-region environmental open-economy general equilibrium model with a life-cycle structure. More precisely, the model contains typical environmental features following, among others, Heutel (2012), Golosov, Hassler, Krusell, and Tsyvinski (2014), Annicchiarico and Di Dio (2015), Annicchiarico, Correani, and Di Dio (2018), and Ernst, Hinterlang, Mahle, and Stähler (2023).[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 that allow structural policy changes in one region to spill over to other regions. In contrast to the standard open-economy modelling framework with an infinitely-lived representative household, 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, our model features many elements that are central to our research question: It incorporates feedback mechanisms between the economy and the environment as well as between endogenous interest rates and international trade. In addition, it captures the income and wealth distribution between old and young within each region, to name a few. Our simulation results can be summarized as follows.

In the first phase of the transmission, carbon pricing leads to emissions reductions but also a fall in output as production becomes more expansive. Over time, emissions-induced production damage decreases as emissions fall. However, it takes time – potentially a generation's lifetime – before these positive effects more than offset the adverse effects on

[1] In 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).

[2] In 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. In our framework, it is endogenous (see also Bodenstein, 2011, for a discussion).

output. For this to occur, emissions reductions and, thereby, the associated decline in damage must be sufficiently large. Thus, the more regions participate in carbon pricing, the better it is for regions that already participate. In addition, we find evidence for carbon leakage as products from regions without carbon pricing become relatively cheaper. Hence these regions benefit from higher demand. A carbon border adjustment mechanism (i.e. taxing imported foreign goods and subsidizing exported domestic ones) dampens carbon leakage, but overall effects are rather small. These findings are analogous to Ernst et al. (2023), who use a multi-sector, multi-region DSGE model without a life-cycle structure for their analysis.

In our model the carbon pricing-induced negative impact on consumption is much shorter and less pronounced than in a standard model with an infinitely-lived representative household. The reason is that consumption dynamics are primarily driven by changes in savings behavior, which in turn crucially depend on the chosen carbon revenue recycling scheme.[3] The same is true with respect to effects on the natural interest rate r^*, net foreign asset positions and the trade balance.

When a region increases carbon pricing and redistributes revenues to all households in a lump-sum manner, aggregate saving in this region falls, as both retirees and workers have an incentive to save less. The effect on the former stems from higher income from transfers, and the effect on the latter from reduced wage income (which more than offsets higher transfers) and higher expected old-age income. As aggregate saving in regions that do not introduce carbon pricing increases only mildly, the natural interest rate r^* increases. This positive effect on r^* becomes even larger, if more regions introduce carbon pricing with uniform revenue recycling.

The described effects revert when revenues from carbon pricing are redistributed to the working-age population only. In that case, workers and retirees both have an incentive to save more. For workers, this incentive arises from higher net income, which increases their consumption and saving. For retirees, it results from higher relative consumption costs, while their net income remains unchanged. The effect on aggregate saving in regions that do not introduce carbon pricing is unchanged: it increases mildly. Hence, in this case the natural interest rate r^* falls.

With respect to net foreign assets, the revenue recycling scheme determines whether aggregate saving exceeds or falls short of the national investment opportunities, which fall in both cases. Lower savings in case of a uniform revenue recycling scheme lead to aggregate saving being lower than investment opportunities. Hence, net foreign assets fall. The opposite holds true when revenues are redistributed to workers only. The trade balance, which ultimately determines the domestic net foreign asset position, is primarily driven by relative prices across regions. Exports from regions with a carbon pricing-induced cost push fall. Due to a reduction in capital input (and, thereby, investment demand), imports also fall initially. However, decreasing production damage and increasing consumption gradually reverse this effect Depending on the extent to which medium-term income increases, imports (in quantities) may actually exceed their initial steady-state values. This is more likely if carbon pricing revenue is redistributed to the working-age population only.

[3] The literature typically analyzes carbon pricing revenue recycling scenarios relative to a scenario without recycling. In our analysis, this comparison would not add additional insight beyond the existing literature. Instead, we focus on how different revenue recycling schemes affect saving and interest rates.

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

Our work is related to a growing literature on environmental macroeconomic models. Annicchiarico et al. (2022) provide a comprehensive overview of analyzes in environmental DSGE models, which differ among other things in the way pollution is modelled. While some papers model optimal pollution as a direct input (see, for example, Fischer and Springborn, 2011, Böhringer, Fischer, and Rosendahl, 2014, and Böhringer and Fischer, 2020), others implement emissions as a by-product of production (see Heutel, 2012, and Golosov et al., 2014). Yet others implicitly combine both modelling approaches through the input-output structure of a production network model (see, for example, Hinterlang, Martin, Röhe, Stähler, and Strobel (2022) or Ernst et al. (2023)). In these studies emissions are a by-product of production and firms use inputs produced in other sectors following Atalay (2017) and Bouakez, Rachedi, and Santoro (2022)). We employ a one-sector economy and model emissions as a by-product of production. Damage from emissions is modelled following Heutel (2012), Golosov et al. (2014) or Khan, Metaxoglou, Knittel, and Papineau (2019) and is limited to economic losses, which are a function of the stock of emissions. By contrast, other modelling approaches include environmental aspects in the welfare function (see, for example, Chang, Chen, Shieh, and Lai (2009), Angelopoulos, Economides, and Philippopoulos (2013), Cai and Lontzek (2019) and Cai (2020)).

In addition, we contribute to a growing literature that addresses the effects of carbon pricing. Annicchiarico and Di Dio (2015) model the effects on business cycle fluctuations, revealing a dampening effect of emissions taxation in general and emission caps in particular. Chan (2020) confirms this finding using a two-region model and highlights that fluctuations are higher in the case of non-cooperation between both regions. Chen, Zhao, Cheng, and Qiu (2025) analyze optimal cyclicality of carbon taxes in an E-DSGE model with supply chains. Different papers using production network models contribute to a better understanding of the sectoral effects of carbon pricing. For example Devulder and Lisack (2020) and Frankovic (2024) find in a static framework that dirty sectors tend to be affected more severely by carbon pricing and benefit more from border adjustment. Ernst et al. (2023) confirm this result in a dynamic framework. Garcia, Jacquinot, Lenarcic, Mavromatis, Papadopoulou, and Silgado-Gomez (2026) focus on the effects of temporary energy price shocks on output and inflation using a DSGE model with brown and green energy sectors. Their results point to carbon taxes acting as a negative supply shock, leading to rising inflation and lower output.

Using a DSGE model with heterogeneous (rich and poor) households, Malafry and Brinca (2022) focus on differences in households' preferences for carbon pricing. They find that the poor prefer a stricter climate policy, as they are less well insured against the risks of climate change. Due to the OLG structure, our model also entails two household types (old and young), which are affected differently by carbon pricing. This intergenerational perspective of carbon pricing is also adopted by Fried, Novan, and Peterman (2018) and Rausch and Yonezawa (2023), who both analyze different climate policies in an OLG framework. Rausch and Yonezawa (2023) show that different to the future generation, the current one prefers green technology policies over a carbon tax. The analysis by Fried et al. (2018) focuses on how different generations benefit from different recycling schemes of carbon tax revenue. They find, that future generations benefit most, if revenues are used to decrease distortional taxes, while current generations prefer uniform lump-sum redistribution. Our results also point in this direction. However, we focus on the effects of carbon pricing on saving and the natural interest rate r*. Therefore, our revenue recycling options differ between a lump-sum redistribution to all households or to workers only (the latter of which may represent a labor tax reduction).

Moreover, there are many papers, which address revenue recycling in the context of climate policies. Grüning and Kantur (2024) use a New Keynesian multi-sector E-DSGE model with production and investment networks to simulate what happens if carbon revenue is used to build green public capital, thereby boosting productivity of the green sector. They find that this combination best resolves the trade-off between achieving positive economic growth and reducing carbon emissions. Burgold, Ernst, Hinterlang, Jäger, and Stähler (2025) show in a production network model with sectoral heterogeneity that depending on the revenue recycling scheme, the European cap and trade system may (labor tax reduction) or may not (lump-sum redistribution) outperform the Chinese tradeable performance standard. Kettner, Leoni, Köberl, Kortschak, Sommer, and Kulmer (2026) analyse different revenue recycling options in a combined macro- and micro-modelling approach and focus on different effects on households living in peripheral or rural areas. Annicchiarico et al. (2018) use a DGE model with endogenous firm entry to show that labor or consumption tax reductions may diminish markups and hence detrimental effects of carbon pricing on competition. Other papers find, that a reduction of distortional taxes can be more beneficial than a lump-sum redistribution (see, for example, Antosiewicz, Lewandowski, and Witajewski-Baltvilks (2016), Hinterlang et al. (2022) and Varga, Roeger, and Veld (2022)).

There are rather few papers, which analyse the effects of carbon pricing on trade, net foreign assets and/or the natural rate r*. Zheng, Liu, and Gu (2024) use a two-country DGE model with asymmetric climate policies that is calibrated to China. They find that the strengthening of climate policy improves China's trade balance and current account. Annicchiarico and Diluiso (2019) analyze the effect of carbon pricing on trade spillovers. Duan, Ji, Lu, and Wang (2021) focus on the interaction between international trade, the environment, and environmental regulations. Carattini, Kim, Melkadze, and Pommeret (2024) simulate financial flows and trade in a two-sector, two-country, DGE model with financial frictions, carbon tariffs and macroprudential policies. They point out that accounting for cross-border financial flows and frictions in credit markets is crucial for the results. Casey, Fried, and Peterman (2024) show that the long-run interest rate may increase because of climate policies. We confirm that all of this is important and additionally highlight that it further matters how carbon revenues are redistributed.

Finally, we contribute to an extensive literature on carbon leakage, border adjustment, and climate clubs (see Ernst et al. (2023) for a more detailed description). More recent work by Delgado-Tellez, Quintana, and Santabarbara (2025) and Planelles and Sanin (2025) analyzes the European Carbon Border Adjustment Mechanism (CBAM) with production-network models. In line with the existing literature, Delgado-Tellez et al. (2025) find that CBAM reduces carbon leakage but has slightly adverse effects on GDP and inflation as the competitive gain is offset by the higher costs of imported intermediate inputs. Planelles and Sanin (2025) find stronger negative effects of CBAM, but the same dampening effect on carbon leakage. According to their results, the European economy may be worse off with CBAM due to amplification effects through the production network.

Also note that the climate module of our model is DICE-like (see Nordhaus, 2013, 2018). 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. If this is true, the economic costs of emissions reduction could be lower and benefits would start materializing much earlier, relative to what present below. However, although very important for the analysis, the precise impact of emissions reduction on the environment is hard to judge for economists. Hence, we take the general damage functions as given.

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. 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

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

and

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

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, $c_t^{z,i}$:

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

where ρ determines the intertemporal elasticity of substitution. 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

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

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

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

We abstract from old-age benefits. Hence, the retiree needs to finance consumption expenditures through savings and potential lump-sum transfers $LS_t^{i,j}$ received from the government. Retirees do not work. We will discuss the implications of old-age benefits and endogenous labor supply (also of retirees) below.

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).[4] $\tau_t^{b,i}$ is the border adjustment mechanism-implied tax rate on consumption in

[4] In 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).

region i. We will discuss it in more detail below.

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

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

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

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

where

$$h_t^{r,i,j} = LS_t^{i,j} + \frac{\gamma^i}{1+r_t} \, h_{t+1}^{r,i,j}$$

is the recursive law of motion of human capital (i.e. life-time income from potential government transfers 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

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

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

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

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 obtain firm profits, $f_t^{i,j}$, and potentially worker-specific lump-sum payments, $\tau_t^{i,j}$.[5] They also receive the wage income at rate w_t^i. We

[5]If we allowed retirees to also own firms, this would not affect our results much, as discussed by

assume inelastic labor supply in our baseline model, which we normalize to one (but discuss the implications of endogenous labor supply below). The solution of the worker's decision problem is:

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

as the consumption-Euler equation, with

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

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

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

and

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

where

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

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 $N_t^{w,i}$, and the normalization of individual labor supply to unity, aggregate labor supply is given by $l_t^i = l_t^{w,i} = N_t^{w,i}$. Aggregate consumption is given by $c_t^i = c_t^{w,i} + c_t^{r,i}$, 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

$$(1+\tau_t^{b,i}) \cdot c_t^{w,i} = \zeta_t^{w,i} \left[(1+r_{t-1})(1-\lambda_{t-1}^i) \, a_{t-1}^i + h_t^{w,i}\right], \tag{4}$$

$$(1+\tau_t^{b,i}) \cdot c_t^{r,i} = \zeta_t^{r,i} \left[(1+r_{t-1}) \, \lambda_{t-1}^i \, a_{t-1}^i + h_t^{r,i}\right]. \tag{5}$$

Fujiwara and Teranishi (2008).

In equations (4) and (5), 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

$$h_t^{r,i} = LS_t^i + \frac{\gamma^i}{(1+r_t)}\, h_{t+1}^{r,i}, \tag{6}$$

$$h_t^{w,i} = w_t^i + f_t^i + \tau_t^i + LS_t^i + \frac{\omega^i \cdot h_{t+1}^{w,i,j}}{(1+r_t)\,\Omega_{t+1}^i} - \left(1 - \frac{\omega^i}{\Omega_{t+1}^i}\right) \frac{h_{t+1}^{r,i}}{(1+r_t)\Psi^i}, \tag{7}$$

The absence of γ^i in equation (5) 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 $(1-\lambda_t^i)\, a_t^i = \omega^i \left[(1-\lambda_{t-1}^i)(1+r_{t-1})\, a_{t-1}^i + w_t^i + f_t^i + \tau_t^i + LS_t^i - (1+\tau_t^{b,i}) \cdot c_t^{w,i}\right]$. 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: $\lambda_t^i\, a_t^i = \lambda_{t-1}^i (1+r_{t-1})\, a_{t-1}^i + LS_t^i - (1+\tau_t^{b,i}) \cdot c_t^{r,i} + (1-\omega^i) \left[(1-\lambda_{t-1}^i)(1+r_{t-1})\, a_{t-1}^i + w_t^i + f_t^i + \tau_t^i + LS^i - (1+\tau_t^{b,i}) \cdot c_t^{w,i}\right]$. Combining these expressions and using equations (4) and (5), we get

$$\begin{aligned} \lambda_t^i\, a_t^i = &\omega^i \left\{ \left(1-\zeta_t^{r,i}\right) \left[(1+r_{t-1})\, \lambda_{t-1}^i\, a_{t-1}^i + h_t^{r,i}\right] - \left(h_t^{r,i} - LS_t^i\right) \right\} \\ &+ (1-\omega^i)\, a_t^i. \end{aligned} \tag{8}$$

3.4 Production

The representative producer in region i operates with production technology

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

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. Remember that $l_t^i = N_t^{w,i}$ is inelastically supplied in our baseline version of the model. 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 $D_i(M_t) = \gamma_{0,i} + \gamma_{1,i} \cdot M_t + \gamma_{2,i} \cdot M_t^2$. 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

$$\frac{l_t^i}{k_{t-1}^i} = \frac{\alpha^i}{1-\alpha^i} \cdot \frac{r_t^{k,i}}{w_t^i}. \tag{9}$$

Hence, real marginal costs are given by

$$mc_t^i = \left(\frac{w_t^i}{\alpha^i}\right)^{\alpha^i} \cdot \left(\frac{r_t^{k,i}}{1-\alpha^i}\right)^{1-\alpha^i}. \tag{10}$$

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

$$\phi_{1,i} \cdot \phi_{2,i} \cdot U_{i,t}^{\phi_{2,i}-1} = P_{i,t}^{em} \cdot \left(1 - \sum_{i \neq j} \tilde{I}_t^{i,j} \cdot \frac{Exp_t^{j,i}}{y_t^i}\right) \cdot \kappa_i. \tag{11}$$

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 whenever there is a border adjustment mechanism with export subsidies (i.e. when exports from region i to j, denoted by $Exp_t^{j,i}$, are subsidized) and zero otherwise.

Firms are price setters and, under flexible prices and perfect competition, it holds that

$$P_{i,t} = \tilde{mc}_{i,t}, \tag{12}$$

which almost is the standard pricing equation (prices equal marginal costs) with one difference: For factor demand, the relevant marginal costs are $mc_{i,t}$, whereas they are

$$\tilde{mc}_{i,t} = mc_{i,t} + \phi_{1,i} \cdot U_{i,t}^{\phi_{2,i}} + P_{i,t}^{em} \cdot \left(1 - \sum_{i \neq j} \tilde{I}_t^{i,j} \cdot \frac{Exp_t^{j,i}}{y_t^i}\right) \cdot \kappa_i \cdot (1 - U_{i,t}) \tag{13}$$

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). Hence, the zero profit condition applies (however, allowing firms to charge markups would not alter our results qualitatively).

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 and international assets. International assets are assumed to pay an interest $i_t^{d,i}$ 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

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

where d_t^i denotes net foreign assets 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 subject to the border adjustment tax, too). p_t^k denotes the CPI-deflated price of real investment. It differs from one in case the composition of the investment goods bundle is different to the one of the consumption goods bundle.

Capital follows the conventional law of motion:

$$k_{t+1}^i = (1-\delta^i)k_t^i + inv_t^i, \tag{14}$$

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

$$(1+r_t) = (1+i_t^{d,i}) = \frac{r_{t+1}^{k,i} + (1-\delta^i)\,p_{t+1}^k\,(1+\tau_{t+1}^{b,i})}{(1+\tau_t^{b,i})\,p_t^k}. \tag{15}$$

Financial markets must clear, which implies that

$$a_t^i = k_t^i + d_t^i \tag{16}$$

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

$$P_{i,t}^{em} \cdot \left(1 - \sum_{i \neq j} \tilde{I}_t^{i,j} \cdot \frac{Exp_t^{j,i}}{y_t^i}\right) \cdot Z_{i,t} + \tau_t^{b,i} \cdot (c_t^i + inv_t^i) = \tau_t^i + LS_t^i. \tag{17}$$

Hence, any transfer to the household sector, either to the working-aged population, $\tau_t^i = N_t^{w,i} \cdot \tau_t^{i,j}$, or to everyone $LS_t^i = (N_t^{w,i} + N_t^{r,i}) \cdot LS_t^{i,j}$, must be financed by revenues from carbon pricing net of export subsidies, $P_{i,t}^{em} \cdot \left(1 - \sum_{i\neq j} \tilde{I}_t^{i,j} \cdot \frac{Exp_t^{j,i}}{y_t^i}\right) \cdot Z_{i,t}$, and border adjustment taxation-implied import taxes, $\tau_t^{b,i} \cdot (c_t^i + inv_t^i)$. For simplicity, we abstract from any other revenues or expenditure component and assume a balanced budget.

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

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

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 $\eta^i \to 0$, 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, $\vartheta_i^{c,i}$ can be interpreted as the home bias in consumption of region i. We assume that $\vartheta_a^{c,i}+\vartheta_b^{c,i}+\vartheta_c^{c,i}=1$. Given a border adjustment tax rate $\tau_t^{b,i,j}$ potentially different from zero, cost minimization of consumption expenditures, $(1+\tau^{b,i})P_t^i c_t^i = (1+\tau_t^{b,i,a})P_t^{i,a} c_{a,t}^i + (1+\tau_t^{b,i,b})P_t^{i,b} c_{b,t}^i + (1+\tau_t^{b,i,c})P_t^{i,c} c_{c,t}^i$, implies

$$c_{j,t}^i = \vartheta_j^{c,i} \left(\frac{(1+\tau_t^{b,i,j})P_t^{i,j}}{(1+\tau^{b,i})P_t^i} \right)^{-\frac{1}{1-\eta^i}} \cdot c_t^i. \tag{18}$$

The consumer price index (CPI) results to be

$$P_t^i = \left[\vartheta_a^{c,i} \cdot \left(P_t^{a,i}\right)^{-\eta^i/(1-\eta^i)} + \vartheta_b^{c,i} \cdot \left(P_t^{b,i}\right)^{-\eta^i/(1-\eta^i)} + \vartheta_c^{c,i} \cdot \left(P_t^{c,i}\right)^{-\eta^i/(1-\eta^i)} \right]^{-\frac{1-\eta^i}{\eta^i}}, \tag{19}$$

which we can use to derive the border adjustment tax-implied consumption tax rate, see also Ernst et al. (2023). We assume that an analogous aggregator holds for investment goods such that we can derive analogous equations for inv_t^i and $inv_{j,t}^i$. However, the home bias parameters $\vartheta_j^{i,i}$ of the investment-based aggregator may differ. If they do, $pk_t^i \neq 1$, as already mentioned above. CPI-deflated net exports in region i, nx_t^i, are hence given by

$$\begin{aligned} nx_t^i = & \underbrace{\frac{P_t^{j,i}}{P_t^i} \cdot \left(c_{i,t}^j + inv_{i,t}^j\right)}_{=Exp^{j,i}} + \underbrace{\frac{P_t^{\tilde{j},i}}{P_t^i} \cdot \left(c_{i,t}^{\tilde{j}} + inv_{i,t}^{\tilde{j}}\right)}_{=Exp^{\tilde{j},i}} - \frac{P_t^{i,j}}{P_t^i} \cdot \left(c_{j,t}^i + inv_{j,t}^i\right) \\ & - \frac{P_t^{i,\tilde{j}}}{P_t^i} \cdot \left(c_{\tilde{j},t}^i + inv_{\tilde{j},t}^i\right), \end{aligned} \tag{20}$$

where $i, j, \tilde{j} = a, b, c$, and $i \neq j \neq \tilde{j}$. Given net exports and using the no-arbitrage conditions (15), we get that net foreign assets in region i evolve according to

$$d_t^i = (1+r_{t-1})\, d_{t-1}^i + nx_t^i. \tag{21}$$

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.[6]

Product market clearing implies that whatever is produced in region i must be con-

[6] At 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.

sumed/used somewhere around the world. Formally, we get

$$y_t^i = \left(c_{i,t}^i + inv_{i,t}^i\right) + \left(c_{i,t}^j + inv_{i,t}^j\right) + \left(c_{i,t}^{\tilde{j}} + inv_{i,t}^{\tilde{j}}\right) + C\left(U_{i,t}\right). \tag{22}$$

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. (2023) by grouping countries according to attitudes towards 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".

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). The exact value of these parameters is not crucial for our qualitative results. 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 $\beta = 0.92$. 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 Ernst et al. (2023), we target per-capita output levels of 1, 0.985 and 0.3885 in regions a, b and c, respectively (per-capita includes retirees). Given environmental damage, which we describe below, this allows us to derive ϵ_i. Structural parameters are summarized in Table 2. The non-targeted consumption and investment-to-output ratios range from 0.75 to 0.78 and from 0.25 to 0.22, respectively, which closely corresponds to regional averages in the data. This also holds for the savings-to-consumption ratios. Our calibration implies that US households have a higher propensity to consume than

European households, which indeed tend to save more in aggregate than their US counterparts.

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.

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 transfers to workers, τ^i.

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 consumption goods in a typical European and North American country to 80%, and the import content from each other to 10%. As the investment goods bundle entails a somewhat higher home bias (see Ernst et al., 2023), we assume values of 90% and 5% for investment goods. This 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.

To calibrate region-specific CO2 emissions per unit of output κ_i, we follow Ernst et al. (2023) 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. 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 $1 - \rho^{EM} = 0.985$ following Heutel (2012) and Annicchiarico and Di Dio (2015). Following the recent E-DSGE literature, the slope parameter of the abatement cost function is set to $\phi_{2,i} = 2.8\,\forall s$ as in Nordhaus (2008) and Annicchiarico and Di Dio (2015). Following Ernst et al. (2023), we set are $\phi_{1,a} = 0.034$,

$\phi_{1,b} = 0.036$ and $\phi_{1,c} = 0.066$. A critical discussion about different abatement cost functions and their parameterizations can be found in Cline (2011).

Table 2: Structural parameters

Variable/Parameter	Symbol	Value		
		Europe	North America	Rest of world
Discount rate	β	0.92	0.92	0.92
Intertemporal elasticity of substitution	σ	0.5	0.5	0.5
Substitution elasticity home/foreign	$1/(1-\eta)$	1.5	1.5	1.5
Bias for con. goods produced in Europe	ϑ_a^c	0.8	0.1	0.0206^e
Bias for con. goods produced in North America	ϑ_b^c	0.1	0.8	0.0505^e
Bias for con. goods produced in Rest of World	ϑ_c^c	0.1^e	0.1^e	0.9289^e
Bias for inv. goods produced in Europe	ϑ_a^c	0.9	0.005	0.0206^e
Bias for inv. goods produced in North America	ϑ_b^c	0.005	0.9	0.0505^e
Bias for inv. goods produced in Rest of World	ϑ_c^c	0.005^e	0.005^e	0.9289^e
Cobb-Douglas share of labor	σ	2/3	2/3	2/3
Productivity parameter	ϵ	0.6202^e	0.6311^e	0.3593^e
Capital depreciation	δ	0.1	0.1	0.1

Source: The superscript e marks 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.

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. As in Ernst et al. (2023), the targeted steady-state damage is 1.14%, 1.33% and 1.15% 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 roughly increases damage by 1.5 following Kalkuhl and Wenz (2020), which is also in line with Ernst et al. (2023).

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, 2021), 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. Overall, it holds that the higher/faster the damage reduction is, the larger/sooner positive macroeconomic effects emerge, and the better all this is for welfare.

Table 3: Environmental parameters

Variable/Parameter	Symbol	Value		
		Europe	North America	Rest of world
Decay rate of pollution stock	$1 - \rho^{EM}$		0.985	
Emissions intensity^e	κ	0.1977	0.3518	0.6753
Abatement costs (linear parameter)	ϕ_1	0.034	0.036	0.066
Abatement costs (exponential parameter)	ϕ_2	2.8	2.8	2.8
Independent damage term^e	γ_0	-0.0059	-0.0069	-0.0065
Linear damage term^e	γ_1	-0.0013	-0.0016	-0.0013
Quadratic damage term^e	γ_2	1.8590e-4	2.1722e-4	1.8429e-04

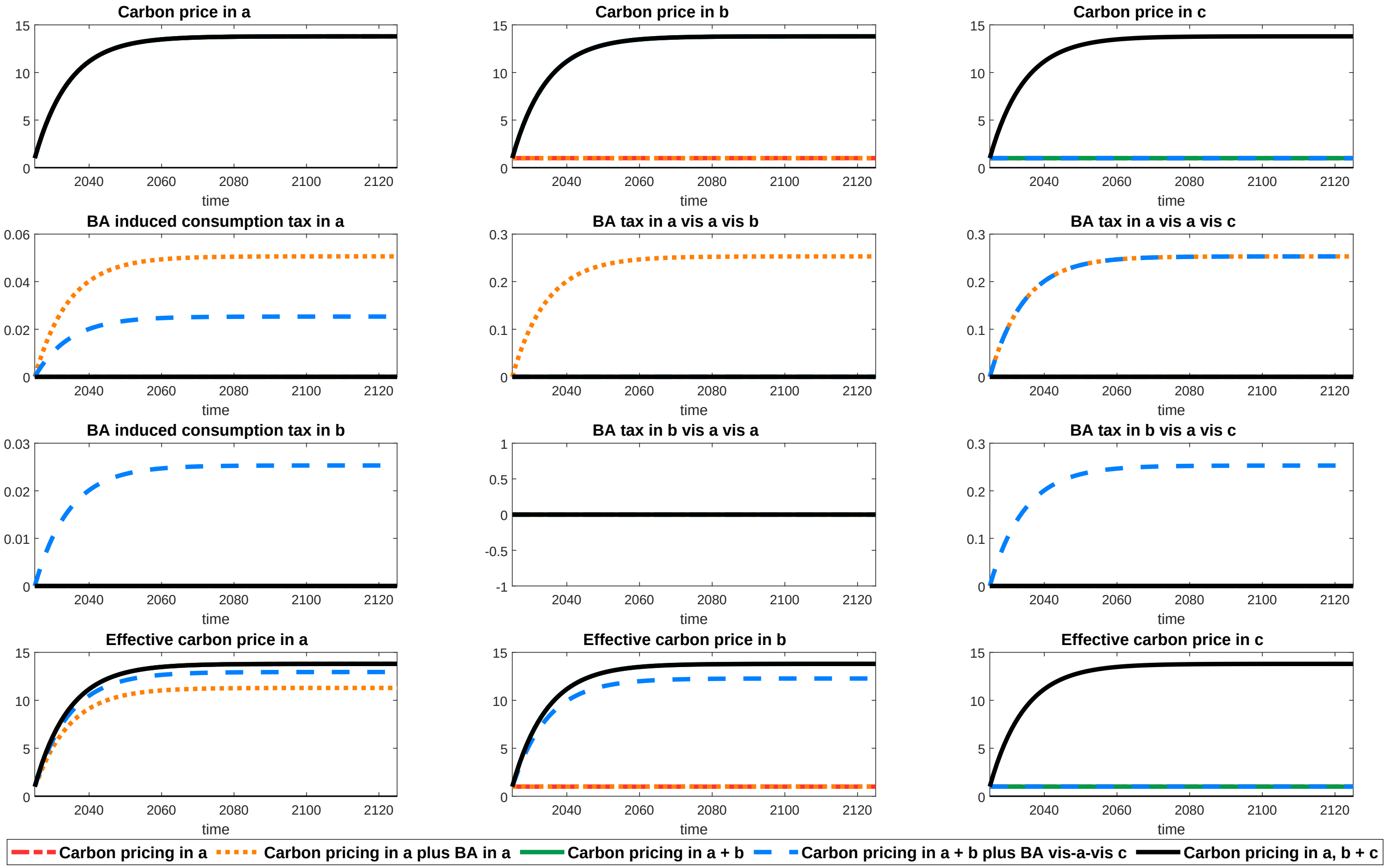
Source: The superscript e marks endogenously derived values to meet targets. Parameters without a mark are set exogenously as described in the main text. We omit the country index i for convenience.

5 Baseline simulations

We will now describe the simulation design and the simulation results. We closely follow Ernst et al. (2023) in simulating carbon pricing, border adjustment and climate clubs.

Simulation design We distinguish between five policy scenarios. First, we increase carbon pricing in Europe (region a) only. Second, we assume that Europe increases 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 all regions introduce the same carbon price. 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.

Figure 1: Evolution of (effective) carbon prices and border adjustment tax rates



Notes: Figure plots the evolution of (effective) carbon prices (relative to its steady-state value) and carbon border adjustment taxes (in percantage point deviations) according to the corresponding simulations. 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 solid black line. These are the (implied) policy inputs in our scenario analyses.

As regards the carbon price path that we feed into the model, we assume that it is the same across regions for those who increase carbon pricing. It is given exogenously and its final value – almost 15 times its current value – 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. The increase follows an AR(1) process. In the final steady state, it will remain constant at the higher level (see Figure 1). Hence, formally $P^{em}_{i,t}$ is 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.

For 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 $P^{em}_{i,t}$. In addition, they subsidize exports to protect their domestic industries by setting the indicator function to one. The tax rate is formally given by $\tau^{b,i,j}_t = P^{em}_{i,t} \cdot \kappa_j$ as it applies to quantities produced in the foreign regions.[7]

We differentiate between two fiscal scenarios. In our baseline scenario, carbon-related revenues are redistributed in a lump-sum manner to all households (by using LS^i_t to close to government budget). In our alternative scenario, only the working-aged population benefits (by using τ^i_t to close the government budget). In a way, this can be seen as a proxy for using revenues to alleviate labor taxation, for example.

Results The evolution of selected variables are shown in Figures 2 to 7. The new steady state (relative to the initial one) is depicted in Table 4. 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 the evolution of several key macroeconomic and environmental variables is almost independent of the fiscal scenario, we only show their evolution under the lump-sum redistribution scenario to save even more space. To verify the similarities, compare Figures 2 and 3 to their counterparts in the Appendix.

As Figure 2 reveals, an increased carbon price leads to a fall in domestic production, at least initially. The underlying mechanism is straightforward: as pollution becomes costly, marginal production costs increase, which leads to higher prices and dampens demand for these goods. The fall in production is associated with reduced capital input and lower investment. As a result, wages fall along with the marginal product of labor. In addition, the higher price for emissions generates an incentive for firms to invest in mitigation efforts which, together with lower production, reduces the emissions stock (see Figure 3). A reduced emissions stock decreases economic damage and improves productivity. Higher productivity, in turn, generates positive economic effects. Whether these effects eventually offset the negative cost-push effects depends on the extent to which the emissions stock is reduced and, consequently, on the magnitude of the resulting damage reduction. Figure 2 shows that, for region a, the positive effects do not outweigh the negative ones if only region a increases the carbon price. If, however, region b also does so, the resulting damage reduction is sufficiently high for region a to eventually offset the cost increase in terms of

[7] We could also assume $\tau^{b,i,j}_t = P^{em}_{i,t} \cdot (1 - U_{j,t}) \cdot \kappa_j$, where abatement efforts are taken into account. The resulting border adjustment tax rate would be a little smaller in this case, relative to the one in the simulations shown below. The resulting quantitative difference are negligible, however. Qualitatively, there are none.

output. This effect becomes even stronger if region c also increases its carbon price (see the Appendix).

In addition, carbon pricing fosters carbon leakage (see Figure 3). As goods in regions with carbon pricing become more expensive, domestic and foreign demand is tilted towards (similar) products produced in regions without carbon pricing, potentially using a dirtier production technology. Hence, those regions benefit from higher demand for their products. A carbon border adjustment mechanism can mitigate carbon leakage, but has only limited effects. The border adjustment mechanism increases the costs of dirty imports and makes exports from regions with carbon pricing cheaper (by reducing the effective carbon price depending on the export content). However, these effects are not strong enough to fully compensate for the carbon pricing-induced cost push.

These findings are in line with Ernst et al. (2023). However, some interesting differences result from our framework. The negative impact on consumption is much smaller compared to a standard DSGE model, and domestic consumption is less aligned with domestic production. Why is this the case?

In our framework, consumption dynamics are primarily driven by changes in savings behavior, which in turn crucially depend on the chosen carbon revenue recycling scheme. When carbon revenues are redistributed to all households in a lump-sum manner, the income of pensioners increases, see Figure 4. This increase in old-age income reduces the incentive to save for all households. We find that, indeed, aggregate saving falls in regions that introduce carbon pricing (Figure 6). Retirees start to consume more (Figure 5). The working-age population also receives part of the carbon revenues, which increases their income ceteris paribus. However, lower output dampens wage income, and this latter effect more than offsets the transfer-induced income gain when carbon revenues are redistributed uniformly. Thus, workers decrease consumption (Figure 5) and saving (due to reduced wage income and higher expected old-age income). The reduction in saving initially boosts consumption. Whether the increase in aggregate consumption is permanent depends on the extent to which aggregate income rises (see Figure 5).[8] The likelihood that this happens increases with the number of regions participating in carbon pricing – reflecting stronger damage reduction – and with the introduction of a border adjustment mechanism, which mitigates wage income losses.

Trade spillovers lead to mildly higher saving in regions that do not introduce carbon pricing (as a result of higher income from trade and carbon leakage). However, the effect is not strong enough to offset the fall in saving in regions that introduce carbon pricing, see Figure 6. As world saving falls, the natural interest rate r^* increases. This effect is larger the more regions participate in carbon pricing (with a lump-sum revenue recycling scheme).

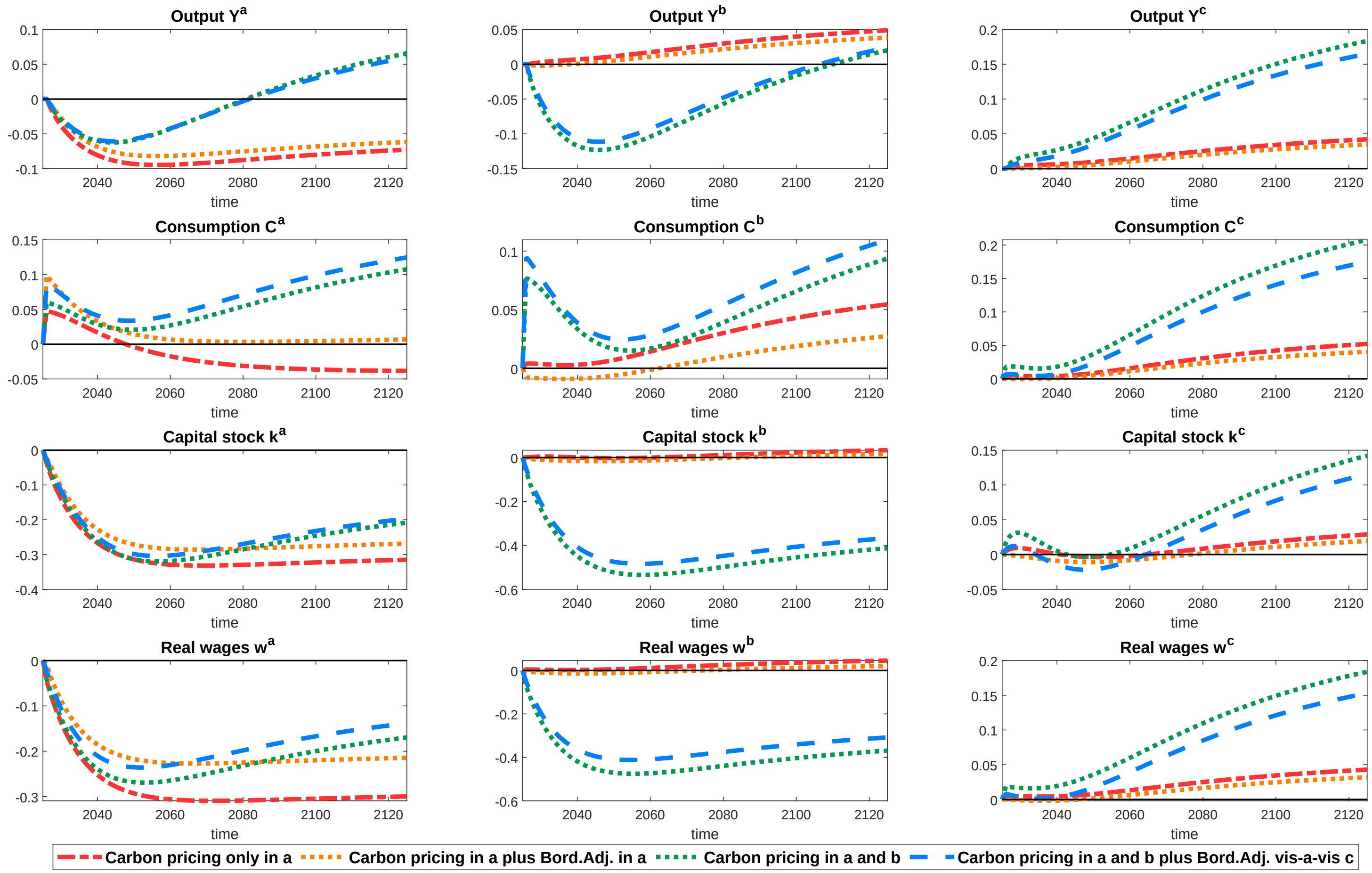
[8]For aggregate consumption to rise permanently, aggregate income in the economy must rise sufficiently such that the drop in the marginal propensity to consume of workers is compensated by the higher income.

Table 4: Long-run effects

Scenario:	$P_a^{em} \uparrow$	$P_a^{em}, \tau_{a,\tilde{i}}^X \uparrow$	$P_i^{em} \uparrow$ for $i = a, b$	$P_i^{em}, \tau_{i,\tilde{i}}^X \uparrow$ for $i = a, b$	$P_i^{em} \uparrow$ for $i = a, b, c$
Output in a	-0.06	-0.06	0.13	0.13	0.91
Consumption in a	-0.03	0.00	0.16	0.19	0.94
Investment in a	-0.30	-0.31	-0.13	-0.13	0.64
Wages in a	-0.29	-0.26	-0.11	-0.09	0.66
Capital interest in a	0.01	0.05	0.02	0.05	0.02
Emissions in a	-11.07	-11.07	-10.90	-10.90	-10.21
Output in b	0.07	0.06	0.09	0.09	1.00
Consumption in b	0.08	0.05	0.16	0.18	1.03
Investment in b	0.05	0.04	-0.33	-0.33	0.56
Wages in b	0.06	0.04	-0.30	-0.29	0.57
Capital interest in b	0.01	0.00	0.03	0.05	0.01
Emissions in b	0.07	0.06	-14.79	-14.79	-14.02
Output in c	0.06	0.06	0.25	0.24	0.67
Consumption in c	0.07	0.06	0.28	0.26	0.88
Investment in c	0.05	0.04	0.22	0.20	-0.10
Wages in c	0.06	0.05	0.25	0.23	-0.06
Capital interest in c	0.01	0.01	0.03	0.03	0.03
Emissions in c	0.06	0.06	0.25	0.24	-14.70
Interest rate r^* (lump-sum)	0.04	0.04	0.10	0.09	0.11
Interest rate r^* (workers only)	-0.04	-0.05	-0.12	-0.14	-0.46

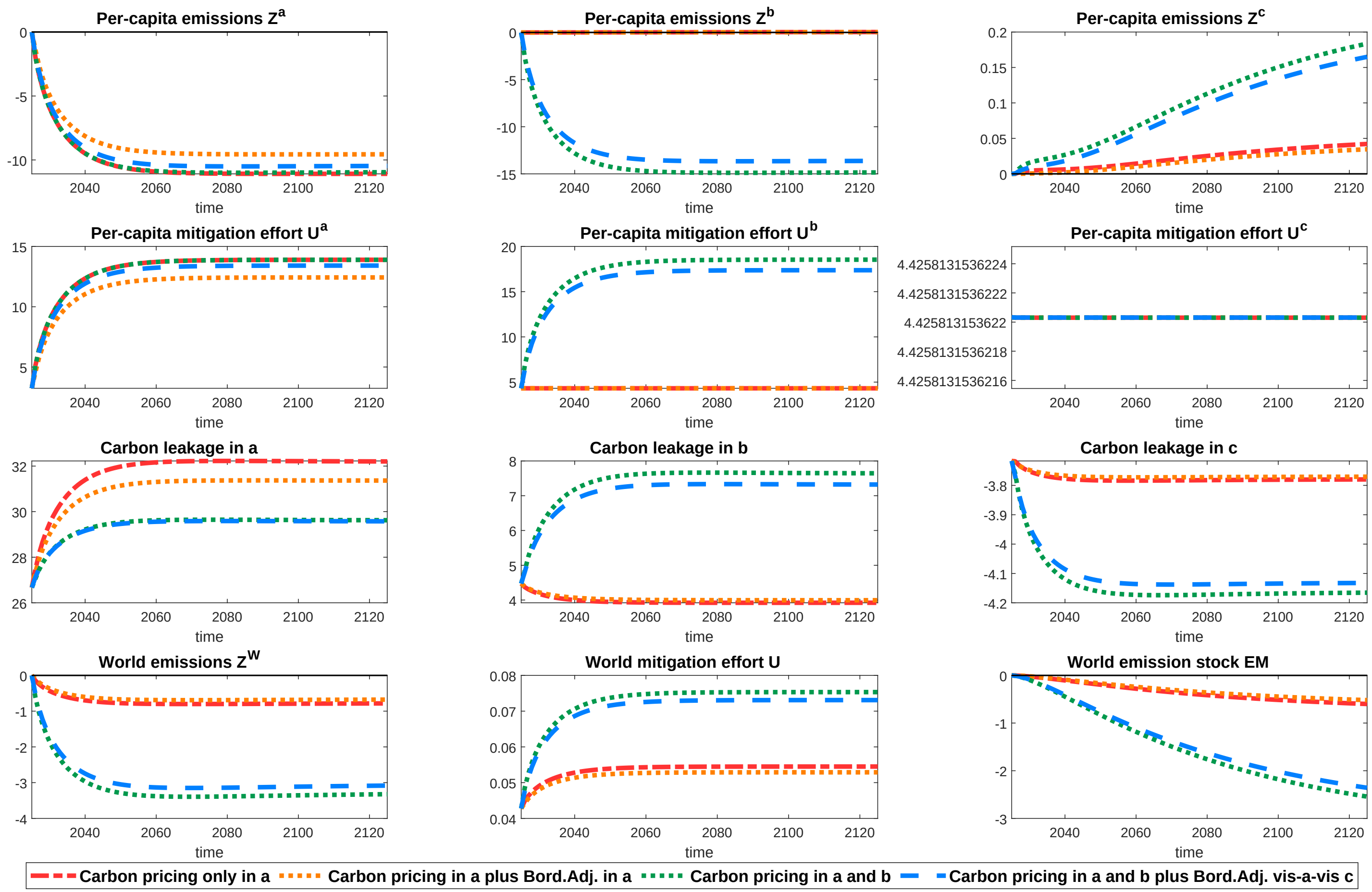
Notes: Table shows long-run effects on selected aggregate macro variables of different carbon pricing scenarios for regions a, b and c as well as for the world emissions stock, in percent deviations from initial steady state.

Figure 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. Baseline scenario with lump-sum redistribution.

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



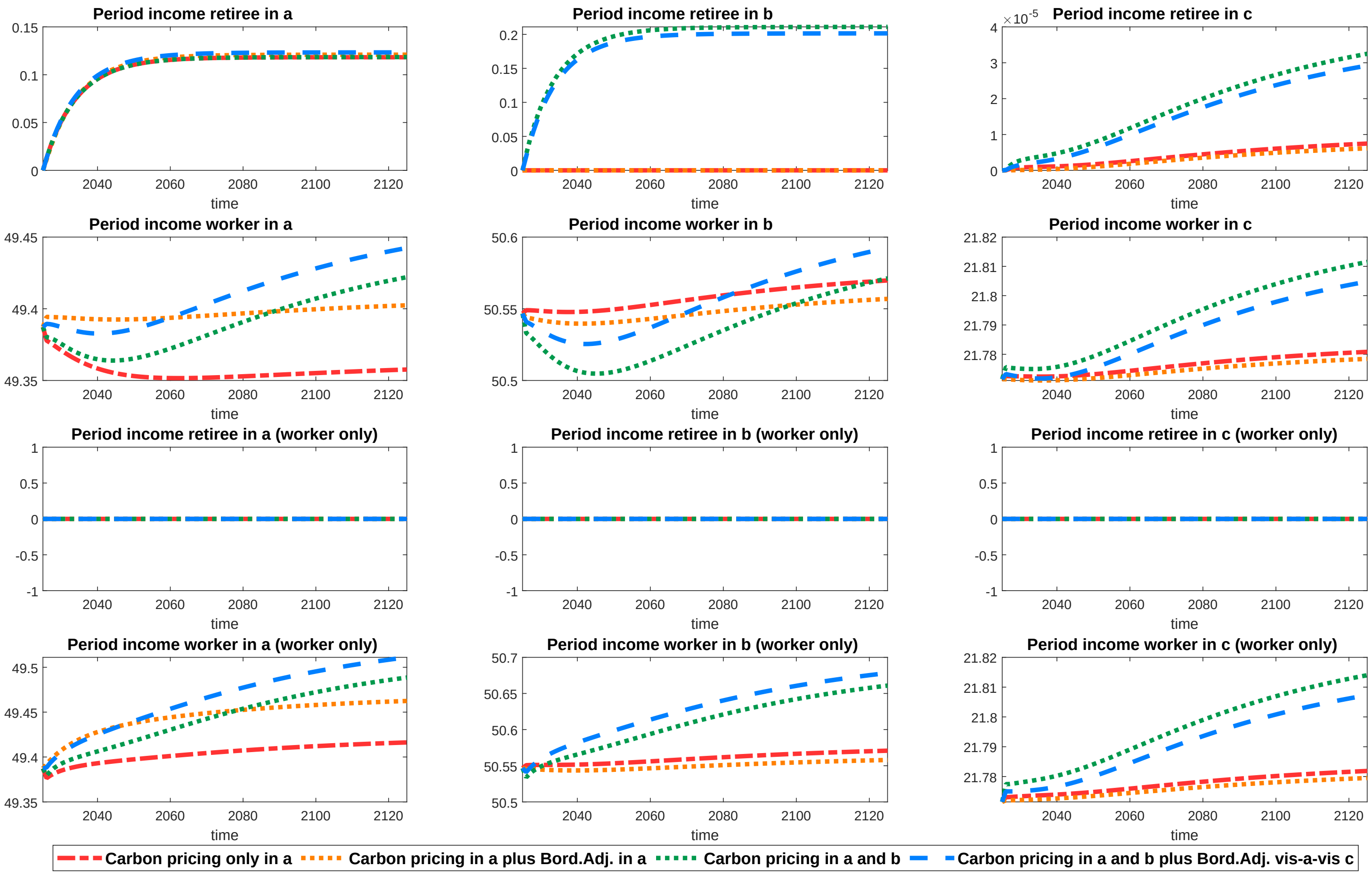
Notes: Figure plots (projected) implications of carbon pricing for selected key environmental variables in percentage(point) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted 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. Baseline scenario with lump-sum redistribution.

When revenues are redistributed to the working-aged population only (for example by lowering labor income taxation), workers' net income rises (Figure 4). While they face a drop in gross wage income, the transfer-induced income gain offsets this loss. Hence, workers consume more (Figure 5). By contrast, there is no direct positive income effect for retirees. At the same time, relative consumption costs increase. Hence, retirees reduce consumption and their incentive to save increases in order to smooth consumption in retirement. Workers save some of the additional income, too. As a result, aggregate saving in regions that introduce carbon pricing rises, at least in the medium to long term (Figure 6). The trade/carbon leakage spillovers increase saving in regions that do not have carbon pricing. Hence, the natural interest rate r^* falls due to higher medium to long-term world saving (Figure 6). Again, this effect is stronger the more regions participate in carbon pricing (with revenue redistribution to the working-age population only).

The impact of carbon pricing on net foreign assets depends on the redistribution scheme, too. It is again driven by the respective saving behavior. Independent of the recycling scheme, factor demand (including for domestic capital) falls on impact as a result of the cost push. It also remains lower due to the productivity gain induced by emissions reduction. When carbon revenue is redistributed to the working-age population, aggregate saving rises. In that case, the additional saving cannot be invested domestically due to falling domestic capital demand. Hence, net foreign assets rise in a region that increase carbon pricing and redistributes revenues to the working-age population only. The opposite is true when carbon revenues are redistributed in a lump-sum manner to all households. In this case, the drop in saving exceeds the reduction in capital investment opportunities (see Figures 2, 6 and 7).

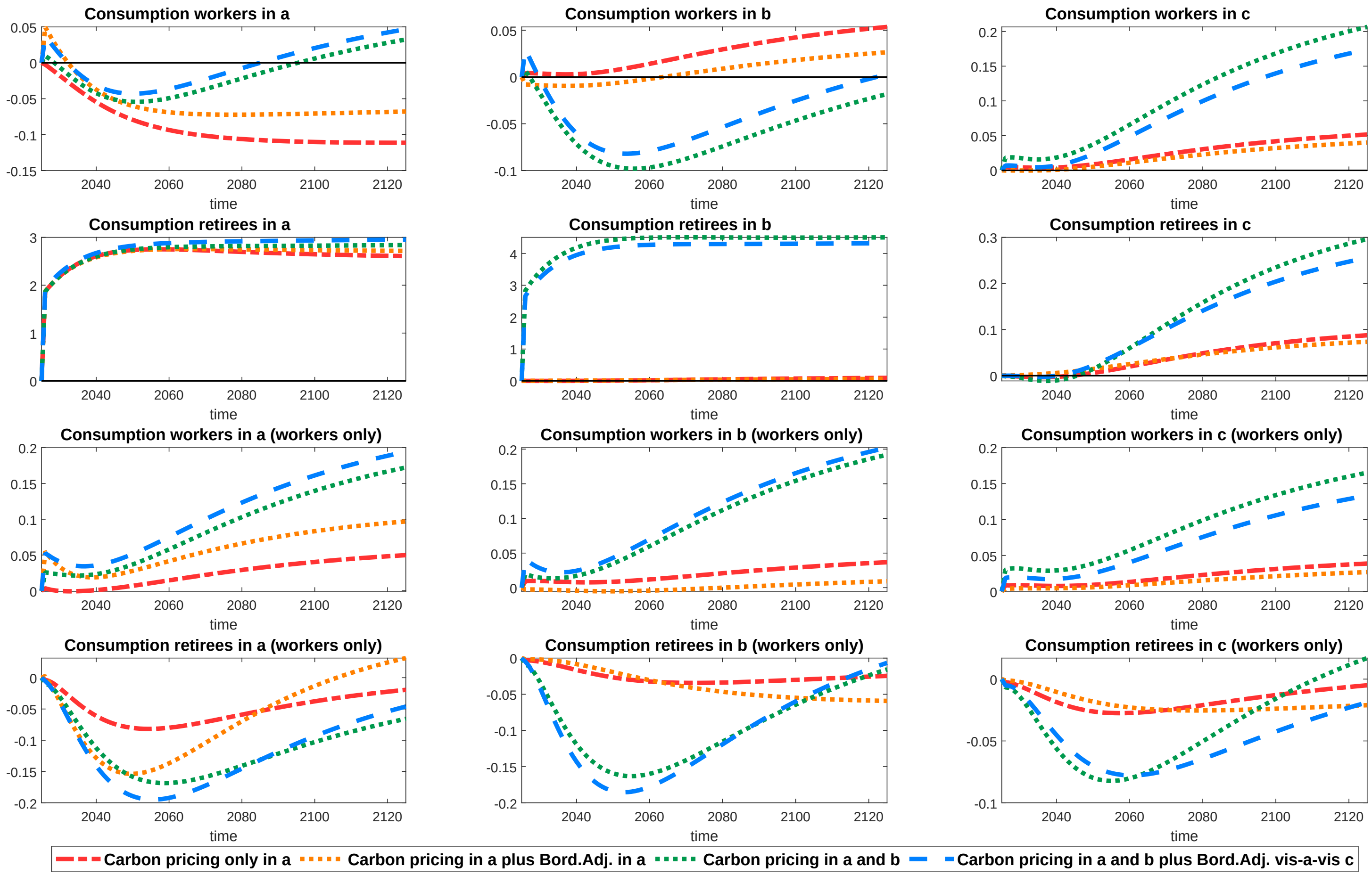
It comes as no surprise, that products from regions that increase carbon pricing become more expensive than those from regions which do not participate (depicted by the real exchange rate in Figure 7). A "dirtier" region takes a somewhat "harder hit" compared to a "cleaner" region that introduces the same carbon price. Hence, the same carbon price in, say, "clean" Europe and "dirty" North America generates a larger price increase in North America ceteris paribus. The trade balance reacts accordingly and deteriorates (Figure 8). It eventually recovers when carbon revenues are redistributed to all, to a significant part because of the weaker exchange rate effect relative to a situation in which only workers benefit from carbon revenues (Figures 7 and 8). As domestic savings are higher in a world in which only workers receive carbon revenues (Figure 6), so is the aggregate level of consumption eventually (see Figure 2 relative to A.1) because workers, who make up the larger share in population, do not decrease their level of consumption (Figure 5). This puts more upward pressure on prices of domestically produced goods as it is domestic households who buy the largest share. Hence, relative prices and, thereby, the real exchange rate are affected more. If they do, the trade balance deteriorates relatively more (Figure 7).

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



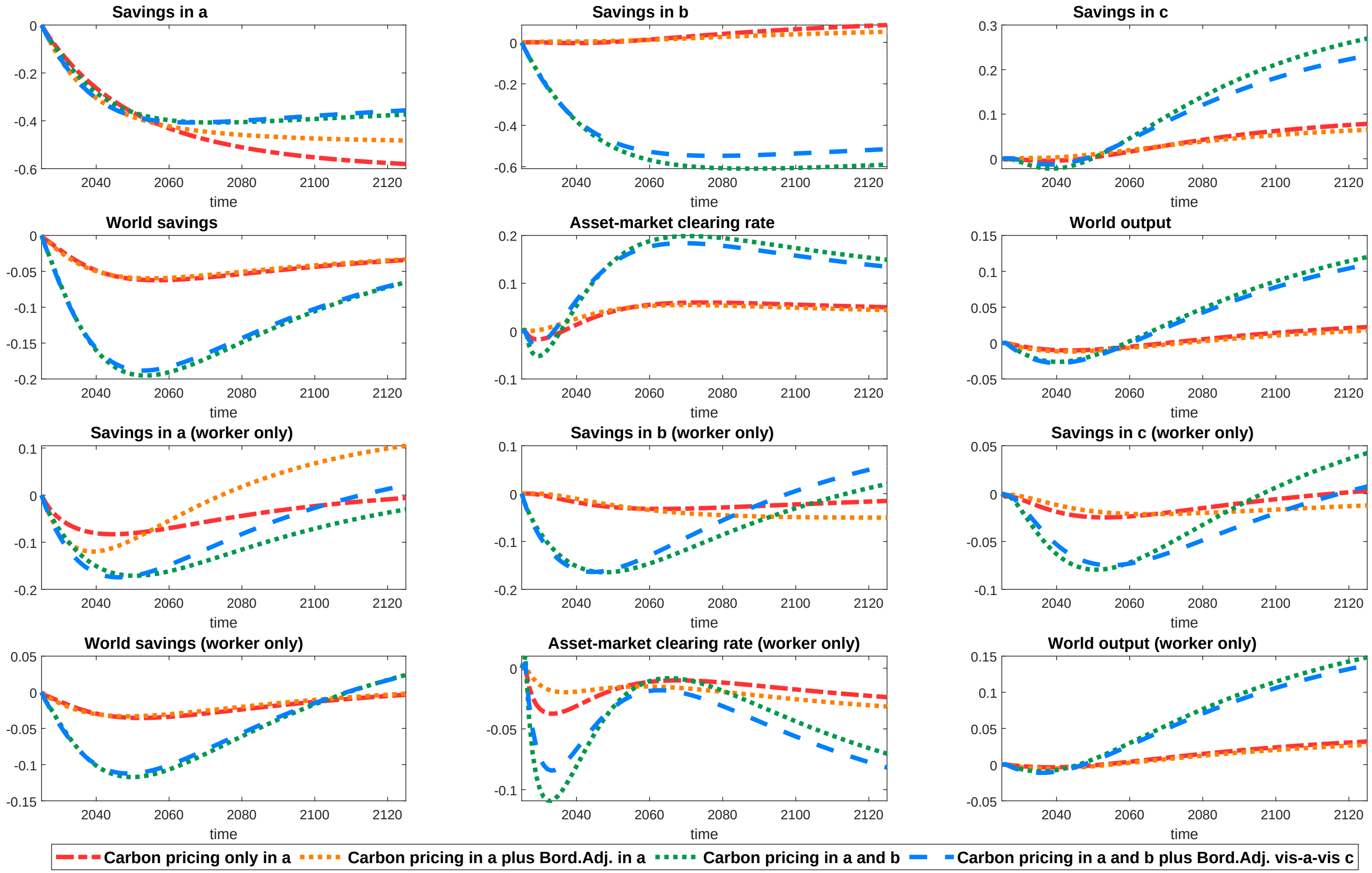
Notes: Figure plots (projected) implications of carbon pricing for income of workers and retirees in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the orange 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. Baseline scenario with lump-sum redistribution in upper two rows, distribution to workers only in lower two rows.

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



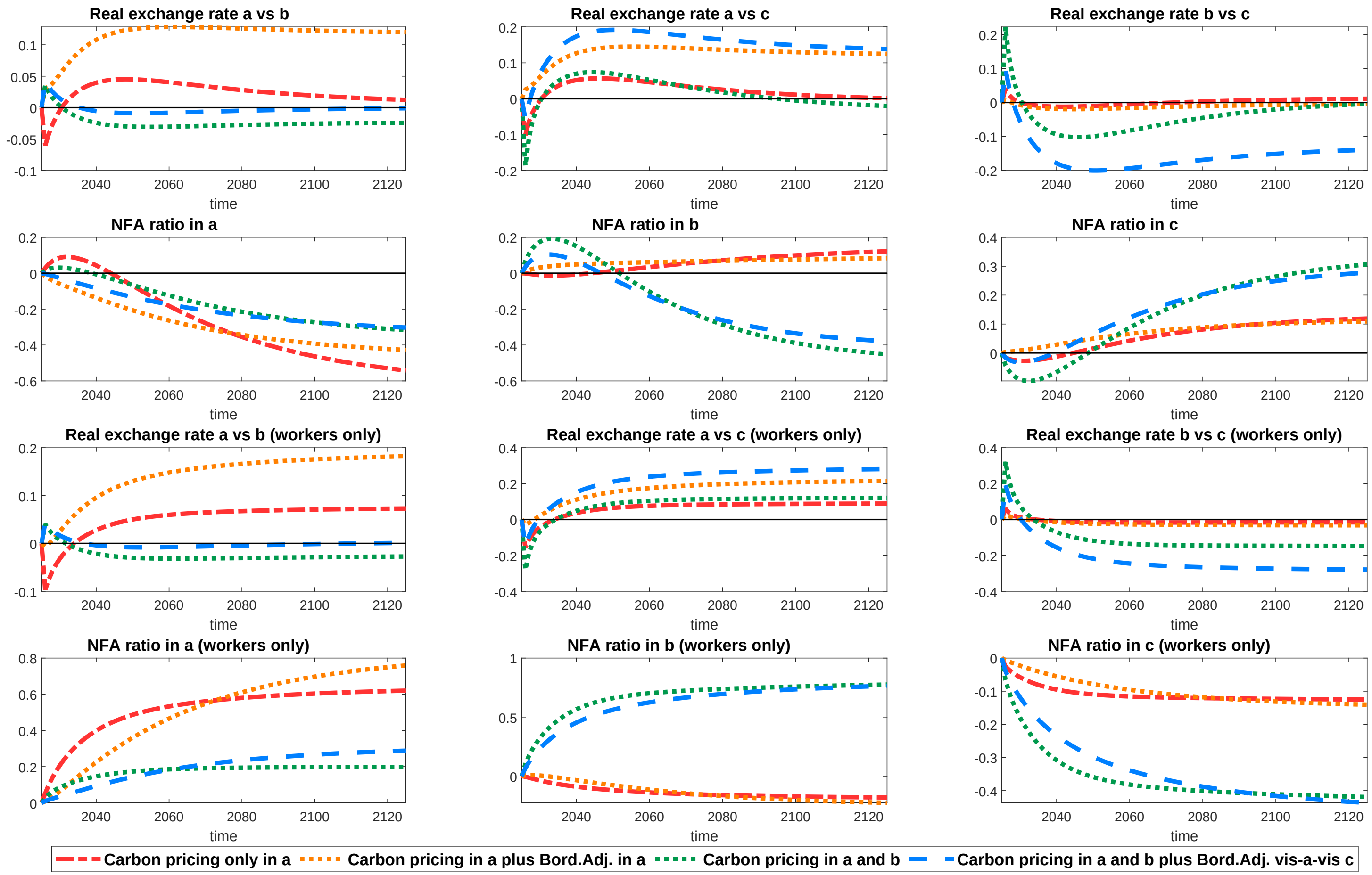
Notes: Figure plots (projected) implications of carbon pricing for consumption of workers and retirees in percentage (levels for marginal propensities to consume) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a 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. Baseline scenario with lump-sum redistribution in upper two rows, distribution to workers only in lower two rows.

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



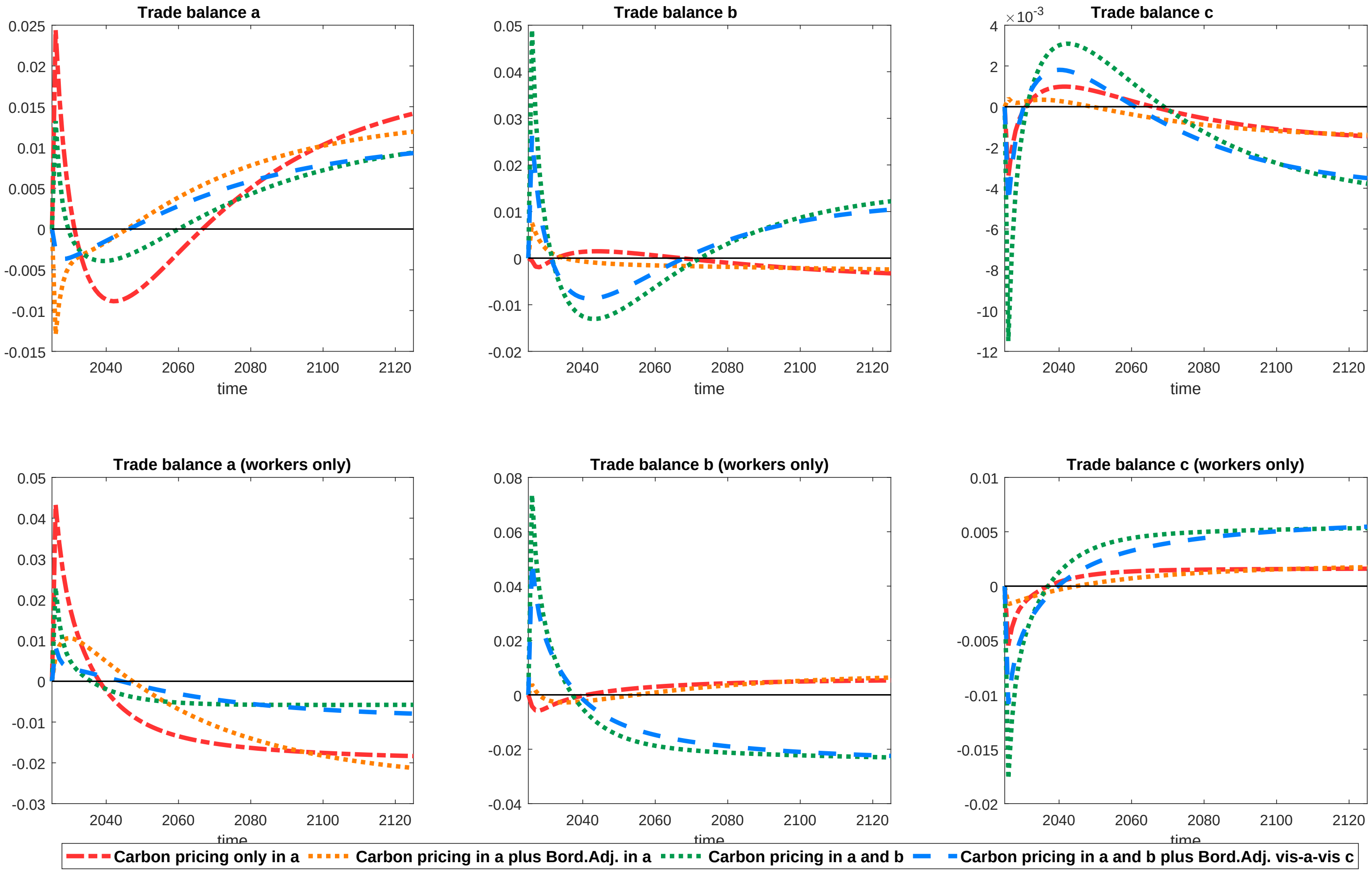
Notes: Figure plots (projected) implications of carbon pricing for savings, interest rates and world output in percentage(point) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted 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. Baseline scenario with lump-sum redistribution in upper two rows, distribution to workers only in lower two rows.

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. Baseline scenario with lump-sum redistribution in upper two rows, distribution to workers only in lower two rows.

Figure 8: Implications of carbon pricing for trade balance



Notes: Figure plots (projected) implications of carbon pricing for the trade balance 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. Baseline scenario with lump-sum redistribution in upper two rows, distribution to workers only in lower two rows.

To sum up, our results show that the impact that carbon pricing policies have on world saving and the natural interest rate r^* primarily depends on the choice of the carbon revenue recycling scheme. r^* is likely to increase when the incentive to save falls. In our model, this is the case when the old-age population receives higher transfers from carbon pricing revenues. Households' incentives to save are also influenced by many other factors. For example, a pay-as-you-go pension system reduces the incentive to save, in general. While at the same time, the associated fall in wages fosters saving due to reduced pension income. In addition, the demographic situation itself fosters saving, namely the increase in the old-age dependency ratio and increasing longevity in many Western economies. Some of these factors may have a stronger and more direct impact on the natural interest rate r^* than climate policies. Nevertheless, as we have seen, the impact of climate policies is relevant and should be borne in mind.

Also note that, in some European economies, there are discussions about improving the pension system by using part of the carbon revenue to foster private savings (see also Wendner, 2001 for a discussion). Additional simulations in the appendix show that households indeed save more in that case. While the macroeconomic implications remain similar both qualitatively and quantitatively, r^* unambiguously falls substantially more as a result of higher savings. In contrast to the baseline simulations, production becomes more capital intensive and net foreign assets increase more. Still, the qualitative findings of the previous simulations remain valid.

6 Conclusions

The introduction of carbon pricing generates a reduction of emissions but also of production, at least in the first phase of the transmission. This is because production becomes more expensive. As soon as the emissions reduction decreases emissions-induced (production) damage, it eventually generates positive economic spillovers. However, it takes time before these positive effects overcompensate the adverse effects of the cost push on output. The more regions introduce carbon pricing, the more likely is the latter to happen (faster).

The cost push and emissions reduction also affect households' savings behavior and, thereby, the natural interest rate r^* in the end. Simulations in a dynamic, three-region environmental life-cycle model show that the interest rate effects crucially depend on how governments recycle carbon revenues. If these are paid back to all households in a lump-sum manner, savings fall and the natural rate increases permanently. Higher carbon pricing-induced income of retirees fosters their incentive to consume less and save more. The opposite holds true if only the working-aged population benefits from carbon revenues.

The impact on net foreign assets, exchange rates and trade flows depends on which regions introduce carbon pricing (and potential border adjustment mechanisms) as this ultimately determines if (potentially higher) domestic savings are invested at home or abroad.

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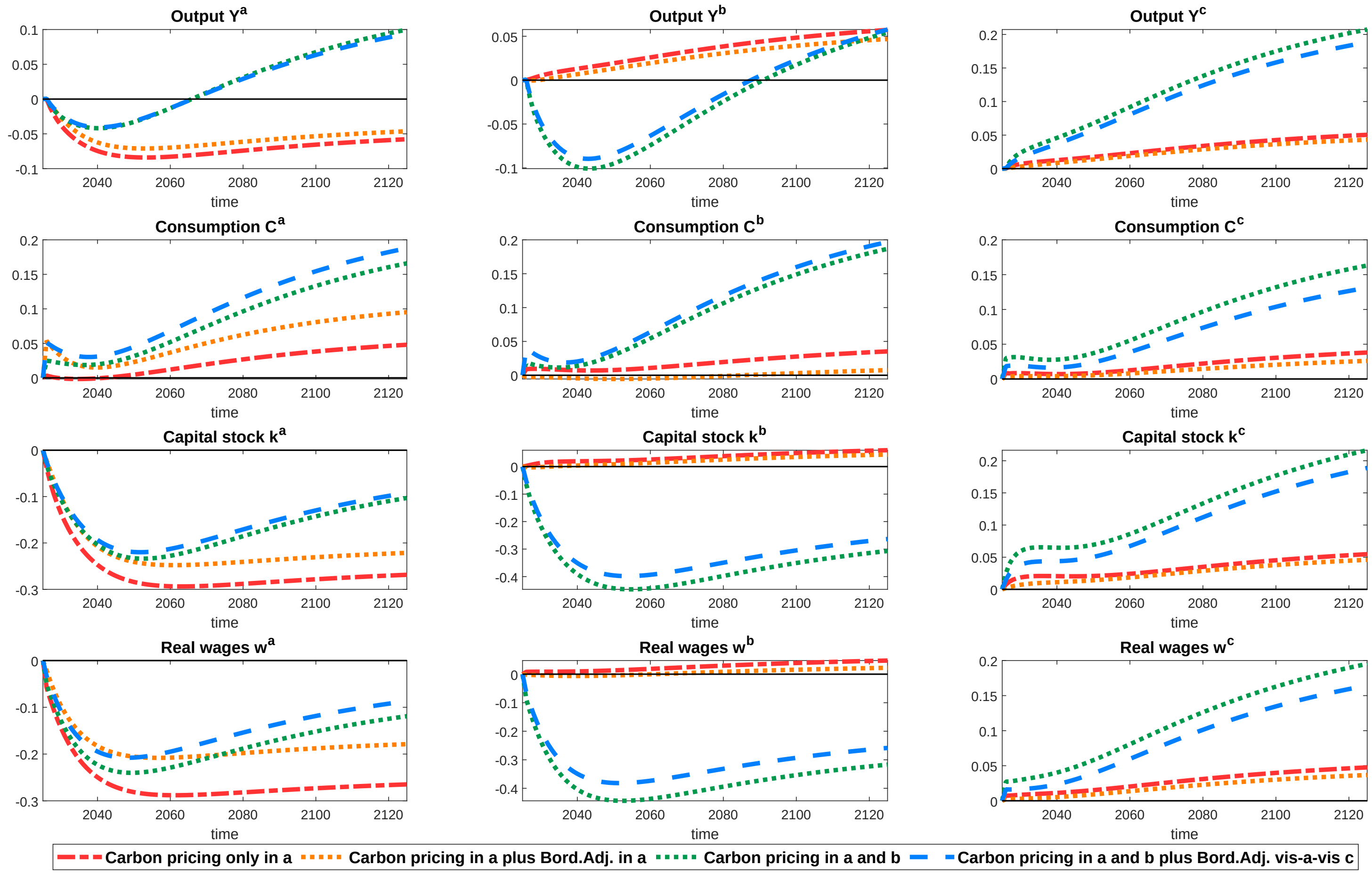
Appendix A: Additional results

In this appendix, we

- show macro and environmental variables when only workers receive carbon pricing revenues (Figures A.1 and A.2, the analogues to 2 and 3);
- replicate the graphs of the main text, now including the fifth scenario (Figures A.3 to A.8);
- replicate the analysis to compare a full border adjustment mechanism (with subsidies) to a mechanism with border adjustment taxation only (Figure A.9),
- show simulation results when carbon pricing revenues are used to foster household savings (Figures A.10 to A.12).[9]

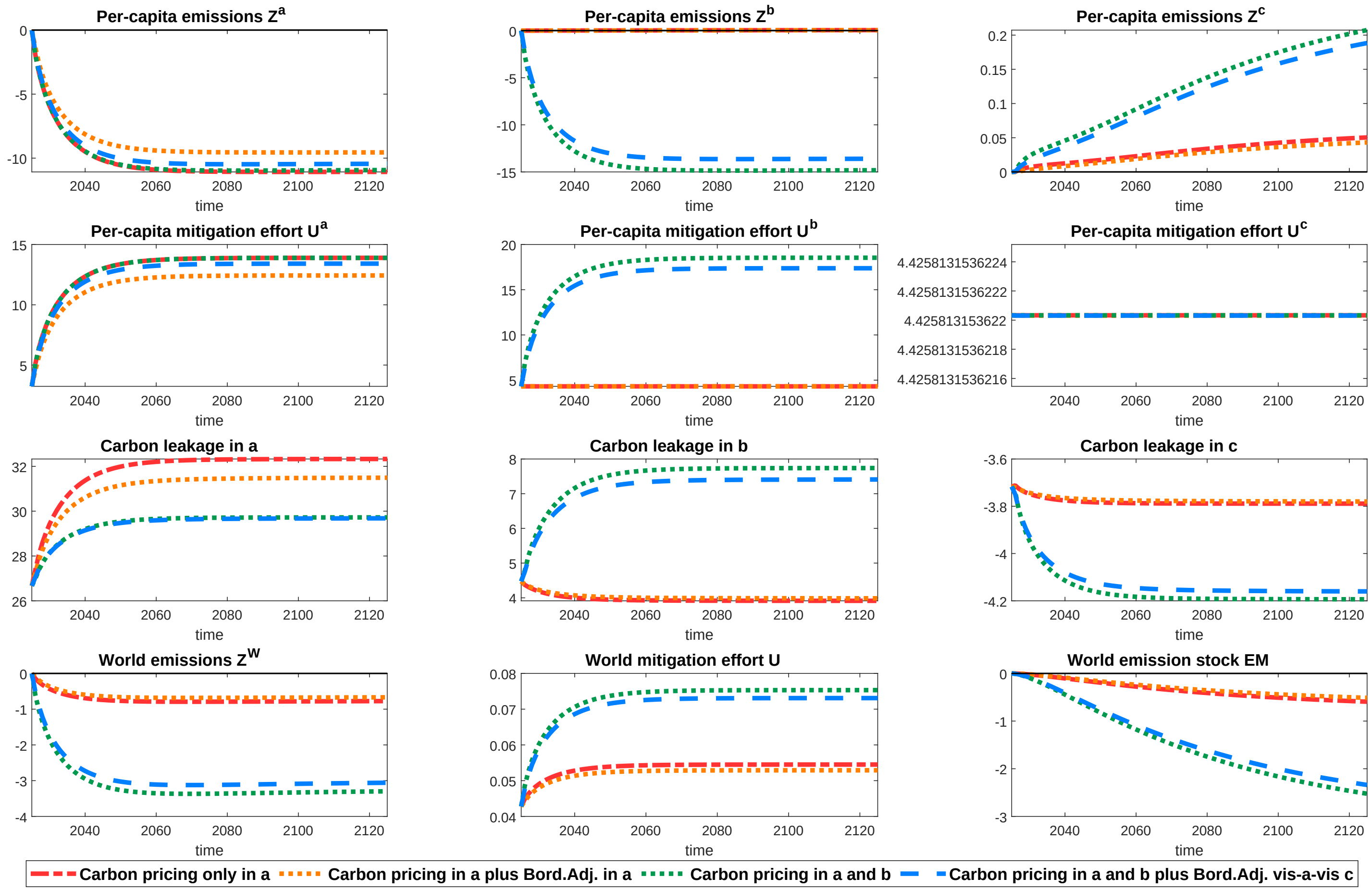
[9] In the simulations presented, we assume that governments that introduce carbon pricing use revenues to subsidize interest on savings. Alternatively, savings could be fostered directly for both groups or for a single group (such as workers). In that case, results would change quantitatively but remain qualitatively similar.

Figure A.1: Implications of carbon pricing for selected key macroeconomic variables (workers only)



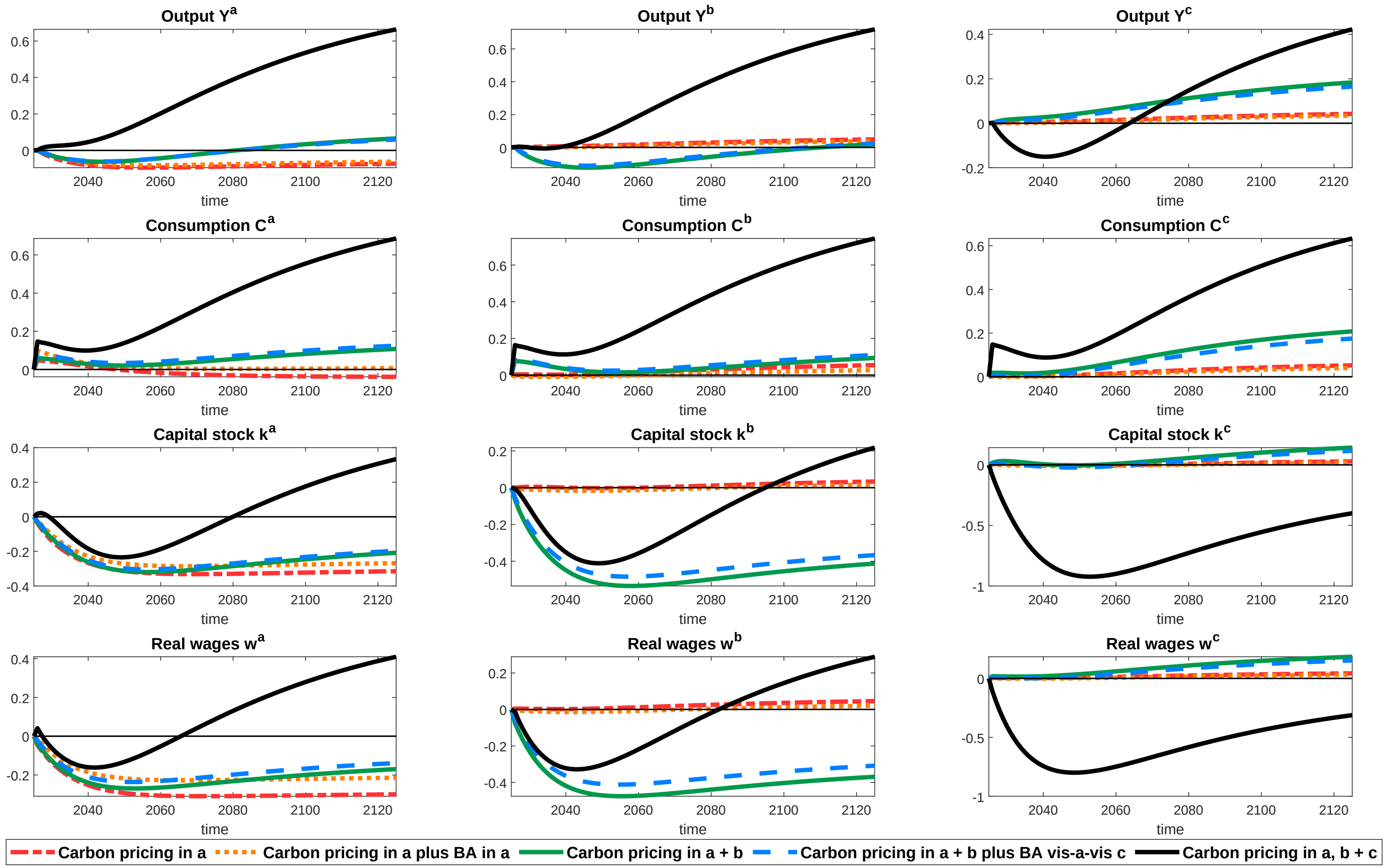
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the 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. Scenario with redistribution to workers only.

Figure A.2: Implications of carbon pricing for selected key environmental variables (workers only)



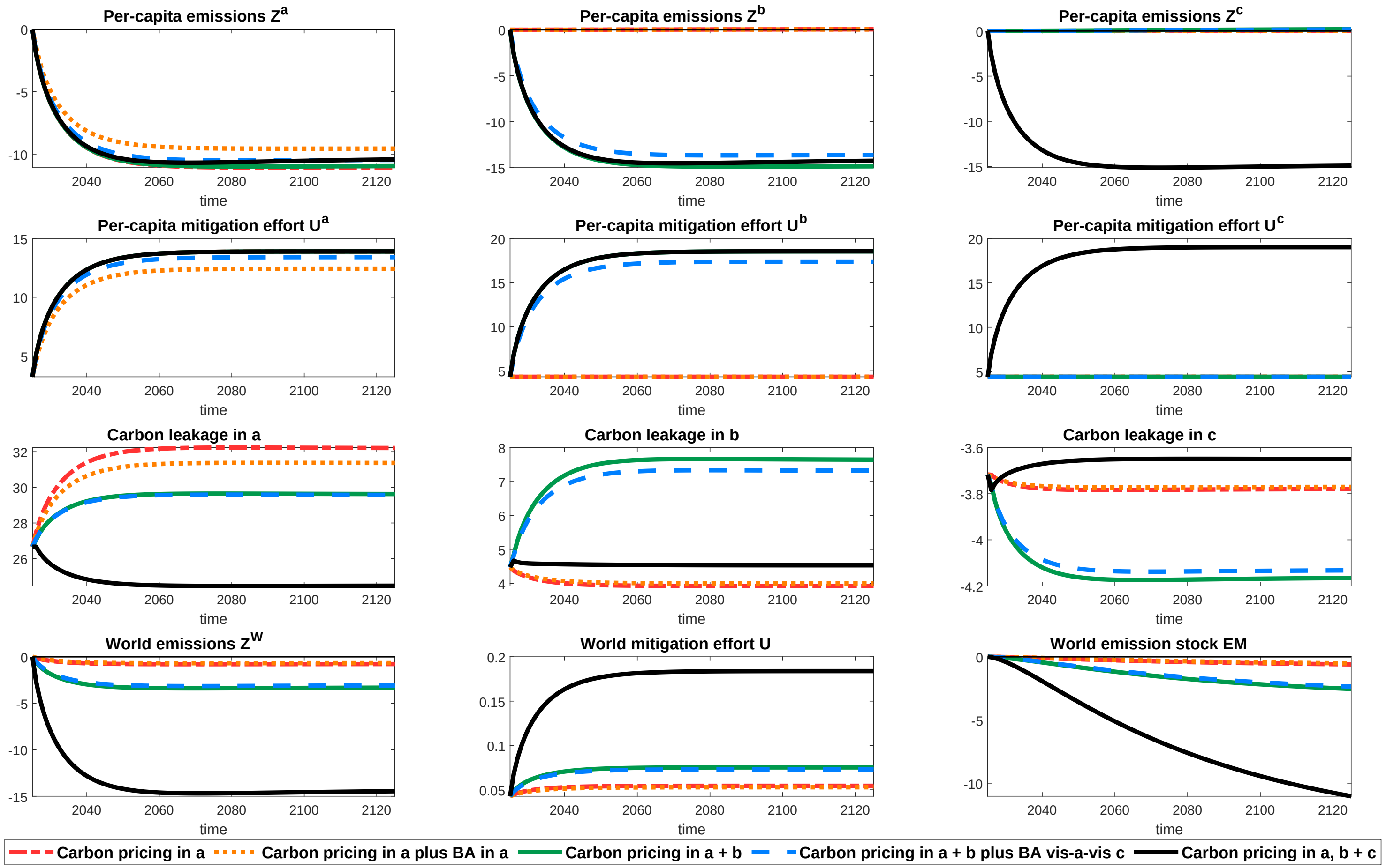
Notes: Figure plots (projected) implications of carbon pricing for selected key environmental variables in percentage(point) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted 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. Scenario with redistribution to workers only.

Figure A.3: Implications of carbon pricing for selected key macroeconomic variables



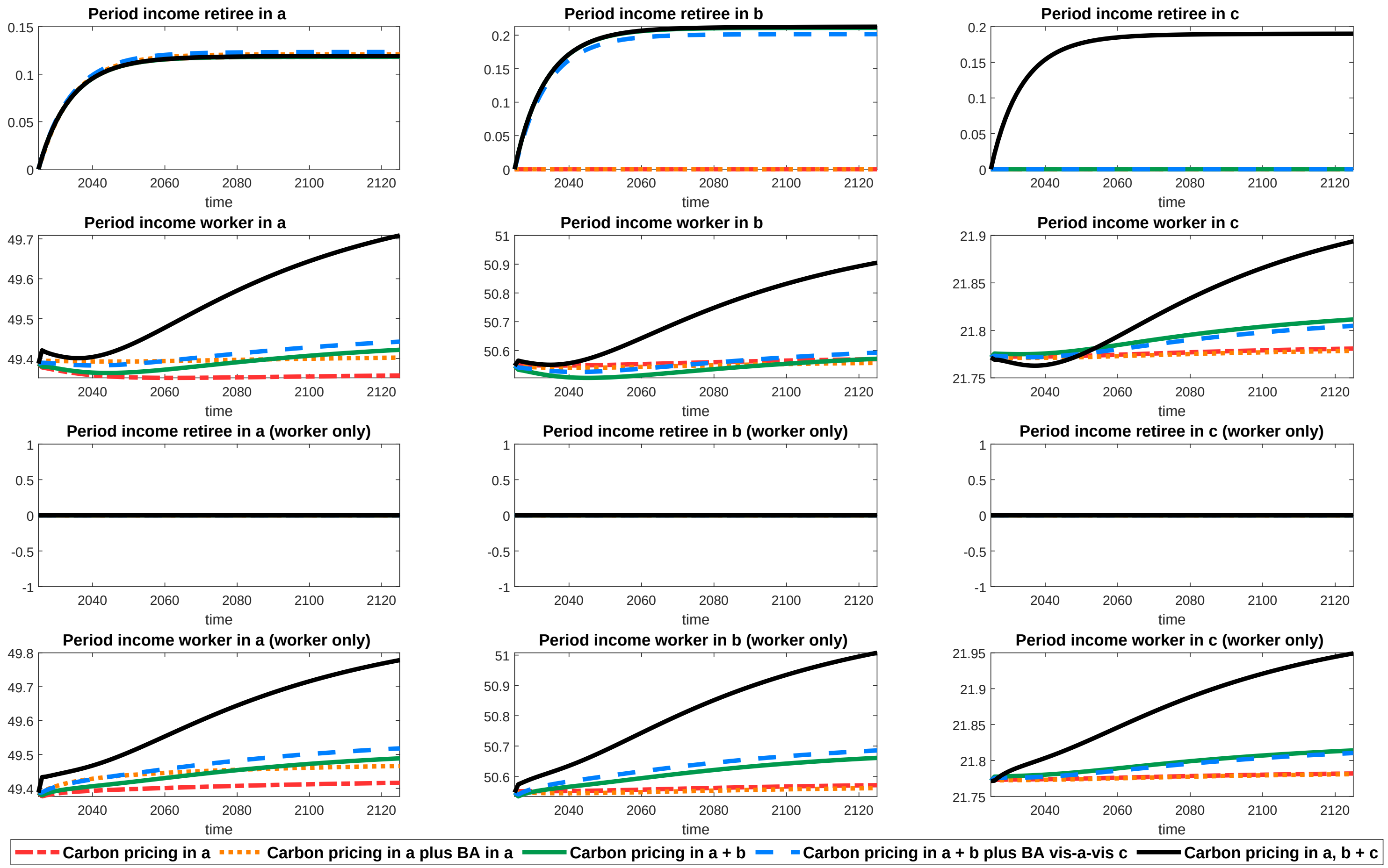
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the 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 A.4: Implications of carbon pricing for selected key environmental variables



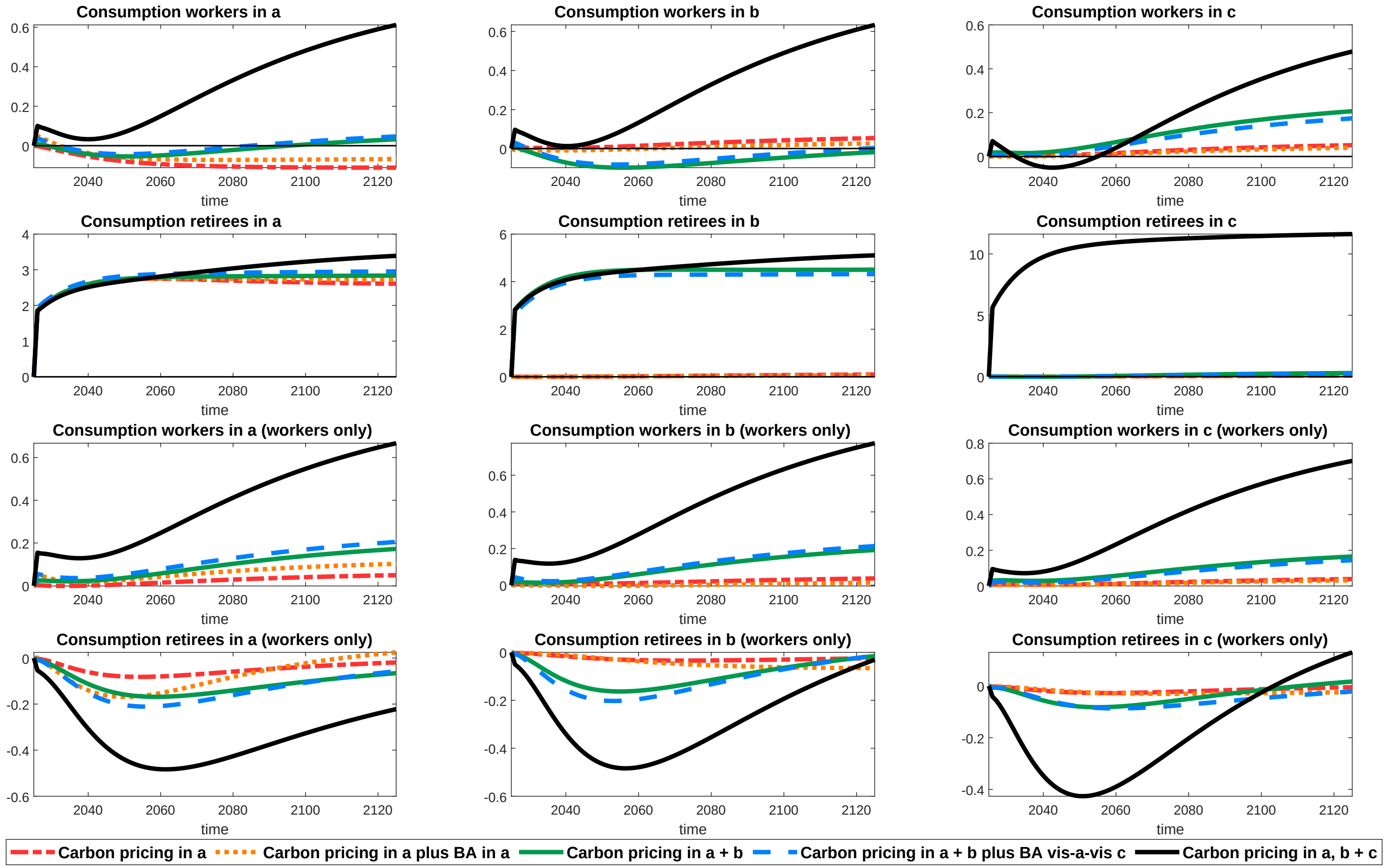
Notes: Figure plots (projected) implications of carbon pricing for selected key environmental variables in percentage(point) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted 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 A.5: Implications of carbon pricing for income of workers and retirees



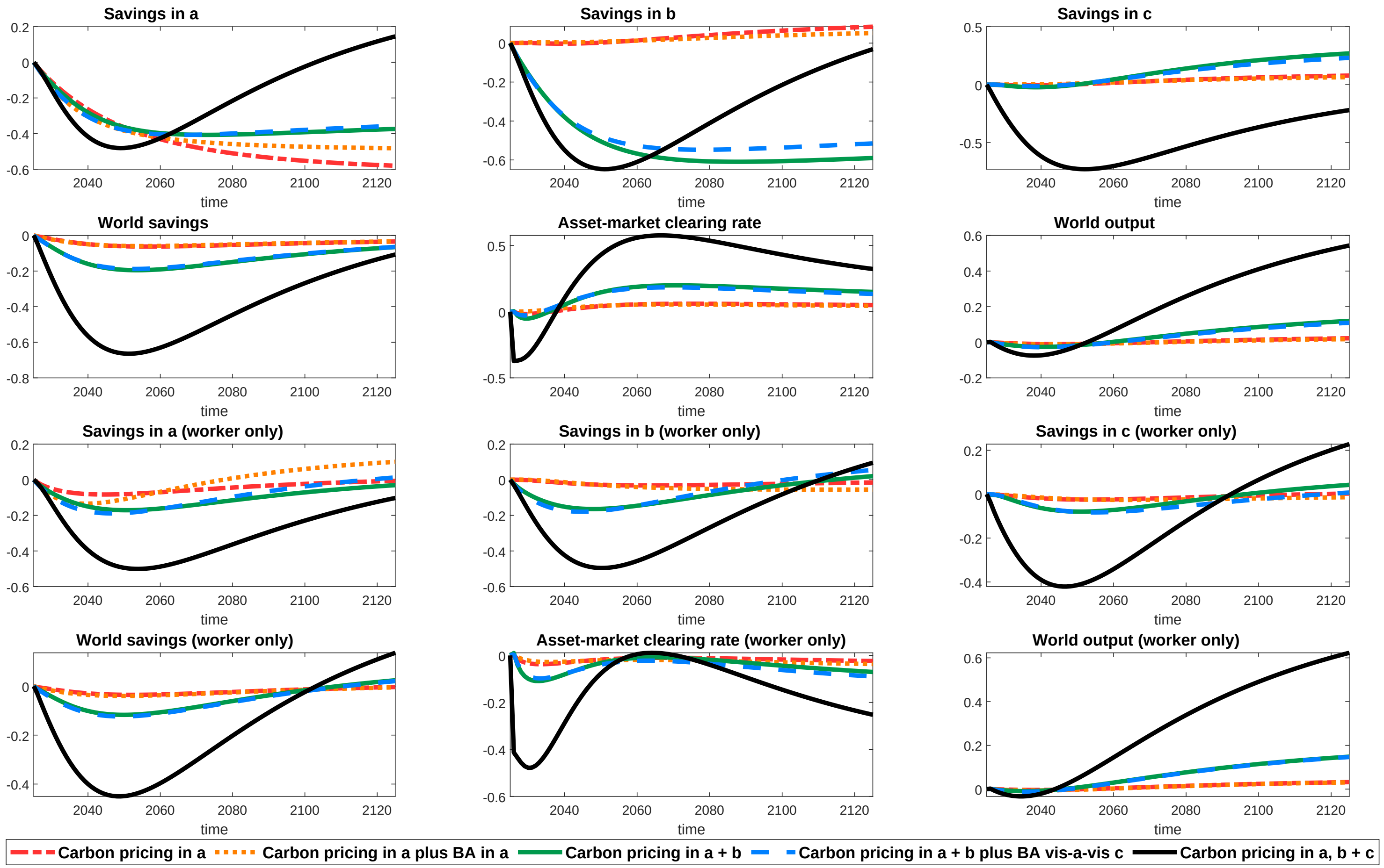
Notes: Figure plots (projected) implications of carbon pricing for income of workers and retirees in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the orange 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 A.6: Implications of carbon pricing for consumption of workers and retirees



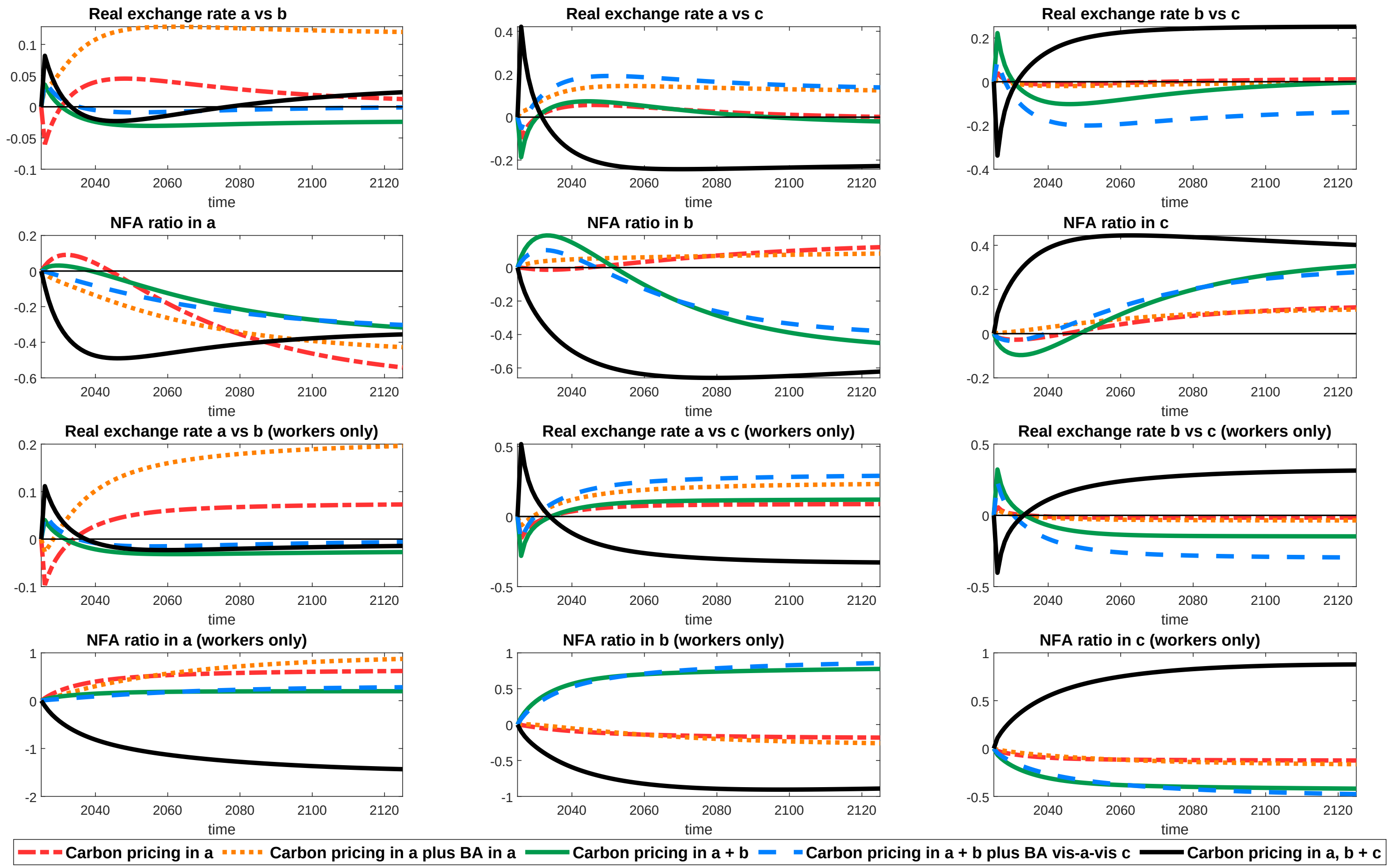
Notes: Figure plots (projected) implications of carbon pricing for consumption of workers and retirees in percentage (levels for marginal propensities to consume) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a 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 A.7: Implications of carbon pricing for savings, interest rates and world output



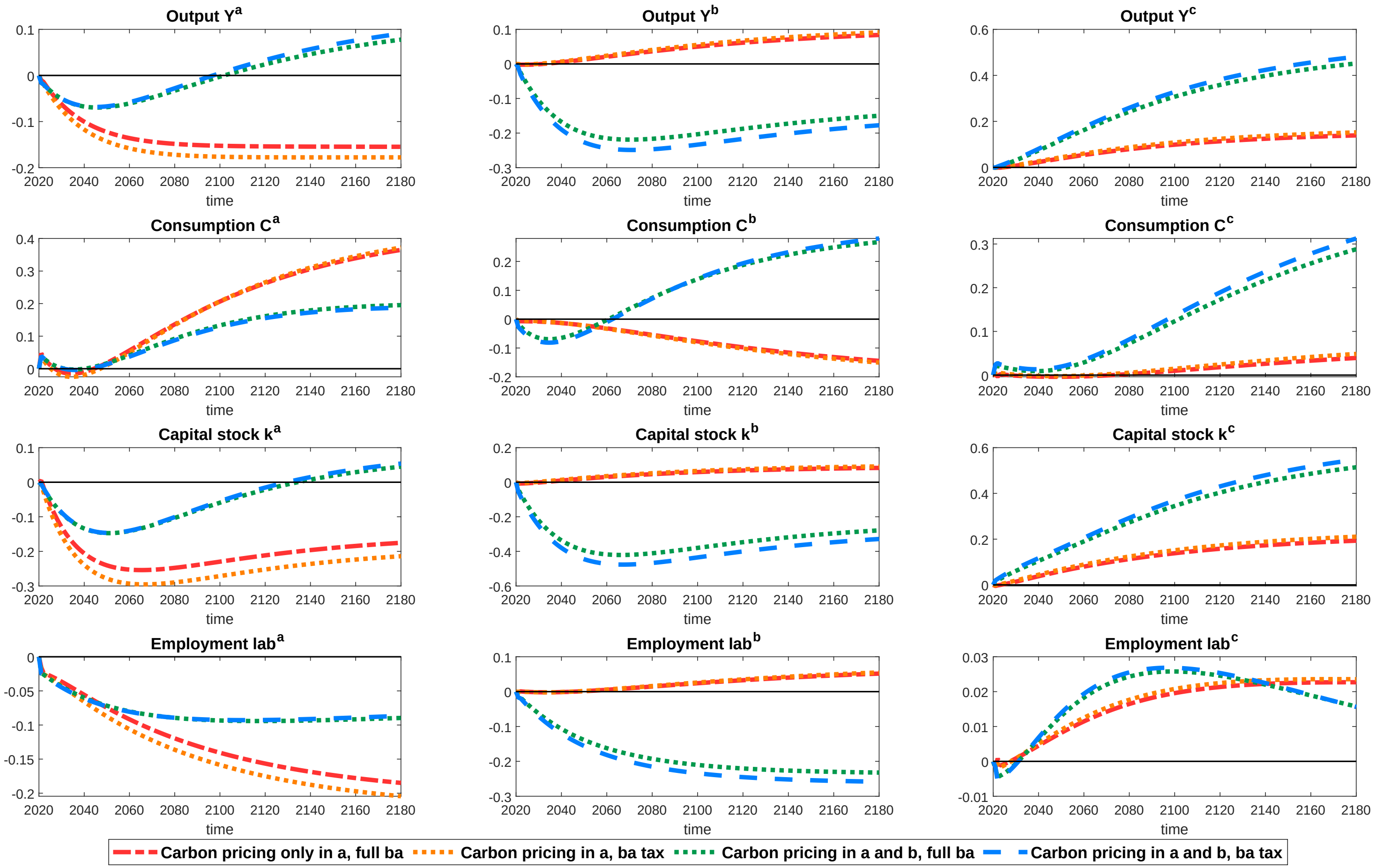
Notes: Figure plots (projected) implications of carbon pricing for savings, interest rates and world output in percentage(point) deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted 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 A.8: Implications of carbon pricing for selected key trade-related variables



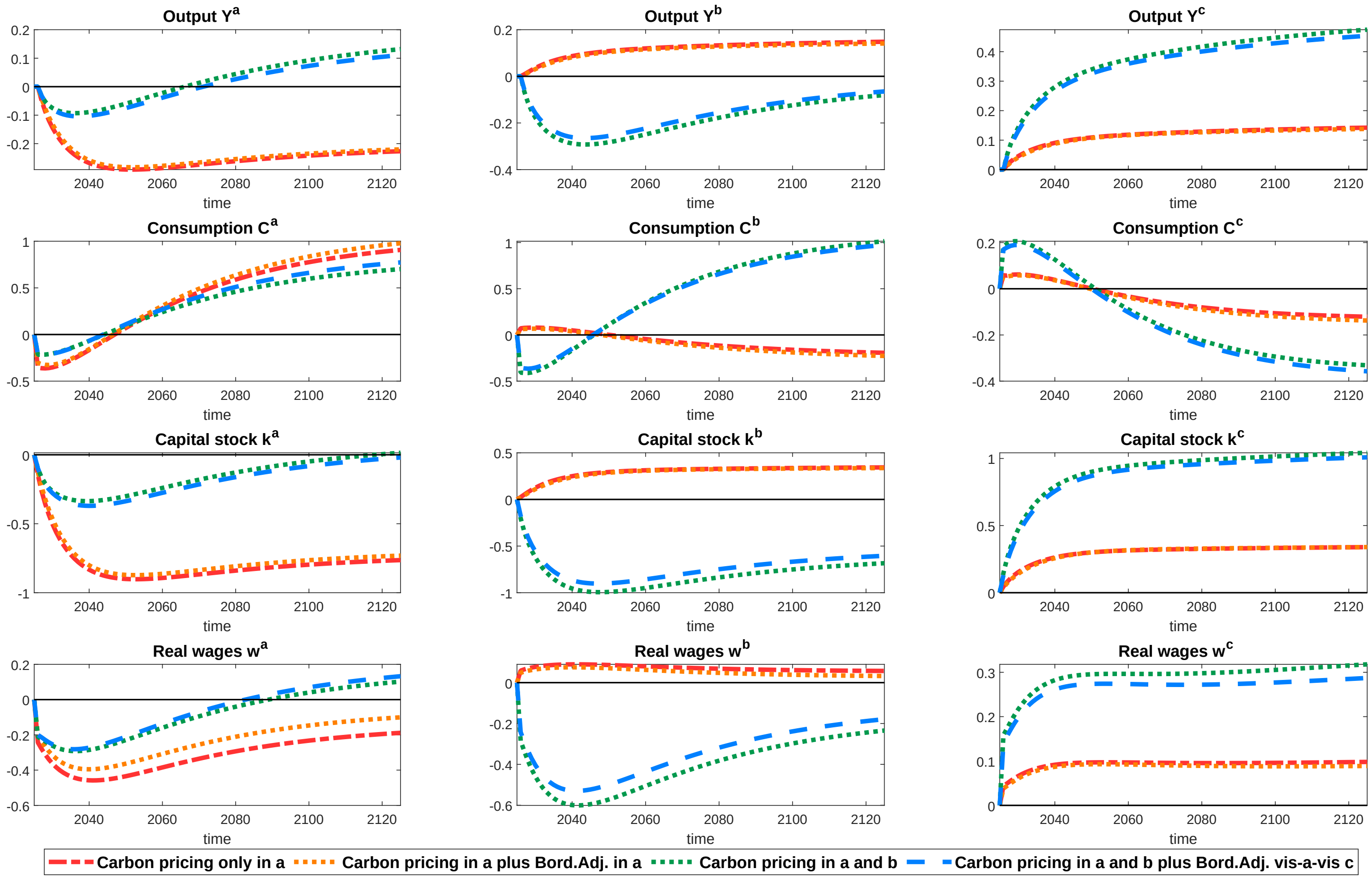
Notes: Figure plots (projected) implications of carbon pricing for selected key trade-related variables in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the 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 A.9: Comparing effects of border adjustment tax and subsidies for selected key macroeconomic variables



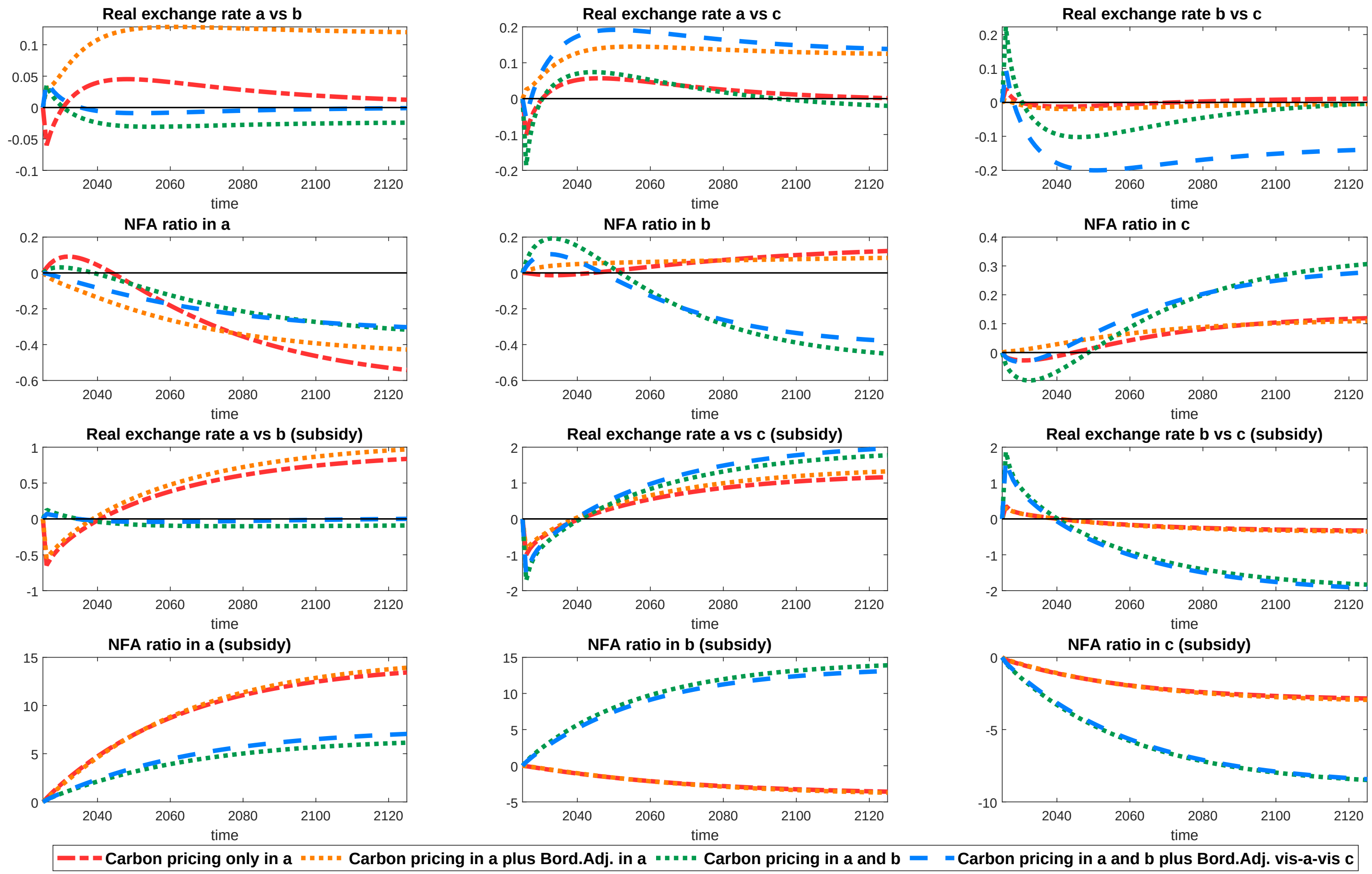
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices and full border adjustment (including subsidies) in region a. Carbon border taxation 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.

Figure A.10: Implications of carbon pricing for selected key macroeconomic variables (with savings subsidy)



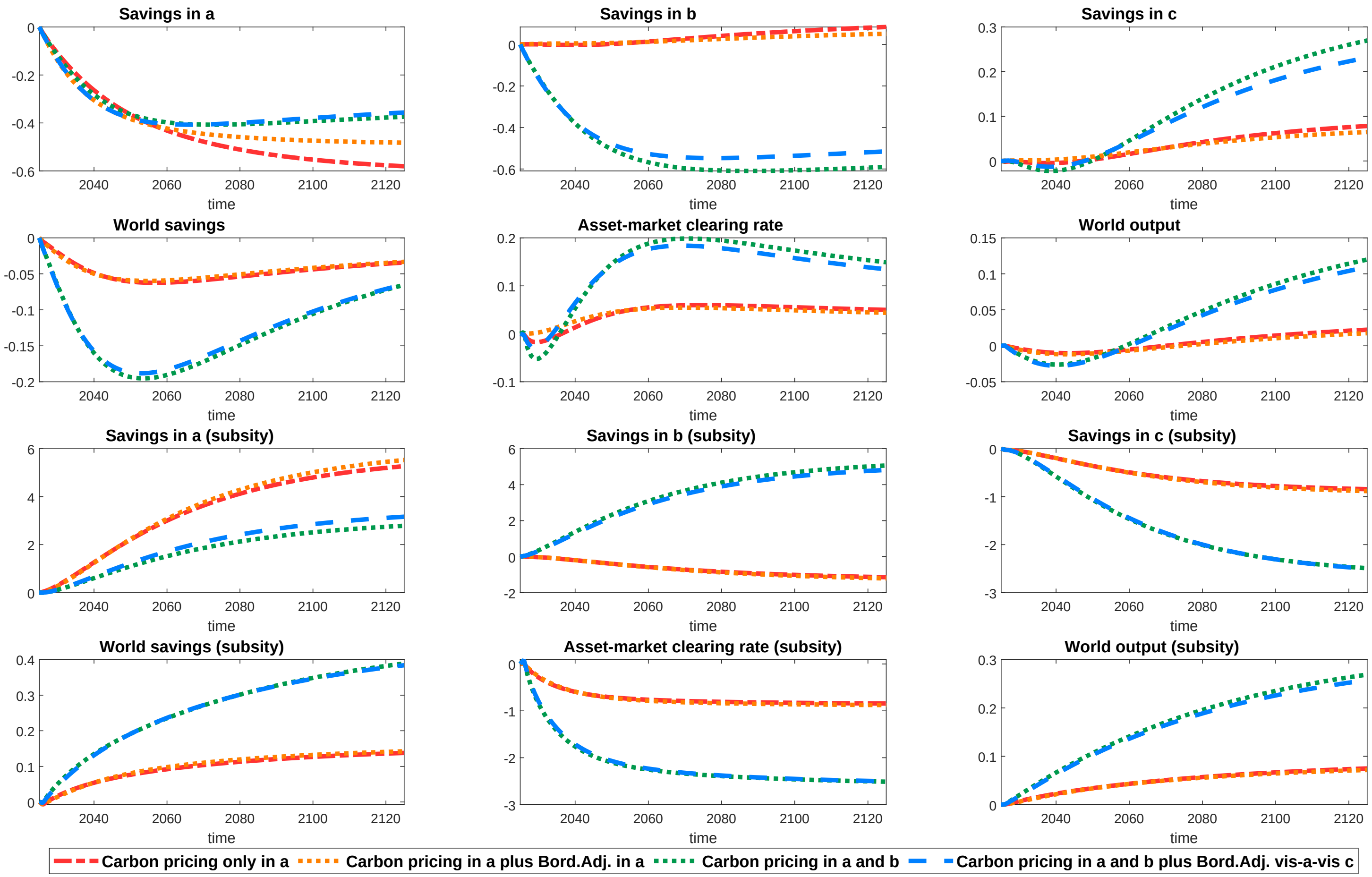
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the 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. Scenarios with savings subsidy.

Figure A.11: Implications of carbon pricing for selected key trade-related variables (with savings subsidy vs baseline)



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. Baseline scenario with lump-sum redistribution in upper two rows, savings subsidy in lower two rows.

Figure A.12: Implications of carbon pricing for savings, interest rates and world output (with savings subsidy vs baseline)



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. Baseline scenario with lump-sum redistribution in upper two rows, savings subsidy in lower two rows.