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Carbon pricing, border adjustment and climate clubs: Options for international cooperation

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ABSTRACT

In a dynamic, three-region environmental multi-sector general equilibrium model, we find that carbon pricing generates a long-lasting downturn as production costs rise. Dirty production is shifted towards countries with laxer climate policies, known as carbon leakage. A border adjustment tax mitigates but does not prevent carbon leakage. Its impact on emissions is limited, and it mainly "protects" dirty domestic production sectors with tradeable goods (in relative terms). Benefits from lower emissions damage materialize only in the medium to long run. From the perspective of a region that introduces carbon pricing, the downturn is smaller and long-run benefits are larger if more regions participate. However, for non-participating regions, there is no incremental incentive to participate as they forego trade spillovers and face higher production costs along the transition. Because of the costly transition, average world welfare may fall as a result of global carbon pricing unless "the rich" assist "the poor".

1. Introduction

Many economies around the world have committed to ambitious climate goals and discuss climate change mitigation policies, including approaches to pricing carbon, and avoid carbon leakage. To evaluate different possible policies, the assessment of their macroeconomic consequences is of utmost importance. This is not only true from an academic perspective, but also for G7/G20 policymakers. Not least following up on the Glasgow Climate Pact, the issue is one of their top priorities on the 2022/2023 agenda.

In this paper, we contribute to the discussion by analyzing the macroeconomic and welfare implications of different policy choices regarding carbon pricing, border adjustments and climate clubs, also with respect to sectoral and reginal redistribution.

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We do this within a three-region version of the environmental multi-sector dynamic general equilibrium model *EMuSe* (see Hinterlang et al., 2022). The model features multiple interrelated production sectors that vary in their emissions intensity, factor intensity, use of intermediate inputs, and contribution to final demand along the lines of Bouakez et al. (2023). In addition to their model, agents in our model also engage in international trade. Following Heutel (2012), Annicchiarico and Di Dio (2015) and Annicchiarico et al. (2018), among others, emissions occur as a by-product of production and differ by sector. Firms in each sector 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 et al., 2022, for a discussion). In our baseline simulations, we derive five important insights with respect to the economic consequences. They can be summarized as follows.

First, our results confirm previous findings regarding the adverse impact of introducing a carbon price because production becomes more expensive. However, emissions reduction eventually decreases emissions-induced (production) damage and generates positive economic effects. It takes time before these positive effects can overcompensate the adverse effects of the cost push on output and consumption.

Second, the more regions participate in carbon pricing, the shorter is the downturn, at least for those regions that introduce a carbon price anyway. The reason is that emissions reduction is larger when more regions participate, and this reduces damage faster.

However, our third finding is that, if one or more regions introduce carbon pricing, there is not really an incremental incentive for the non-participating regions to participate. This is mainly due to the fact that they, then, 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.

Fourth, border adjustment dampens carbon leakage, and especially dirty foreign sectors may indeed be affected negatively (in relative terms). Conversely, dirty domestic production sectors with tradeable goods can benefit as (especially domestic) demand is tilted towards them. However, border adjustment alone does not seem to 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. Environmental benefits of a border adjustment mechanism increase if the dirty domestic production sectors are relatively clean producers relative to their foreign counterparts.

Last, but not least, the time it takes until positive effects from carbon pricing materialize may take a generation's lifetime or more. Hence, public measures compensating the negative effects may be worth considering. We do not explicitly model this in our paper, but these could include public investments in or aid for infrastructures and innovative technologies that foster the transition to an emissions-reduced world (and, hence, speed up the positive gains from that). Given the time it takes before positive effects of emissions reduction materialize, deficit-financing such measures could foster the well-being of those generations that bear downturn-implied costs now, and shift the burden to those that benefit. However, additional research to analyze under which conditions this may be a desirable choice is certainly necessary.

Concerning welfare, our simulations show that introducing a world-wide carbon price is good for the "rich" countries that price carbon already or are planning to do so in any case. However, it is harmful for regions with low per-capita income from the start, the "poor" regions. This is because the downturn resulting from pricing carbon generates much higher welfare losses in low-income regions with already low per-capita consumption levels. In our model simulations, this effect is so severe that the average world-household does not want to introduce a common carbon price.

As the rich benefit if more regions participate in carbon pricing, they may have an interest in providing incentives for the poor to do so, too. In additional model simulations, we combine regionally differentiated carbon prices and per-capita transfers to the poor, which is also discussed in IMF (2022). The transfers are financed by proceeds of carbon pricing in the rich countries. The simulation results show that such an approach may lead to relative welfare gains for everyone, even though the rich countries then face lower welfare gains and a stronger downturn relative to our baseline simulations without price differentiation and transfers. Another promising way to reduce the costs of unilaterally introduced carbon pricing for some regions may be allowing for offsets, i.e. allow the carbon-price introducing region(s) to abate in other regions where the marginal abatement cost is lower. This channels abatement investments towards regions in which they are less costly and/or more beneficial, which may also be considered as a transfer between regions that augments abatement and productivity gains world-wide. In any case, our simulations show that, without further incentives for the poor regions, it may be rather difficult to implement global 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. Section 6 focuses on simulating a mechanism that redistributes welfare gains between regions and discusses caveats of the analysis at hand, and Section 7 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 et al., 2014, and Böhringer and Fischer, 2020, for example, analyze optimal pollution as a direct input. Because we rely on a multi-sector modelling framework in line with Hinterlang et al. (2022), we implicitly incorporate this element through the input-output modelling structure, too.

Specifically, firms determine their intermediate inputs and may avoid products from emissions-intensive sectors depending on their relative price.

Modelling multiple sectors and inter-sectoral linkages is important when it comes to assessing environmental policies, given that some sectors are more carbon-intensive than others, but output of these sectors is needed as input by the others (energy, for example). However, the importance is not restricted to these questions alone. Atalay (2017), for example, lays out how sectoral shocks impact business cycle fluctuations, while Baqaee and Farhi (2019) analyze the implications of modelling production networks regarding trade and tariffs. Similar models are currently applied to the Covid-19 crisis (Baqaee and Farhi, 2022), the fiscal policy response to the crisis (Hinterlang et al., 2023), as well as to assessing the government spending multiplier in general (Bouakez et al., 2023, and Devereux et al., 2020). How the monetary transmission channel depends on heterogenous production structures with a focus on price rigidities is investigated in Pasten et al. (2020) and Bouakez et al. (2014).

Concerning the effect of emissions on the economy, we follow Heutel (2012), Golosov et al. (2014) and Khan et al. (2019) by introducing a "damage function". It describes the 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 et al. (2009), Angelopoulos et al. (2013), Cai and Lontzek (2019) and Cai (2020).

There are several papers analyzing the effects of carbon pricing. 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 cyclicality 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 et al. (2021). Moreover, Annicchiarico et al. (2018) find that the environmental tax regime affects market structure and markups. These models, however, do not really take into account the sectoral structure and linkages of an economy. Relying on a (static) computable general equilibrium model, this is done by Devulder and Lisack (2020) and Frankovic (2022), who also analyze carbon pricing in a multi-sector framework, at the cost of not being able to address the transition between steady states. Antosiewicz et al. (2016) use a DSGE model with 8 sectors to compare the effects of taxing either the intermediate inputs or output of specific emission-intensive sectors, while Hinterlang et al. (2022) use a 54-sector model to compare different ways of energy and emissions taxation as well as recycling of the corresponding proceeds. The latter issue is also discussed in Varga et al. (2022). We add to this literature by providing a comprehensive multi-region and multi-sector framework to also take into account the international dimension of the issue.

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 et al. (2021) 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 Naegele and Zaklan, 2019, and Garnadt et al., 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. (2021) 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 et al. (2012, 2018) find that border adjustment reduces leakage rates, especially if it is applied in emissions-intensive and trade-exposed sectors. Weitzel et al. (2012b) 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 et al. (2012a) 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. Note that, in our baseline simulations, 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., 2021). Such a mechanism, which we briefly discuss in the paper but which should be addressed more in future research, may generate more positive effects of border adjustment.

The idea of a climate club, i.e. a larger group of countries introducing (similar) carbon prices dates back to Nordhaus (2015). Nachtigall et al. (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., 2012a). Additional incentives, such as transfers or price differentiation, may be necessary to reach international agreements (see Winkler et al., 2021; Peterson and Weitzel, 2016; Roolfs et al., 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 falls 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 eleven interlinked sectors, matching actual carbon intensities and input-output production structures within and across regions. First of all, this allows us to study the heterogenous effects of emissions taxation across sectors. 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 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, 2019). However, as argued by Dietz and Venmans (2019), Mattauch et al. (2020) and Dietz et al. (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

Our model is a multi-region extension of the multi-sector model *EMuSe* presented by Hinterlang et al. (2022). The general model description heavily draws on theirs, with a special focus on the newly introduced international linkages as well as border adjustment taxation. Time t is discrete and runs forever. The model economy comprises $\mathcal{S} = \{1, 2, .., S\}$ production sectors and three regions $i = a, b, c$. World population is normalized to unity such that ω^i indicates (relative) population size of region i. It holds that $\omega^a + \omega^b + \omega^c = 1$.

Each region is inhabited by a representative household, perfectly competitive labor and capital agencies, consumption, investment, and intermediate-goods retailers, as well as a fiscal authority. The representative household receives income from providing labor and capital to labor and capital agencies that channel them to sectoral goods producers. Labor is immobile internationally and only imperfectly mobile across sectors. The latter also holds for physical capital. International capital mobility is modelled by trade in international interest-bearing assets. Hence, any domestic household who wants to invest in foreign capital must purchase international assets (i.e. lend money to the foreign household). The foreign household can use these funds to invest them in foreign capital and must pay interest to the domestic household. Households use their income for consumption and investment in physical capital as well as international bonds.

Sectoral output is transformed into bundles of consumption, investment, and intermediate goods. This is accomplished by perfectly competitive retailers. Besides the purchase of intermediate input bundles, firms rent capital and labor from the labor and capital agencies. Producers are price setters and prices may differ across sectors due to different markups. There is also heterogeneity with respect to factor intensities. All goods are traded internationally.

Production causes emissions, which may differ across sectors. Firms can invest in costly abatement technologies and may face sector-specific economic/production damage resulting from the stock of pollution. A fiscal authority runs a balanced budget by paying out lump-sum transfers and receiving income from labor income, consumption, emission and border adjustment taxation. In what follows, we will describe the economy in more formal detail. Unless otherwise indicated, variables are expressed in (regional) per-capita terms.

3.1. Representative household

A representative household in region i chooses consumption $C_{i,t}$, labor supply $N_{i,t}$, physical capital investments $I_{i,t}$ and purchases of internationally traded assets $nfa_{i,t}$ in order to maximize expected utility

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{\left(C_{i,t} - \kappa_{i,N} \cdot N_{i,t}^{\psi} \cdot O_{i,t} \right)^{1-\sigma} - 1}{1-\sigma} \right]. \tag{1}$$

GHH preferences (as specified, for example, by Jaimovich and Rebelo, 2009), which shut off the wealth effect on the labor supply (see Greenwood et al., 1988), are commonly used in open economy DSGE models. In Appendix D, we show that adding environmental damage to the utility function as in Barrage (2020) does not change our results qualitatively. The parameter σ

denotes the inverse of the elasticity of intertemporal substitution. As $\sigma \to 1$, utility is log. β is the discount rate. The curvature of labor supply disutility is determined by ψ, and $\kappa_{i,N}$ is its weight relative to consumption. Note that we allow only the latter parameter to be region-specific. $O_{i,t} = O_{i,t-1}^{1-\gamma^{ghh}} \cdot C_{i,t}^{\gamma^{ghh}}$ makes preferences non-time-separable in consumption and labor. $\mathbb{E}_0$ is the expectations operator at $t = 0$. Given the consumer price index (CPI) in region i, $P_{i,t}^C$, the choices of the representative household are subject to the real budget constraint

$$\left(1+\tau_{i,t}^c\right)C_{i,t} + \left(1+\tau_{i,t}^I\right)P_{i,t}^I\left(I_{i,t} + S\left(I_{i,t}, K_{i,t-1}\right)\right) + nfa_{i,t} = w_{i,t}N_{i,t} + r_{i,t}^k K_{i,t-1} + R_{i,t-1}nfa_{i,t-1} + TR_{i,t} + \Pi_{i,t}, \tag{2}$$

where $P_{i,t}^I$ is the regional CPI-deflated real price of a basket of investment-goods, $I_{i,t}$ the corresponding basket of investment-goods, $w_{i,t}$ the real wage rate and $r_{i,t}^k$ the real rental rate of capital $K_{i,t}$. $R_{i,t}$ is the gross regional CPI-deflated real interest rate on regional holdings on net foreign assets. The average tax rate on the consumption bundle is $\tau_{i,t}^c$ and on the investment bundle $\tau_{i,t}^I$. $TR_{i,t}$ are lump-sum transfers received from the government and $\Pi_{i,t}$ denote aggregate firm profits. Capital accumulation is represented by the following law of motion

$$K_{i,t} = (1-\delta_i)K_{i,t-1} + I_{i,t}, \tag{3}$$

with δ_i denoting the regional rate of depreciation. $S(I_{i,t}, K_{i,t-1}) = \kappa_i^I/2 \cdot (I_{i,t}/K_{i,t-1} - \delta_i)^2$ are capital adjustment costs as in Ireland (2003) and Hinterlang et al. (2023). First-order conditions are standard (see Appendix A).

3.2. Consumption and investment-goods retailers

The representative household demands bundles of consumption and investment goods $C_{i,t}$ and $I_{i,t}$, which are traded at prices $P_{i,t}^C$ and $P_{i,t}^I$, respectively. The production technology of a perfectly competitive, representative retailer that bundles sector-level consumption and investment goods of the S sectors, $C_{s,i,t}$ and $I_{s,i,t}$, is given by

$$X_{i,t} = \left[\sum_{s=1}^{S} \psi_{X,s,i}^{1-\sigma_{X,i}} X_{s,i,t}^{\sigma_{X,i}}\right]^{\frac{1}{\sigma_{X,i}}},$$

where $X \in \{C, I\}$. The parameters $\psi_{X,s,i}$ and $\sigma_{X,i}$ determine the weight in the consumption/investment bundle and the elasticity of substitution between sector-level consumption/investment goods in region i, respectively. The representative retailer's optimization problem in CPI-deflated real terms can be written as

$$\max_{X_{s,i,t}} \left(1+\tau_{i,t}^X\right)P_{i,t}^X X_{i,t} - \sum_{s=1}^{S}\left(1+\tilde{\tau}_{s,i,t}^X\right)P_{s,i,t}^X X_{s,i,t},$$

where $P_{s,i,t}^X$ is the CPI-deflated price of sectoral consumption/investment good $s \in \mathcal{S}$. It will depend on how much of this good is purchased domestically and how much comes from abroad, which we will determine in more formal detail below. $\tilde{\tau}_{s,i,t}^X$ is the corresponding average tax rate for this good, also depending on where the good is produced and on whether or not border adjustment taxes apply. Fist-order conditions and the expressions for relative prices can be found in Appendix A.

3.3. Labor and capital agencies

As mentioned above, labor and the capital stock are not perfectly mobile across sectors, and not at all across regions (remember that domestic households can take the detour via international assets to participate in foreign capital investments). To capture this, we assume that a perfectly competitive, representative regional labor/capital agency hires the total amount of labor/capital, $N_{i,t}$ and $K_{i,t}$, at the CPI-deflated real wage/capital interest rate, $w_{i,t}$ and r_t^K, and sells it to intermediate goods producers operating in S different domestic sectors, such that

$$X_{i,t} = \left[\sum_{s=1}^{S} \omega_{X,i,s}^{1-\nu_{X,i}} X_{s,i,t}^{\nu_{X,i}}\right]^{\frac{1}{\nu_{X,i}}},$$

where $X \in \{N, K\}$. $\omega_{X,i,s}$ is the weight attached to labor/capital provided to sector $s \in \mathcal{S}$, and $\nu_{X,i}$ determines the elasticity of substitution of labor/capital across sectors. This captures the degree of (imperfect) labor/capital mobility. The labor/capital agency's optimization problem can be written as

$$\max_{X_{s,i,t}} \tilde{p}_{s,i,t}X_{s,i,t} - \tilde{p}_{i,t} \cdot X_{i,t},$$

where $\tilde{p} \in \{w, r^k\}$. The first-order conditions and expressions for wages and interest rates are relegated to Appendix A.

3.4. Production

In each sector $s \in \mathcal{S}$ in region $i \in \{a, b, c\}$, a monopolistically competitive firm $z \in [0, 1]$ produces a differentiated sectoral variety $y_{s,i,t}(z)$ by transforming labor, $N_{s,i,t}(z)$, capital, $K_{s,i,t-1}(z)$, and a bundle of intermediate inputs, $H_{s,i,t}(z)$. The differentiated sectoral variety is sold at price $P_{s,i,t}(z)$ to a representative wholesaler who aggregates varieties into a single sectoral good $Y_{s,i,t}$ and sells these wholesale goods to households and investors according to the consumption and investment demand baskets previously described at a price $P_{s,i,t}$. Operating under perfect competition, the optimization problem of the representative wholesaler is given by

$$\max_{y_{s,i,t}(z)} P_{s,i,t} Y_{s,i,t} - \int_0^1 P_{s,i,t}(z) y_{s,i,t}(z)\ dz \quad \forall s \in \mathcal{S} \quad and \quad i \in \{a, b, c\}$$

subject to

$$Y_{s,i,t} \leq \left(\int_0^1 y_{s,i,t}(z)^{\frac{\theta^P_{s,i}-1}{\theta^P_{s,i}}}\ dz \right)^{\frac{\theta^P_{s,i}}{\theta^P_{s,i}-1}}.$$

The parameter $\theta^P_{s,i} > 1$ governs the elasticity of substitution between different varieties and may differ across sectors. This yields standard variety demand functions and sectoral prices (see Appendix A).

The production technology of a monopolistically competitive firm z in sector s and region i exhibits constant returns to scale and is given by

$$y_{s,i,t}(z) \leq \left[1 - D_{s,i}(M_t)\right] \varepsilon_{s,i,t} \left(K_{s,i,t-1}(z)^{1-\alpha_{N,s,i}} N_{s,i,t}(z)^{\alpha_{N,s,i}} \right)^{\alpha_{H,s,i}} \left(H_{s,i,t}(z) \right)^{1-\alpha_{H,s,i}}, \tag{4}$$

where $\varepsilon_{s,i,t}$ is total factor productivity, the α's determine factor intensity and $D_{s,i}(M_t)$ is a sector and 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 $D_{s,i}(M_t) = \gamma_{0,s,i} + \gamma_{1,s,i} \cdot M_t + \gamma_{2,s,i} \cdot M_t^2$. In the simulations presented below, we assume damage not to be sector-specific due to the lack of reliable data (hence, the γ-parameters are assumed to be equal across sectors). Furthermore, damage is assumed to only affect production in our baseline simulations. However, climate change may also affect welfare directly via utility damages, as shown in Barrage (2020), for example. We show in Appendix D that, when including damage in the utility function, results do not change qualitatively for plausible calibrations.

Following Annicchiarico and Di Dio (2015), emissions are a by-product of production taking the form $Z_{s,i,t} = \kappa_{s,i} \cdot \left(1 - U_{s,i,t}\right) \cdot y_{s,i,t}$, where $\kappa_{s,i} \in [0, \infty)$ denotes the emissions intensity before abatement $U_{s,i,t} \in [0, 1)$, which is costly with an abatement cost function $C(U_{s,i,t}) = \phi_{1,s,i} \cdot U_{s,i,t}^{\phi_{2,s,i}} \cdot y_{s,i,t}$, where $\phi_{1,s,i} > 0$ and $\phi_{2,s,i} > 1$ (see Annicchiarico and Di Dio, 2015, Annicchiarico et al., 2018, and Annicchiarico and Diluiso, 2019, for a discussion). Taking factor prices and acknowledging the symmetric equilibrium (which allows dropping the index z), we get the standard first-order conditions for labor, capital, intermediate inputs and abatement (see Appendix A).

What also needs to be determined is factor demand for sector j-intermediates by sector s in each region i, with $j, s \in \mathcal{S}$. In analogy to consumption/investment goods bundles, we assume that intermediates are bundled according to

$$H_{s,i,t} = \left[\sum_{j=1}^{S} \psi_{H,s,j,i}^{1-\sigma_{H,s,i}} H_{s,j,i,t}^{\sigma_{H,s,i}} \right]^{\frac{1}{\sigma_{H,s,i}}} \quad \forall s, j \in \mathcal{S} \quad and \quad i \in \{a, b, c\}.$$

Hence, the CES aggregator for each sector $s \in \mathcal{S}$ aggregates the intermediate goods from all sectors $j \in \mathcal{S}$, after weighting them by the parameter $\psi_{H,s,j,i}$ and taking into account the elasticity of substitution between those intermediate goods which is determined by $\sigma_{H,s,i}$. These parameters may differ across sectors. The optimization problem is

$$\max_{H_{s,j,i,t}} \left(1 + \tau^H_{s,i,t}\right) P^H_{s,i,t} H_{s,i,t} - \sum_{j=1}^{S} \left(1 + \tilde{\tau}^H_{j,i,t}\right) P_{j,i,t} H_{s,j,i,t} \quad \forall s, j \in \mathcal{S} \quad and \quad i \in \{a, b, c\},$$

where $\tilde{\tau}^H_{s,i,t}$ is the average tax rate on intermediate input s (again depending on whether purchased at home or abroad when differentiated taxation applies, which we will discuss below). The demand functions are standard (see Appendix A).

3.5. Policy

The fiscal authority in region i sets transfers to run a balanced budget each period:

$$TR_{i,t} = \tau^{c}_{i,t} \cdot C_{i,t} + \tau^{I}_{i,t} \cdot P^{I}_{i,t} \cdot I_{i,t} + \sum_{s=1}^{S} P^{em}_{s,i,t} \cdot Z_{s,i,t} + \sum_{s=1}^{S} \tau^{H}_{s,i,t} \cdot P^{H}_{s,i,t} \cdot H_{s,i,t}. \tag{5}$$

Tax rates are given exogenously or derived according to the simulation design described below. Allowing for public debt and different fiscal rules along the lines of, for example, Mitchell et al. (2000), is possible. For a discussion about the impact of using different fiscal instrument in our model, see also Hinterlang et al. (2022).

3.6. International linkages, market clearing and aggregation

International trade in goods and assets implies that the three regions are linked together, which not only affects the net foreign asset position but also the market clearing conditions. We assume that households and firms in region i purchase domestic goods as well as goods from the other regions. The corresponding CES bundle for consumption, investment and intermediate goods is given by

$$X_{s,i,t} = \left[\sum_{\tilde{i} \in \{a,b,c\}} hb^{1-\sigma_{X,s,i,\tilde{i}}}_{X,s,i,\tilde{i}} X^{\sigma_{X,s,i,\tilde{i}}}_{s,i,\tilde{i},t} \right]^{\frac{1}{\sigma_{X,s,i,\tilde{i}}}} \quad \forall s \in \mathcal{S} \quad and \quad i, \tilde{i} \in \{a, b, c\},$$

where $X \in \{C, I, H\}$.[1] The parameter $hb_{X,s,i,\tilde{i}}$ is the sector-s preference bias of region i towards goods produced in region $\tilde{i}$. Hence, $hb_{X,s,i,i}$ can be interpreted as home bias. $\sigma_{X,s,i,\tilde{i}}$ is the corresponding elasticity of substitution between home and foreign goods. Given bundle, sector and region-specific taxes for each good, the optimization problem in CPI-deflated real terms can be written as

$$\max_{X_{s,i,\tilde{i},t}} \left(1 + \tilde{\tau}^{X}_{s,i,t}\right) P^{X}_{s,i,t} X_{s,i,t} - \sum_{\tilde{i} \in \{a,b,c\}}^{S} \left(P_{s,i,\tilde{i},t} + \tau^{X}_{s,i,\tilde{i},t}\right) X_{s,i,\tilde{i},t} \quad \forall s \in \mathcal{S} \quad and \quad i \in \{a, b, c\},$$

where $P_{s,i,\tilde{i},t}$ is the producer price of region $\tilde{i}$ deflated by CPI of region i (to be derived below). $\tau^{X}_{s,i,\tilde{i},t}$ denotes region i's quantity tax on goods of sector s that are produced in region $\tilde{i}$ and purchased in region i. It is a policy variable, and we allow policy makers to differentiate between taxes in the consumption, investment and intermediate goods bundles. If region i wants to discriminate imports by a border adjustment tax, it must hold that $\tau^{X}_{s,i,\tilde{i},t} > \tau^{X}_{s,i,i,t}$ for $i \neq \tilde{i}$. These tax rates are exogenously given as specified in detail when describing the simulation design below.

With these demands for home and foreign goods at hand, we can derive the sectoral trade balances for each region as

$$TB_{s,i,t} = \frac{P_{s,i,i,t}}{\omega^{i}} \cdot \sum_{\tilde{i} \neq i} \omega^{\tilde{i}} \left(C_{s,\tilde{i},i,t} + I_{s,\tilde{i},i,t} + \sum_{j=1}^{S} H_{s,j,\tilde{i},i,t} \right) - \sum_{\tilde{i} \neq i} P_{s,i,\tilde{i},t} \cdot \left(C_{s,i,\tilde{i},t} + I_{s,i,\tilde{i},t} + \sum_{j=1}^{S} H_{s,j,i,\tilde{i},t} \right) \tag{6}$$

for all sectors s and regions i. Note that, for exports, we have to take into account country size as the other variables are represented in regional per-capita terms. The aggregate trade balance of region i is, then, given by $TB_{i,t} = \sum_{s=1}^{S} TB_{s,i,t}$. Net foreign assets evolve according to

$$nfa_{i,t} = R_{i,t-1} \cdot nfa_{i,t-1} + TB_{i,t} \tag{7}$$

where $R_{i,t}$ is assumed to include a risk premium as in Schmitt-Grohe and Uribe (2003), among others.[2]

[1] Note that, for notational convenience, we abuse notation here a bit. For the intermediate input bundle, sector s decides about inputs from sector j, which is not the case for the consumption and investment bundles. Hence, the "true" bundles should actually be denoted by $C_{s,i,t}$, $I_{s,i,t}$ and $H_{s,j,i,t}$, and the corresponding inputs by $C_{s,i,\tilde{i},t}$, $I_{s,i,\tilde{i},t}$ and $H_{s,j,i,\tilde{i},t}$. We subsume all this in the X's to save space.

[2] In standard open-economy DSGE models along the lines of Obstfeld and Rogoff (1995), which we also have here, the net foreign asset position is exogenous (zero in our initial steady state). 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, for a discussion). The risk premium does the job in our model.

We can also measure how emissions embodied in international trade in our model move across regions. The sector-specific emissions content of net imports of region i is given by

$$\begin{aligned} EC_{s,i,t} = & \sum_{\tilde{i}\neq i} \kappa_{s,\tilde{i}} \cdot \left(1 - U_{s,\tilde{i},t}\right) \cdot \left(C_{s,i,\tilde{i},t} + I_{s,i,\tilde{i},t} + \sum_{j=1}^{S} H_{s,j,i,\tilde{i},t}\right) \\ & - \sum_{\tilde{i}\neq i} \frac{\omega^{\tilde{i}}}{\omega^{i}} \cdot \kappa_{s,i} \cdot \left(1 - U_{s,i,t}\right) \cdot \left(C_{s,\tilde{i},i,t} + I_{s,\tilde{i},i,t} + \sum_{j=1}^{S} H_{s,j,\tilde{i},i,t}\right), \end{aligned} \tag{8}$$

and measures sector-specific emissions that are imported (or exported, if negative). Dividing $EC_{s,i,t}$ by $Z_{s,i,t}$ gives a measure of the sector-specific “net carbon leakage” share following the idea of Su et al. (2010), Chen and Chen (2011) and Sato (2014), among others. If $EC_{s,i,t}/Z_{s,i,t}$ increases after a policy change, more emissions-intensive goods are imported relative to domestic production of these goods and we have (relative) carbon leakage. The opposite is true if this value falls. Summing over all sector s then measures this share for region i.[3]

It remains to derive some inter-regional prices. When region i buys a product of region $\tilde{i}$ from sector s, region $\tilde{i}$ sells it at its own CPI-deflated producer price $P_{s,\tilde{i},t}$. For country i, this has to be translated by using its own CPI deflator. Hence, $P_{s,i,\tilde{i},t} = P_{s,\tilde{i},t} \cdot P^{C}_{\tilde{i},t}/P^{C}_{i,t}$, where the latter ratio of consumer prices yields the real exchange rate between the two region: $rer_{i,\tilde{i},t} = P^{C}_{\tilde{i},t}/P^{C}_{i,t}$. As internationally traded assets are in zero net supply, we can use this to show that $\omega^{c} \cdot nfa_{c,t} = -rer_{a,c,t} \cdot \omega^{a} \cdot nfa_{a,t} - rer_{a,b,t} \cdot \omega^{b} \cdot nfa_{b,t}$ must hold.

In each sector s and region i, product market clearing implies

$$P_{s,t} y_{s,t} = P^{C}_{s,t} C_{s,t} + P^{I}_{s,t} I_{s,t} + TB_{s,i,t} + \sum_{\tilde{s}=1}^{S} P_{s,h,t} H_{\tilde{s},s,t} + \phi_{1,s,i} \cdot U^{\phi_{2,s,i}}_{s,i,t} \cdot y_{s,t}.$$

We define an emission cost factor $ec_{s,i,t}$ as the sum of abatement costs and emission taxes, i.e. $ec_{s,i,t} = \left[\phi_{1,s,i} \cdot U^{\phi_{2,s,i}}_{s,i,t} + P^{em}_{s,i,t} \cdot \kappa_{s,i} \cdot \left(1 - U_{s,i,t}\right)\right]$. Only the former appears in the sectoral resource constraint (as the latter is redistributed back to households through policy). Defining aggregate output as gross value added, we get

$$Y^{va}_{i,t} = C_{i,t} + P^{I}_{i,t} \cdot I_{i,t} + TB_{i,t} + P^{I}_{i,t} S\left(I_{i,t}, K_{i,t-1}\right). \tag{9}$$

Given that we expressed most variables in (regional) per-capita terms above, total regional emissions are given by $Z_{i,t} = \sum_{s=1}^{S} \omega^{i} \cdot Z_{s,i,t}$, world emissions by $Z_t = \sum_{i\,\in\,\{a,b,c\}} Z_{i,t}$, and the world emission stock, which is responsible for damage, evolves according to

$$M_t = \left(1 - \rho^{M}\right) \cdot M_{t-1} + Z_t. \tag{10}$$

$\rho^{M} \in (0, 1)$ determines how fast additional emissions are relieved.

This completes the model description. All decisions must be such that they are mutually consistent and the above equations hold. We now turn to the model calibration.

4. Calibration

In calibrating the model, we heavily rely on Hinterlang et al. (2022). Hence, the calibration strategy comprises three parts. The first part concerns general parameters. We mainly rely on values from the literature. The second part consists of the sector-specific parameters. On the production side, we allow the sectors to differ along several dimensions such as factor intensities, input-output linkages and contributions to final demand. Finally, the third part refers to parameters of the environmental module of the model. It captures carbon intensities, abatement costs and economic damage from emissions. We calibrate the model to three regions, grouping countries according to attitudes towards climate protection. The first region represents the EU27 countries, Norway, Switzerland and the United Kingdom. All of these countries either directly participate in the European Union Emissions Trading System (EU-ETS) or have established an ETS that is compatible with the former. The United States (US), Canada, Mexico, Australia, Japan and South Korea form the second region. 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

[3] Carbon leakage refers to a situation in which emissions-intensive products are purchased from countries with laxer emission constraints for reasons of costs related to climate policies. However, it is worth noting that, despite the nowadays frequent use of this term, there is not yet a clear definition for it. A comprehensive discussion about the pros and cons of different concepts, including the one we use, can be found in Michalek and Schwarze (2015). We are able to match the emissions import share of industrialized regions quite well without targeting it explicitly in the calibration section (see also Hübler, 2012).

trade agreement. The remaining countries form the third region including, for example, China and India. To save space, we relegate all detailed calibration tables to Appendix B.

General parameters. The model is calibrated to the quarterly frequency. Population data, needed to compute relative sizes and relative value added per capita of the regions, is taken from the United Nation's World Population Prospects for 2020. We choose a discount factor of $\beta = 0.985$. Along the lines of Jaimovich and Rebelo, 2009, we set $\sigma = 1$ and $\gamma^{ghh} = 0.001$. Following Coenen et al. (2013), we calibrate the Frisch elasticity of labor supply to 0.5 (i.e. $\Psi = 2$). Disutility of labor is region-specific and its relative weight $\kappa_{i,N}$, $i = a, b, c$ targets an aggregate labor supply of $\overline{N}_i = 0.33$. Capital depreciates at a typical annual rate of 10% (see, for example, Cooley and Prescott (1995)) and the respective adjustment cost parameter κ^I is fixed at 25. The consumption tax rate amounts to 0.2 in all regions. We set the substitution elasticities for goods produced in the different sectors as follows. Along the lines Atalay (2017) and Baqaee and Farhi (2019) we choose a value of 0.9 for the consumption basket. Concerning the investment goods basket, we assume a lower elasticity of substitution of 0.75. Following Bouakez et al. (2023) and Atalay (2017), we fix the value for intermediate inputs at 0.3. Baqaee and Farhi (2019) allow for a higher substitution elasticity (of 0.4). However, changing the value does not alter our results qualitatively and only mildly quantitatively (the adjustment of relative prices is mitigated). This is also true for the elasticity between home and foreign goods, which we set close to one. Labor and capital can be substituted quite easily in our model with a substitution elasticity of 10. We do not have to assume perfect substitutability as in Bouakez et al. (2023), but the system can no longer be solved for too low values. See Antoszewski (2019) for a critical discussion.

Sector-specific production parameters. Relying on the standard NACE Rev. 2 classification, we distinguish between $S = 11$ producing sectors in three regions ($i \in \{a, b, c\}$). We have two manufacturing (MF) sectors, where we group sectors according to the applicability of the ETS. Hence, manufacturing (ETS) includes MF of (i) paper and paper products (C17), (ii) coke and refined petroleum products (C19), (iii) chemicals and chemical products (C20), (iv) other non-metallic mineral products (C23) and (v) basic metals (C24).[4] We further build a composite of mining, quarrying (B) and energy (D) and take the transport sectors that fall under ETS separately, which are water (H50) and air (H51) transport. A table in Appendix B provides an overview of the chosen regions and sectors.

The sectors differ along the following dimensions. In the model, labor and capital shares are given by $\omega_{N,s,i}$ and $\omega_{K,s,i}$, respectively, making them not perfectly mobile across sectors. Moreover, we allow for heterogenous production technologies of intermediate goods producers by different factor intensities for labor, capital and intermediate inputs. Furthermore, all sectors contribute differently to final demand. All of these sector-specific parameters are derived using the most recent release of the World Input-Output Database (WIOD), covering the years 2000–2014 (see Timmer et al., 2015). It includes data on socioeconomic accounts as well as input-output tables for 56 sectors and 43 countries. We build three country aggregates as outlined above. Using the socioeconomic accounts, we can pin down the sector-specific labor and capital supply $\omega_{N,s,i}$, $\omega_{K,s,i}$, as well as factor intensities $\alpha_{N,s,i}$ and $\alpha_{H,s,i}$ in each country. In order to determine the former, we compute the sector-specific shares in the cumulated number of persons engaged and the nominal capital stock over all sectors. The factor intensities for intermediate inputs, $1 - \alpha_{H,s,i}$ are computed by dividing the amount of intermediate inputs by gross output per industry. The values for $\alpha_{N,s,i}$ can then be fixed using the share of labor compensation in gross output. Parameters $\psi_{H,s,j,i}$ describe the share of intermediate inputs consumed by sector s that are produced by sector j. These are calibrated using the input-output tables by first computing the total sum of intermediate inputs for each sector and then the respective shares of the producing sector. Following the same routine, we can compute the preference bias parameters $hb_{H,s,i,\bar{i}}$ of region i towards intermediate goods produced in region $\bar{i}$. The distribution of final consumption expenditure by households and gross fixed capital formation across sectors as mirrored by the CES bundle shares $\psi_{C,s,i}$ and $\psi_{I,s,i}$ can be derived with WIOD's national accounts data. The same holds true for the preference biases $hb_{X,s,i,\bar{i}}, X \in \{C, I\}$ of region i towards consumption or investment goods produced in region $\bar{i}$. In order to explore how important tradability of goods and services is for our results, we assume that the output of the power production sector (sector 4) is non-tradeable. Hence, we set its respective home biases parameters equal to one. Assuming the entire sector to be non-tradeable is indeed somewhat extreme. But it is useful for illustrative purposes and enables us to show that the effects of carbon border adjustment taxes are limited for (even dirty) sectors that are not traded very much. To facilitate calculations, we also normalize relative prices to one in the initial steady state.

Environmental parameters. To calibrate sector-specific CO2 emissions per unit of output, we use environmental accounts provided by the European Commission that are consistent with WIOD (see Corsatea et al., 2019). Information on sectoral emissions is available from 2000 to 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 efforts, we ensure that $(1 - \overline{U}_{s,i})\kappa_{s,i}$ coincides with the values in the data. As the tables show, region c, including China and India, has the most carbon intensive production across sectors (see Appendix B). The European region a emits least carbon per unit of output. The mining, quarrying & energy sector has the largest carbon intensity, while IT and communication yields the lowest. We assume a linear decay rate for the stock of pollution of $1 - \rho^{EM} = 0.9979$ following Heutel (2012) and Annicchiarico and Di Dio (2015). The parameters of the abatement cost function are equal across sectors. While $\phi_{2,s} = 0.185$ in all regions, $\phi_{1,s}$ is region-

[4] In most cases, only subsectors of these sectors fall under ETS. However, we lack more disaggregated data for calibration. Moreover, note that we exclude the sections activities of households as employers; undifferentiated goods- and services-producing activities of households for own use (T) and activities of extraterritorial organizations and bodies (U).

specific and corresponds to estimates of Nordhaus (2007). A critical discussion about different abatement cost functions and their parameterizations can be found in Cline (2011). Our parametrization for the damage function implies that sectoral output losses almost double if the pollution stock increases by 10% relative to its initial steady state level. The parametrization is loosely tied to Kalkuhl and Wenz (2020) and calculations made by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS; see NGFS, 2020, 2021a). We account for the fact that the economic impact of climate change differs between regions by following Nordhaus (2007). More specifically, we translate the emission stocks into temperature increases and use the region-specific total damage estimates at 25 °C warming. Choosing a lower economic damage from emissions would reduce the damage reduction and thereby slow down the productivity increase in the simulations shown below (the opposite is true for assuming a higher damage). Still, the results do not change qualitatively as long as damage is sufficiently large. Simulation results when assuming no damage (admittedly an extreme scenario) can be found in the appendix. Furthermore, we also conduct a simulation in which firms can invest in abatement abroad, where abatement costs may differ (see Appendix E). Further research should definitely focus on (quantitative) sectoral differences with a view to damage and abatement costs.

5. Baseline simulations

In this section, we describe the simulation design and the simulation results. For the latter, we first describe the macroeconomic effects of introducing carbon pricing, including transition dynamics and the long run, and then turn to the welfare implications.

Simulation design. When assessing the implications of the increase of carbon pricing, there are certainly many ways to tackle the issue. In this paper, we are interested in the economic and welfare implications of different carbon pricing regimes, including a climate club. In particular, we differentiate whether or not carbon pricing is introduced regionally or worldwide, and with or without border adjustment. More specifically we distinguish between five policy scenarios. First, we increase carbon pricing in region a only. Second, we introduce the same carbon price in region a and assume that region a also undertakes border adjustment by taxing all imports of regions without (or lower) carbon prices. Third, we assume that the carbon price is introduced in regions a and b. In a fourth step, we also introduce border adjustment of regions a and b vis-a-vis region c. We call this the climate club scenario following Nordhaus (2015). In a last simulation, we assume that the carbon price is introduced in all regions a, b and c. This scenario shows what would happen if the entire world participated in carbon pricing. We conduct a deterministic simulation 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 and sectors for all regions that increase carbon pricing. Prices are expressed relative to CPI in our model. Hence, price changes fed into our model are scaled by this factor. Regional and sectoral differentiation seems to be a plausible political outcome given the different current emissions trading systems and the ongoing political discussions (see, for example, OECD, 2021, and EP, 2022). Such a differentiation is possible in our model, but we abstract from it in the baseline simulation. Following the Network of Central Banks and Supervisors for Greening the Financial System (NGFS), we assume that, from now until 2100, those regions put a steadily increasing price on carbon emissions. After 2100, it will stay constant at the higher level. Based on calculations using the integrated assessment model REMIND, 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 (in Fig. 2, we see that the carbon price in the final steady state is about 13 times higher then it was in the initial steady state). Under this path, the global temperature increase is calculated to remain below 2 degrees Celsius (see NGFS, 2020, 2021a, 2021b, 2021c, for details). Results presented below depend on these price developments. The NGFS provides paths for several other scenarios. The results regarding the general economic consequences and welfare implications remain unchange qualitatively as long as we assume analogous price increases in the different regions. For illustrative purposes, we show simulation results of the scenario with zero net emissions in the appendix. Formally, $P^{em}_{s,i,t} = P^{em}_{i,t}$ 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. For the other regions the carbon price remains at the initial steady state level. Note also that we assume no technological change beyond the endogenous changes in abatement in the simulation results shown below. Because the REMIND model is more elaborated regarding the environmental side, and additionally assumes (exogenous) technological progress, it does not come as a surprise, that the same price path leads to different emissions reductions in both models.

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 $P^{em}_{i,t}$. However, the tax rate applies on the quantity of imported goods in our model and we are interested in pricing carbon emissions. Hence, the tax rate is formally given by $\tau^X_{s,i,\tilde{i},t} = P^{em}_{i,t} \cdot \kappa_{s,\tilde{i}}$, for $\tilde{i} = b, c$. We could also take abatement efforts into account here. 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.

Results. The results of these policy scenarios are summarized in Figs. 1 to 4 as well as Table 1. Fig. 1 summarizes the effects of the first four scenarios on selected key macroeconomic variables (figures with more detailed regional and sectoral differentiation can be found in the appendix). Fig. 2 shows the effects on wages, real exchange rates and the carbon prices (in each case relative to the initial steady state). In addition it exemplarily shows the tax burden of imports of sector 8 in case border adjustment is undertaken. Due to the fact that emissions intensity is different across sectors, the pattern is the same for all sectors, but the level depends on the emissions intensity. Fig. 3 plots the effects for selected environmental variables. The results of the fifth

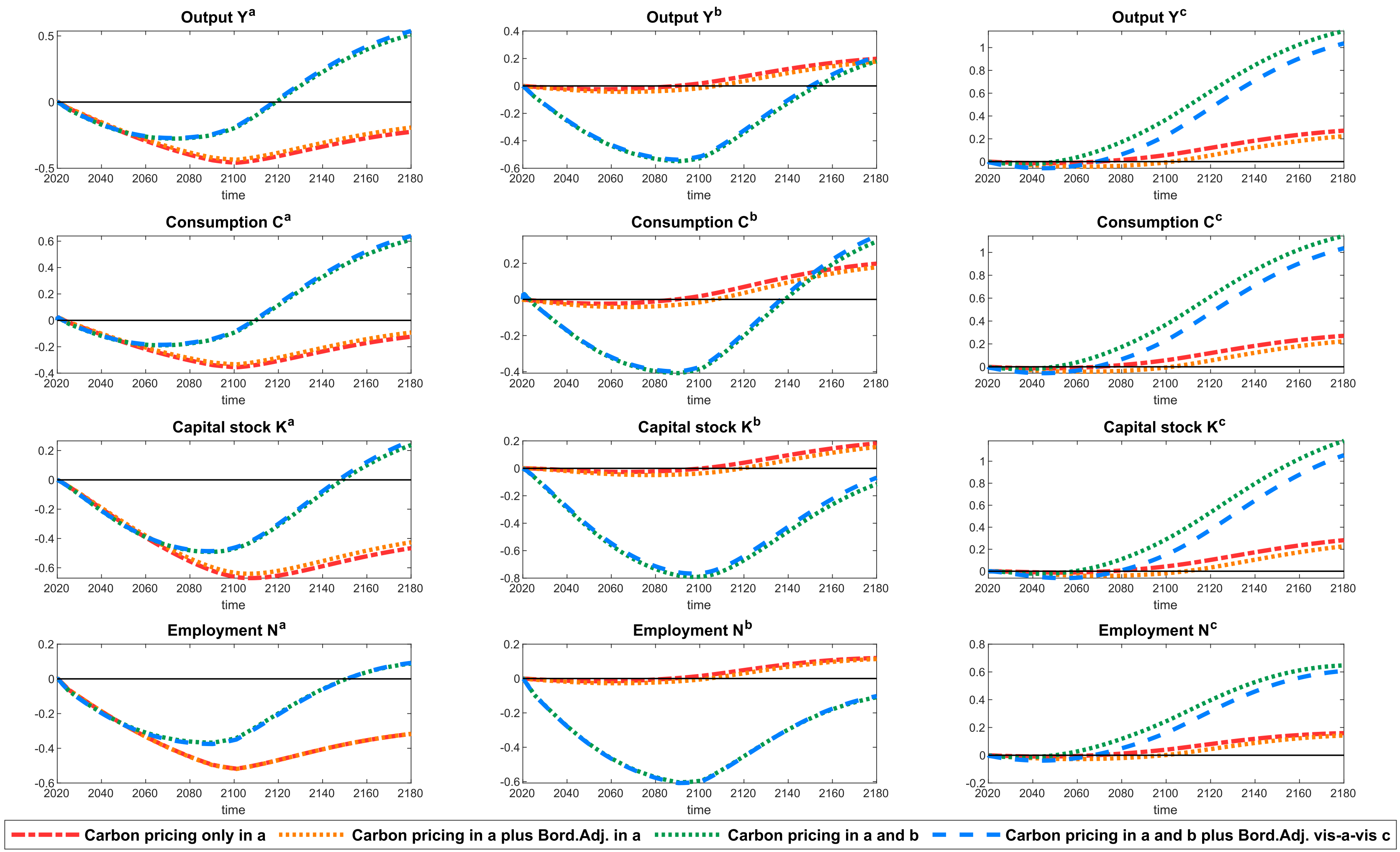

Fig. 1. Implications of carbon pricing for selected key macroeconomic variables.
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the 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.

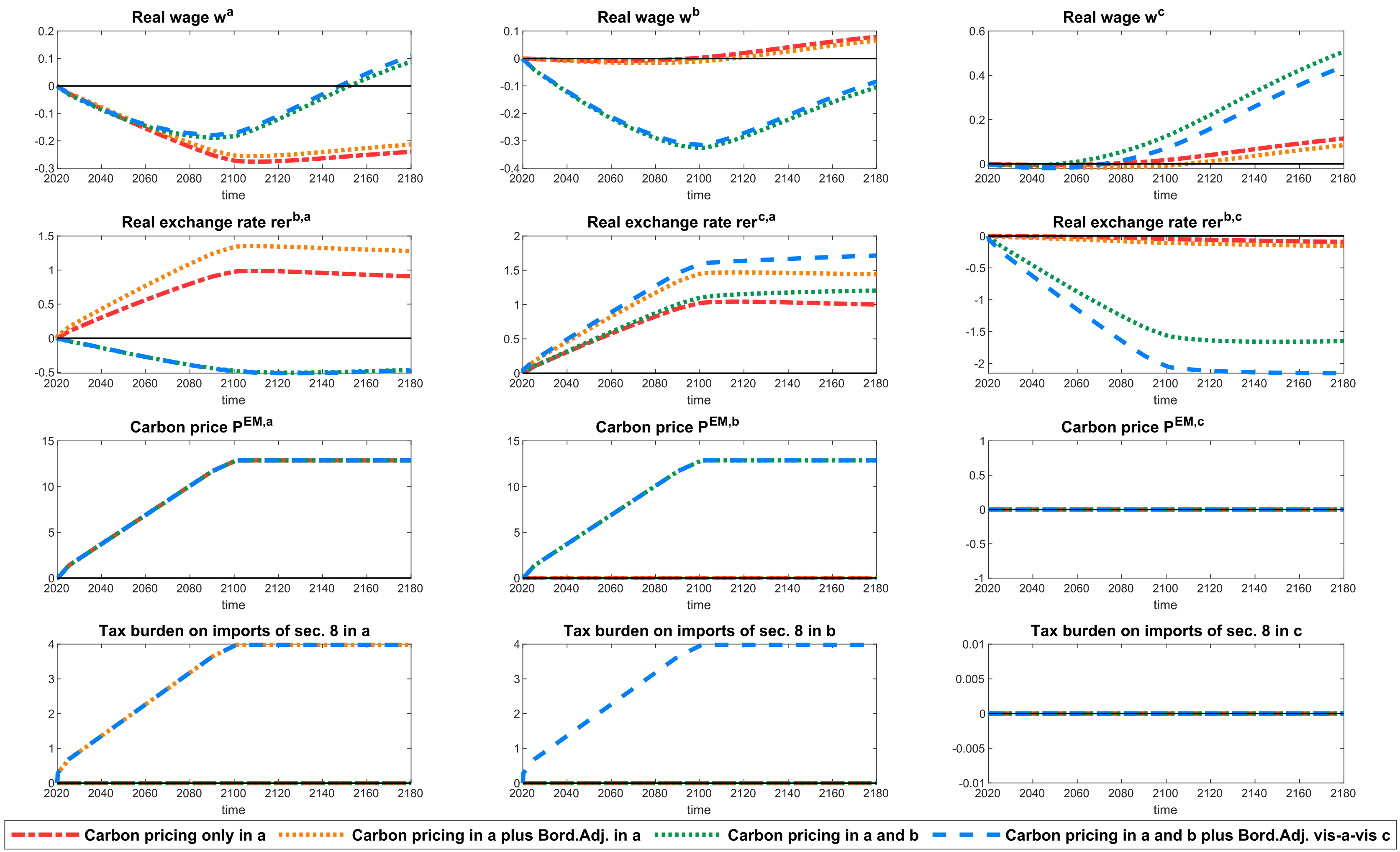

Fig. 2. Implications of carbon pricing for selected factor/relative prices.
Notes: Figure plots (projected) implications of carbon pricing for selected factor/relative prices in percentage(point) deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables 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.

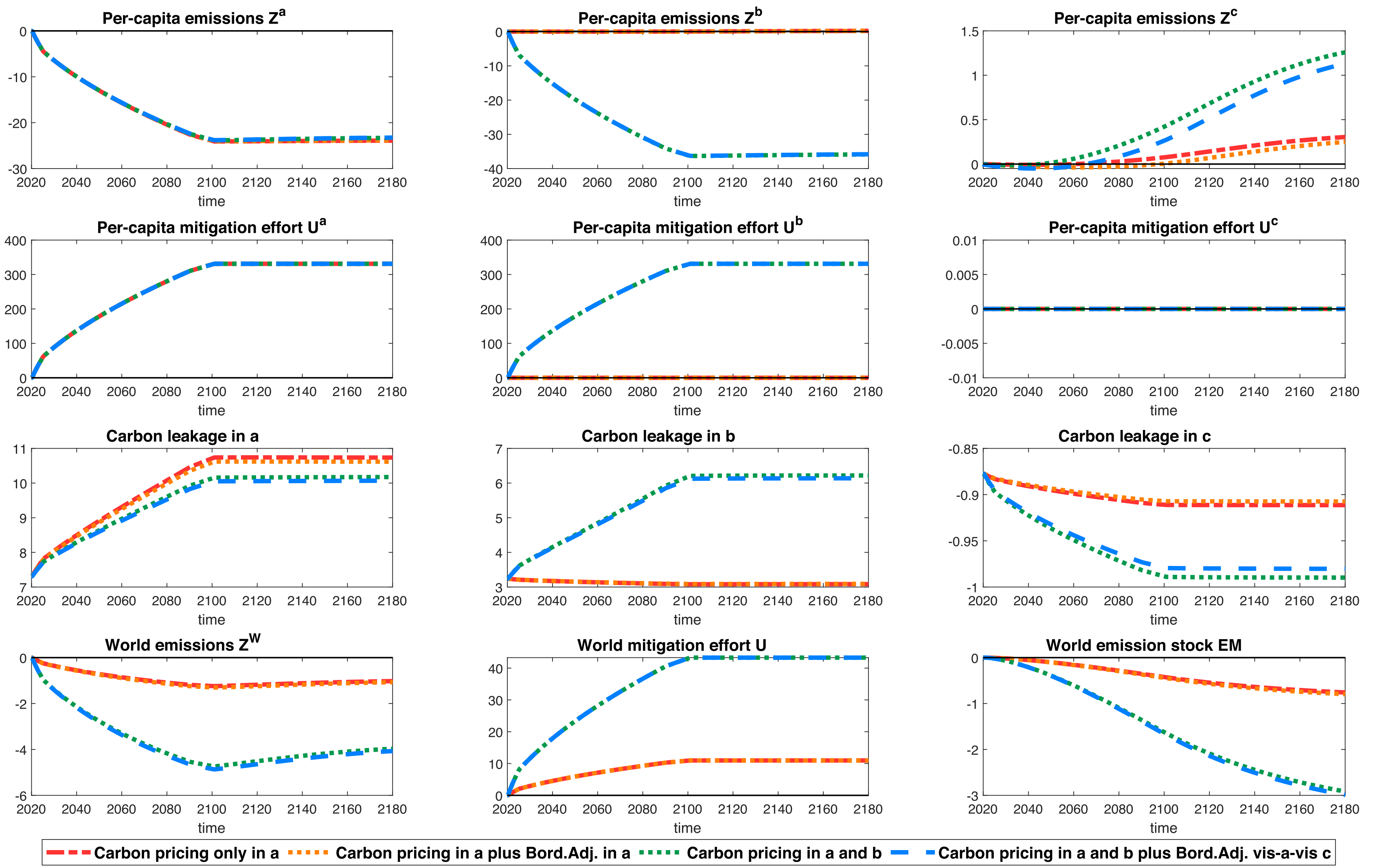

Fig. 3. Implications of carbon pricing for selected environmental variables.
Notes: Figure plots (projected) implications of carbon pricing for selected environmental variables in percentage deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables 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.

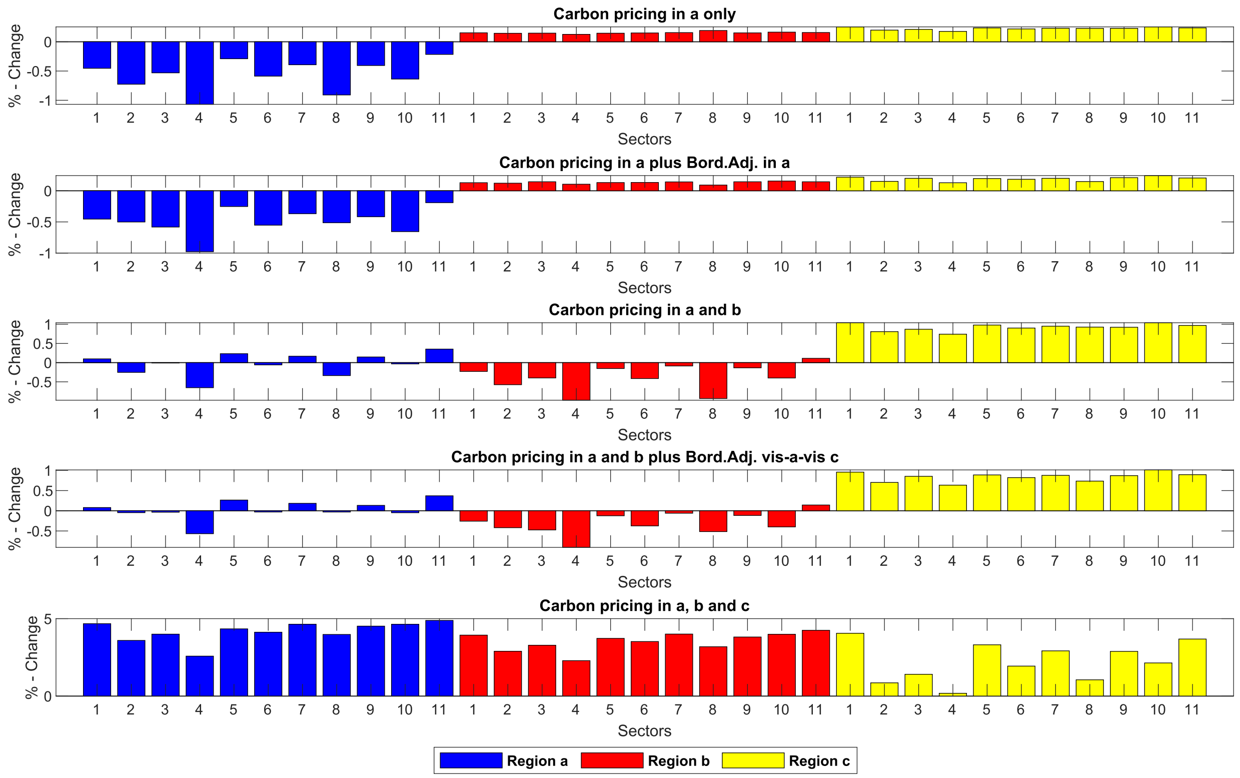

Fig. 4. Long-run changes in sectoral value added implied by carbon pricing.
Notes: Figure plots (projected) percentage deviations of new from initial steady state values of sectoral value added implied by carbon pricing for region *a* (blue bars), *b* (red bars) and *c* (yellow bars). Scenarios are according to headline, sector numbers correspond to those presented in Table B.3.

simulation (all regions introduce carbon pricing) can be found in the appendix. Table 1 summarizes the long-run implications (including the fifth simulation), whereas Fig. 4 brakes these down to different sectors.

Fig. 1 reveals our first main result. Independent of the exact policy experiment undertaken, the effects on the macroeconomic variables can be divided into two phases: A downturn (at least in the region introducing the price) followed by an upturn until a new steady state is reached. This new steady state may be characterized by output and consumption gains or losses (relative to the initial steady state), depending on the scenario, the region and the sector we look at (see Table 1 and Fig. 4).

Table 1
Long-run effects.

Scenario:	$P_a^{em}\uparrow$	$P_a^{em},\tau^X_{a,\tilde{i}}\uparrow$	$P_i^{em}\uparrow$ for $i=a,b$	$P_i^{em},\tau^X_{i,\tilde{i}}\uparrow$ for $i=a,b$	$P_i^{em}\uparrow$ for $i=a,b,c$
Output in a	−0.17	−0.15	0.38	0.40	4.68
Consumption in a	−0.07	−0.05	0.48	0.50	4.81
Hours in a	−0.30	−0.32	−0.30	−0.31	−0.28
Wages in a	−0.20	−0.16	0.35	0.38	4.68
Emissions in a	−23.86	−23.80	−23.40	−23.34	−19.72
Output in b	0.15	0.14	0.13	0.16	4.11
Consumption in b	0.15	0.14	0.28	0.30	4.28
Hours in b	0.00	0.00	−0.37	−0.38	−0.35
Wages in b	0.15	0.14	0.12	0.15	4.12
Emissions in b	0.18	0.16	−35.88	−35.84	−33.03
Output in c	0.22	0.19	0.91	0.84	3.86
Consumption in c	0.22	0.19	0.91	0.84	4.51
Hours in c	0.00	0.00	0.02	0.02	−1.33
Wages in c	0.22	0.19	0.92	0.85	3.92
Emissions in c	0.27	0.23	1.08	0.99	−38.41
World emission stock	−1.05	−1.09	−4.12	−4.19	−36.83

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.

When increasing carbon pricing, emissions, which are priced only little in the initial steady state, become more expensive. This augments marginal production costs and thereby relative prices (via the carbon price itself but also via increased investments in mitigation efforts to avoid having to pay it). Higher prices reduce demand and, thereby, income. Output, consumption and capital investment fall. Because of the GHH utility function, hours worked fall, too. This is because GHH preferences shut off the wealth effect that would be present when assuming additively separable utility functions. Wages and capital interest rates also fall because of the reduced marginal productivity of these production factors.

At the same time, emissions are reduced, which lowers the world emission stock. This eventually translates into a reduction in economic damage, which causes relative productivity gains. Whenever they are sufficiently strong, the downturn is over and the economy starts booming. Because damage depends on the world emission stock, the size of the boom depends on the amount of the world emissions reduction. The larger it is, the stronger is the boom. If only region *a* introduces carbon pricing, emissions reduction is rather small (see also Fig. 3). In the climate club scenario, the positive effects are more notable, and they are largest when the entire world participates in carbon pricing (see appendix). In any case, it takes time before the positive effects, which may increase long-run output and consumption, materialize. Note that the time span it takes before positive effects start materializing is highly sensitive to the calibration of damage functions, for which data is extremely weak. In the appendix, we also show the results for simulations in which we neglect damage. Then, only the negative effects (i.e. the downturn) prevail. Also note that, when neglecting damage, introducing carbon pricing becomes more costly when more regions participate, even for a region that introduces a carbon price (and potentially border adjustment) in any case. This is because, then, the resulting distortions reduce world income such that the negative income effect dominates potentially positive trade effects (see also Frankovic, 2022, and Hinterlang et al., 2022, for a more in-depth discussion).

The price-induced downturn followed by a productivity gain-induced upturn generates u-shaped output effects, which translate into u-shaped patterns for consumption, the capital stock and employment. The effects on factor prices are as we would expect (Figs. 1 and 2). In the long-run, the upturn compensates for the downturn if the world emissions stock and, thereby, damage is reduced sufficiently to overcompensate for the cost increase (see Table 1). For region *a*, which augments carbon pricing in all our simulation scenarios, this is the case only if at least region *b* participates, too.

The second main result is that, when only a single region introduces carbon pricing (region *a* in our first simulation), it faces relatively large negative economic effects as a result of the production cost increase. At the same time, the regions that do not introduce a carbon price benefit more or less immediately (see red dotted-dashed lines in Fig. 1). The small initial output loss in the foreign economies is explained by the relatively large drop in demand in *a* on impact which is, relatively quickly, overcompensated for by domestic agents shifting demand towards foreign goods because products of region *a* become relatively more expensive such that the real exchange rate increases (see Fig. 2). Hence, agents all around the world substitute demand for goods produced in *a* to relatively cheaper foreign products that are not affected by higher carbon prices. Demand for these foreign goods and output in these regions increase. Also domestic agents in *a* substitute expensive but clean domestic goods by cheap(er) but dirty foreign goods. Given that emissions are a by-product of production, per-capita emissions in the foreign regions increase. This fosters carbon leakage. World emissions and thereby the emission stock fall only little (Fig. 3). Productivity gains are, therefore, small. They mildly contribute to the positive developments in the foreign economies. However, they definitely are not strong enough to compensate for the negative effects in region *a* induced by the production cost push (see Table 1 and Fig. 4). In the end, region *a* loses from introducing carbon pricing in terms of output and consumption.

The third main finding is that border adjustment taxation helps to reduce carbon leakage (see orange dotted lines relative to red dotted-dashed lines in case only *a* introduces carbon pricing, and dashed blue line relative to straight green line when *a* and *b* do so in Fig. 3). As imports are taxed, it becomes less attractive for domestic agents of the carbon price-introducing region to substitute domestic goods for foreign ones.

Hence, output losses are mitigated in the regions that introduce carbon pricing and border adjustment. Output *gains* in the regions that do not introduce carbon pricing are also (slightly) smaller, which is a result of the lower trade spillovers. Given that region *a* has a cleaner production technology in terms of carbon intensities (relative to *b* and *c*, which also holds for *b* relative to *c*; see Section 4), world emissions and the emissions stock fall more relative to a situation without border adjustment. This implies that productivity gains are relatively larger. In the end, they can (but must not) be large enough to overcompensate for the carbon pricing-induced production cost push. Besides the more positive productivity effect, there is also a trade shift, which we discuss in more detail in the next paragraph. In our simulation, the negative effects in *a* are not overcompensated for by the small positive effects of border adjustment in the long run (see Table 1). Additionally introducing border adjustment subsidies to exporting firms improves the situation for the region that introduces carbon pricing. Carbon leakage is reduced further, but still not prevented (in Appendix A, we show its formal introduction; simulation results can be found in Appendix C).

Also note that region *c* benefits from carbon pricing and border adjustment in our model (relative to status quo, not relative to carbon pricing without border adjustment) due to the trade spillovers described above. In a setting with (much) higher border adjustment taxes or an alternative trading structure, in which region *c* mainly serves as a (downstream) intermediate input exporter to other regions, for example, this can be different. As exports would, in this case, be the sole source of income in *c*, border adjustment would reduce region *c*'s income more significantly. However, our model calibration does not support this view for the (entire) rest of the world (region *c*). Nevertheless, it may be correct for some of its sub-regions.

The fourth main finding is that, the more regions participate in carbon pricing, the larger is the positive effect in the long run, for all regions. And the more regions participate, the smaller is the economic downturn for those regions that introduce carbon pricing anyway. For them, output starts increasing above steady state earlier when more regions participate, too. The reason is simple. The more regions price carbon emissions, the larger is emissions reduction. Thus, productivity gains are larger. Regions that plan to introduce carbon pricing in any case should therefore have an interest in other regions participating, too. This seems to be the case for EU member states, for example. The other regions will also benefit from participating in the long-run. However, initially they face adverse effects. This is because they forgo the positive trade spillovers and face the increase in production costs. For region b, this becomes evident by comparing the situation in which only region a introduces carbon pricing with the situation in which regions a and b do so (compare red dotted-dashed lines with the green solid lines in Fig. 1; see also appendix for a simulation in which region c also participates). This result is important from a policymaker's perspective, and we will discuss it in more detail below.

Before getting there, however, we want to address our last main finding, which again relates to carbon leakage and border adjustment. The latter positively affects emissions reduction and aggregate macroeconomic performance of the region introducing it (at least mildly). However, this does not necessarily hold for all sectors alike. Taxing imports according to their emissions content, as described above, increases the import costs of emissions-intensive sectors disproportionately. As a result, imports from these sectors fall and the trade balance improves. In our simulations, the tradeable, emissions-intensive sectors 2 and 8 (manufacturing and transport subject to ETS) gain most relative to a situation without border adjustment taxes (i.e. they lose less). The non-tradeable sector 4 also profits by border adjustment, but to a much smaller extent as it only benefits from the positive domestic demand effect. Clean(er) sectors, such as non-ETS manufacturing (sector 3) as well as communications and services (sectors 9 and 10), lose (see also Appendix C). Their trade balance deteriorates. In regions that do not introduce carbon pricing, the dirty sectors mildly lose compared to a situation without border adjustment (see Fig. 4). This holds even without treating different sectors differently in a structural way (as does the European Emissions Trading System EU ETS, for example, in which some sectors are exempt). Furthermore, Fig. 4 reveals that, even in a situation in which all sectors' emissions are priced alike in all regions, some sectors (and regions) benefit more than others. Hence, carbon pricing and carbon-based import taxation affects the structure of the economy as carbon intensities differ.

Welfare. The above discussion as well as the results shown in Table 1 indicate that, in the long run, and from a pure steady-state comparison, the best situation is achieved if all regions participate in carbon pricing. Then, households can increase consumption and leisure most (see also Table 2). If this does not happen, it still holds that the more regions participate, the better. However, the transition to the new steady state takes time, and people initially lose when introducing carbon pricing. This raises the question of how to evaluate carbon pricing in total, taking into account the steady state implications and the transition paths. We seek to answer it within our model by conducting a welfare analysis. In doing so, we compute the lifetime consumption-equivalent gain of the representative household in line with Lucas (2003) as a result of the change in tax policy. The welfare function of region i is given by Eq. (1). The alternative region-i welfare function is given by

$$\mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{\left((1+ce_i) \cdot \overline{C} - \kappa_{i,N} \cdot \overline{N}^{\psi} \cdot \overline{O} \right)^{1-\sigma} - 1}{1-\sigma} \right],$$

where the bar indicates initial steady-state values. If we equate this equation with Eq. (1), we can extract the corresponding lifetime consumption-equivalent gain ce_i. We define world-welfare as a population-weighted average, i.e. $ce_w = \omega^a \cdot ce_a + \omega^b \cdot ce_b + \omega^c \cdot ce_c$. Results are summarized in Table 2. Fig. 5 shows the per-period evolution of welfare along the transition.

There are several interesting observations from the results presented in Table 2. First, it is important to use a dynamic model in order to evaluate the implications for well-being. The use of common computational general equilibrium models (such as Devulder and Lisack, 2020, Frankovic, 2022, and IMF, 2022, for example) taps the long-run implications (as shown in Table 1 and described above) but misses the transition paths. As we can see in Table 2, the transition is extremely costly. While welfare gains seem large when comparing steady states, especially if more and more regions participate, the picture reverts when taking

Table 2
Welfare 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 $i = a, b, c$
Steady state…					
…in a	0.07	0.09	0.46	0.49	3.59
…in b	0.11	0.10	0.34	0.36	3.28
…in c	0.16	0.14	0.67	0.62	3.86
…globally	0.15	0.13	0.60	0.57	3.75
With transition…					
…in a	−0.02	−0.02	−0.02	−0.01	0.05
…in b	−0.01	−0.01	−0.04	−0.04	0.01
…in c	−0.00	−0.02	0.00	−0.02	−0.01
…globally	−0.01	−0.02	−0.00	−0.02	0.00

Notes: Table shows welfare implications of different carbon pricing scenarios, expressed as consumption-equivalent gain for the representative household of region $i = a, b, c$ as well as the weighted average of households in the entire world in line with Lucas (2003), in percentage deviations from initial steady state.

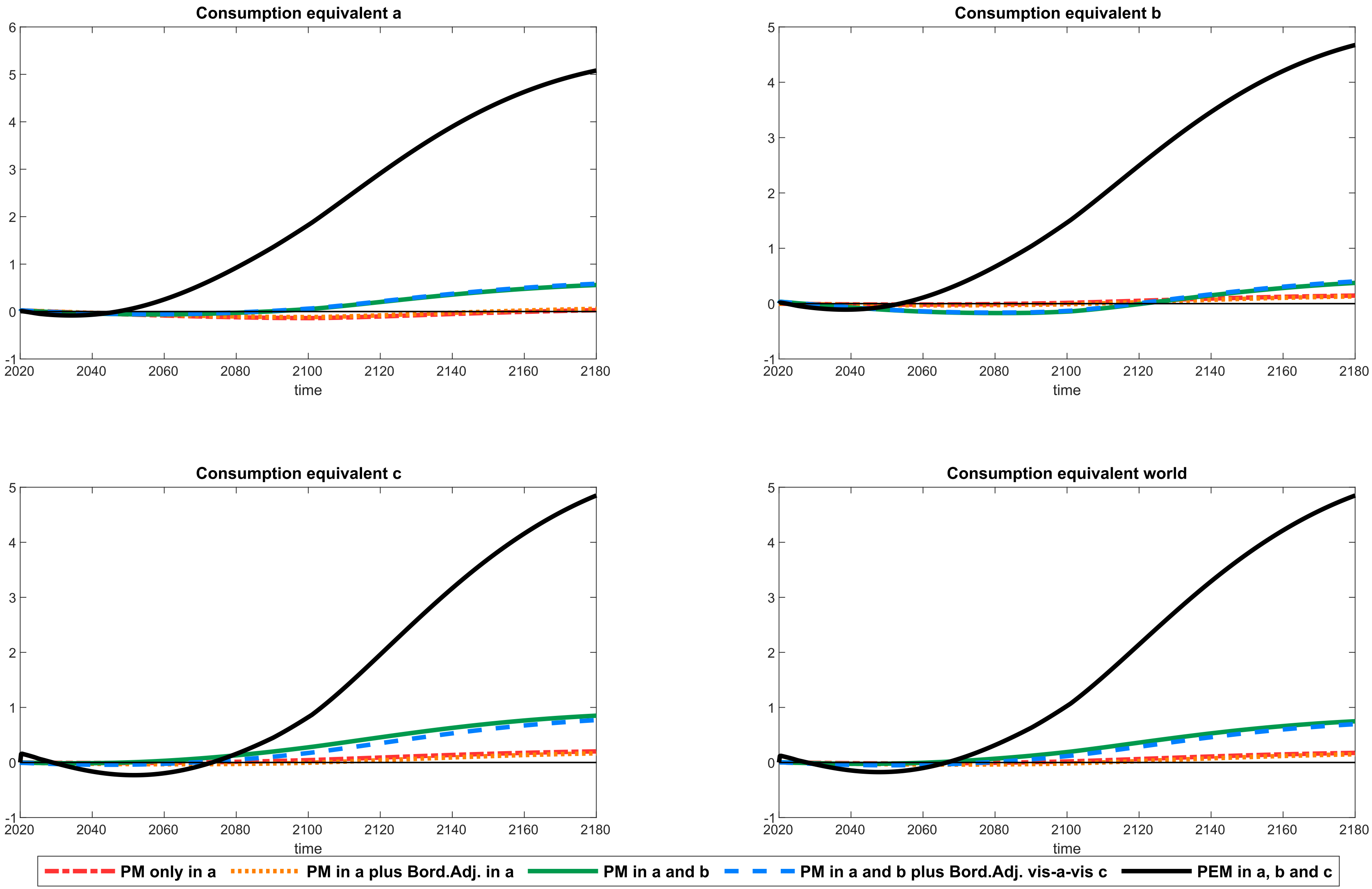

Fig. 5. Evolution of welfare implied by carbon pricing.
Notes: Figure plots (projected) evolution of welfare expressed in consumption equivalents per period from initial to new steady state. The red dotted-dashed lines show the variables for carbon prices in region *a* only. Carbon prices in *a* with 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 *a*, *b* and *c* by the solid black line.

into account the transition paths. In our baseline simulations shown here, the average person around the world would prefer not to introduce carbon pricing globally. The main reason for this is that, along the transition, region-*c* households face disproportionately large welfare losses (see also Fig. 5).

However, before turning to the second observation, some words of caution related to this finding seem warranted. In our model, benefits from carbon taxation are generated by a reduction in emissions-induced damage. As already stressed in Section 4, the calibration of the damage function is loosely tied to Kalkuhl and Wenz (2020) and to the damages calculated by the NFGS. Gillingham et al. (2018) and Nordhaus (2019), among others, have already discussed extensively that uncertainty regarding economic damage of emissions is high. Therefore, and because Kalkuhl and Wenz (2020) are said to underestimate the full impact from physical climate risks, the NGFS set up a working team to provide more insights on the economic damage of emissions in the course of 2022/2023. If damage turns out to be larger, and thereby emissions reduction generates more reduction in damage benefits will rise, also from a welfare perspective. The same is true if emissions reduction decreases damage faster, as discussed in Section 2. And it is all the more the case, if without emissions-reducing measures, the world will be heading towards a catastrophic climate scenario, which is not incorporated in our model. Nevertheless, it is not unlikely that climate policy comes along with negative effects on welfare in the medium term, and policymakers should be aware of this.

The second important observation from Table 2 is that, when one or more regions introduce carbon pricing, it is generally not beneficial for the remaining regions to join. This is due to the increase in production costs and foregone trade benefits, especially when taking into account the transition paths. For regions characterized by low per-capita income in the initial steady state (region c in our model), in particular, the load of bearing the (temporary) income and consumption losses is heavier than it is for households in the other regions (remember, marginal utility is decreasing in consumption). Although long-run benefits are large in the fifth scenario, region c still faces welfare losses when taking into account the transition.

Third, the results in Table 2 also show that carbon pricing alone does not necessarily raise well-being, at least not for all generations currently alive. Fig. 5 shows that it takes a while for welfare to move back into positive terrain. How long this takes exactly, is region-specific. For regions introducing carbon pricing, the negative impact on welfare along the transition can last for a lifetime of a generation or more.

6. Discussion and alternative simulations

The results of the previous section indicate that it may be difficult to introduce carbon pricing around the world because (i.) carbon pricing on impact generates a costly recession, also in terms of welfare, and (ii.) non-participating regions tend not to have an incentive to participate in the end. The analysis suggests that it is important to provide especially low-income regions with incentives to participate, which is already discussed by, for example, Edenhofer et al. (2015), Kornek et al. (2017) and Kornek and Edenhofer (2020). The analysis also shows that it will be beneficial for economies that introduce carbon pricing anyway if other regions also participate. Garnadt et al. (2020), Nyambuu and Semmler (2020) and IMF (2022) discuss regional carbon price discrimination and direct transfers between regions as a policy option that could achieve this goal. Note that carbon price differentiation implies cost inefficiency per se because abatement incentives may be reduced in economies with lower prices. These could be the dirtier ones in which benefits of abatement may be disproportionately high. We abstract from this aspect in our analysis. Our model provides a suitable laboratory to simulate such scenarios.

More precisely, we undertake three additional simulations and compare the results to those of the scenario above in which all regions introduce a common carbon price. First, we assume that region *c*'s price increase only amounts to 30% of the increase in other regions *a* and *b*. Second, we assume that regions *a* and *b* use 20% of their proceeds from carbon pricing to subsidize the poorer region *c*. Third, we combine the first two scenarios and assume that region *a* introduces the highest carbon price, followed by region *b*, whose price amounts to 67.5% of *a*, and *c*, with a price amounting to 62.5% of the price in *a*. Furthermore, regions *a* and *b* pay a transfer to *c* amounting to about 7% and 8% of the regional proceeds from carbon pricing, respectively. In all scenarios, we assume that carbon prices are set such that the model generates the same reduction in the emissions stock as simulated above. The results of these simulations are summarized in Table 3 (as well as in macro and welfare figures that can be found in Appendix C).

Relative to baseline, both measures prolong the downturn in the rich regions, but shorten it in the relatively poor region *c*. In terms of welfare, a prolonged recession increases the duration for the rich region to face welfare losses. Aggregate welfare effects

Table 3
Welfare effects under alternative world-wide pricing scenarios.

Scenario:	Price diff.	Transfers	Price diff. and trans.	Int. trade in abatement	Baseline
With transition…					
…in a	−0.02	−0.01	0.00	0.50	0.05
…in b	−0.10	−0.07	0.00	0.39	0.01
…in c	−0.01	0.05	0.00	0.24	−0.01
…globally	−0.02	0.02	0.00	0.29	0.00

Notes: Table shows welfare implications of different world-wide carbon pricing scenarios, expressed in consumption-equivalent gain for the representative household of region $i = a, b, c$ as well as the weighted average of households in the entire world in line with Lucas (2003), in percentage deviations from initial steady state.

including the transition dynamics are shown in Table 3. Results suggest that it is possible to find a combination of price differentiation and inter-regional transfers that benefits all regions in terms of welfare, or at least makes them indifferent compared to the initial steady state when including transition. Transfers from the rich to the poor regions remain below 0.5% of GDP in all simulated scenarios. It may be argued that, instead of transfers or price discrimination, a (large enough) climate club could use higher border adjustment taxation to prevent carbon leakage. Eventually this could also incentivize non-participating regions to participate. According to model simulations in which the carbon tax is set ten times the price charged in the climate club, carbon leakage can indeed be prevented (see Appendix C). In that case, region *c* also faces output and consumption losses. However, these are still smaller than the losses region c faces when it joins the climate club. Hence, transfers may still be necessary. In any case, it is arguable if such a discrimination is politically feasible.

The simulations above have shown that it is possible to find a combination of transfers and price discrimination in which all regions at least mildly benefit from introducing carbon pricing. However, one my be sceptical if such a policy is feasible in practice. Another way to reduce the costs of unilaterally introduced carbon pricing for region *a* (and *b*) is to allow for offsets, i.e. allow the carbon-price introducing region(s) to abate in other regions where the marginal abatement cost is lower. Allowing firms to undertake abatement investments abroad channels these towards regions in which they are less costly and/or more beneficial. This may also be considered as a transfer between regions which, in the end, augments abatement and productivity gains world-wide. Table 3 shows the welfare implications (including transition) when allowing for internationally tradable abatement efforts in a situation in which all regions introduce carbon pricing. Details on the simulation design and further results (also those when only single regions introduce carbon pricing) are in Appendix E. There, we also address the role of monitoring costs. Because, of course, the efficiency of internationally tradable abatement crucially depends on how difficult it is for the investing region to monitor that abatement investments abroad are actually undertaken.

7. Conclusions

In the dynamic, three-region environmental multi-sector general equilibrium model *EMuSe*, we analyze the macroeconomic and welfare implications of carbon pricing, border adjustment and climate clubs. We find that carbon pricing generates a recession initially as production costs rise. Benefits from lower emissions damage materialize only in the medium to long run. A border adjustment mechanism mitigates but does not prevent carbon leakage. It "protects" dirty domestic production sectors with tradeable goods in particular (at least in relative terms). From the perspective of a region that introduces carbon pricing, the downturn is smaller and long-run benefits are larger if more regions levy a price on emissions. However, for non-participating regions, there is no incremental incentive to participate as they forego trade spillovers from carbon leakage and face higher production costs along the transition. In the end, they may be better off not participating. Because of a costly transition, average world welfare may fall as a result of global carbon pricing unless the rich assist the poor. Our analysis clearly highlights the importance of a comprehensive coordinated action against climate change, able to factor in the contingent needs of different regions.

A caveat of our analysis is that our welfare conclusions are based on a representative household in the economy. We entirely abstract from distribution within economies. However, low-income households with a higher energy expenditure share or those who depend heavily on transfers may be affected even more negatively in a heterogenous agent world. The same is true where relatively poor households tend to be employed in emission and energy-intensive sectors that are particularly touched by the mitigation policies (see e.g. Känzig, 2023). All this could further worsen the welfare implications, and mechanisms to alleviate these effects may also be an issue in policy debates (see, for example, Kornek et al., 2021).

Another caveat of the analysis is that we assume the parameters concerning production, the damage function and the factor intensities to be constant over time. This also holds for the inter-sectoral linkages. Hence, we abstract from likely, but unknown future changes due to structural transformation. In order to make climate policy (more) beneficial for households in general, the economies have to adopt better and faster towards climate friendly production technologies. To some extent, this process might be induced by carbon pricing itself. However, analyzing this is beyond the scope of our model because it does not include technological change beyond investments in emission abatement. The same is true for possible incentives for foreign producers to invest in cleaner production technology in order to avoid border adjustment taxation.

In addition to that, governments could, for example, undertake or subsidize investments in innovative technologies or infrastructures (see Acemoglu et al., 2012, and Lilliestam et al., 2020), or help industries to get rid of climate-damaging production technologies faster (as discussed in Kalkuhl et al., 2012). When accompanying carbon pricing by necessary infrastructure investments or public sponsorship of innovative technologies, debt-financing may be an option (if proceeds of carbon pricing do not suffice). It could mitigate the negative effects of carbon pricing today by making those pay tomorrow who benefit from the reforms. We leave the analysis of these – and probably many more – questions to future research.

Data availability

Supplementary material of "Carbon pricing, Border Adjustment and Climate Clubs: Options for International Cooperation" (Original data) (Mendeley Data)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jinteco.2023.103772.

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