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Carbon pricing, border adjustment and climate clubs: An assessment with EMuSe

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Non-technical summary

Research Question

What are suitable climate mitigation policies? In the wake of ambitious climate goals, many economies around the world currently face this question. Carbon pricing, border adjustment taxation to prevent carbon leakage and the formation of climate clubs are considered as promising policies in the discussion. For a comprehensive evaluation of such policy measures, it is essential to analyse their economic implications.

Contribution

We use a three-region version of an **e**nvironmental **mu**lti-**se**ctor dynamic general equilibrium model called *EMuSe* to assess the macroeconomic consequences of different policy options for pricing carbon. The model entails a detailed production network as well as environmental externalities in order to account for the heterogeneity regarding, for example, emission intensities, the interconnectedness of production through intermediate inputs and regional differences.

Results

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 (i.e. the transfer of production of "dirty" goods in non-pricing regions). It "protects" dirty domestic production sectors in particular. From the perspective of a region that introduces carbon pricing, the downturn is shorter 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 positive 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 the costly transition, average world welfare may fall unless "the rich" countries assist "the poor" regions.

Nichttechnische Zusammenfassung

Forschungsfrage

Was sind geeignete Maßnahmen zur Eindämmung des Klimawandels? Angesichts ambitionierter Klimaschutzziele stehen viele Volkswirtschaften weltweit vor dieser Frage. Von vielen als besonders geeignet angesehen werden eine CO2-Bepreisung, eine Grenzausgleichs-Besteuerung, um Carbon Leakage zu vermeiden, oder der Zusammenschluss zu einem Klimaclub. Für eine umfassende Evaluierung solcher Politikmaßnahmen ist es unabdingbar auch ihre ökonomischen Implikationen zu analysieren.

Beitrag

Wir verwenden ein drei Regionen umfassendes, dynamisches stochastisches allgemeines Gleichgewichtsmodell mit einem detaillierten Produktionsnetzwerk sowie Umweltexternalitäten. Dadurch berücksichtigen wir Heterogenität u.a. in Bezug auf Emissionsintensitäten, die Verflechtung der Produktion durch Vorleistungen oder zwischen den Regionen.

Ergebnisse

Wir zeigen, dass die Einführung von CO2-Bepreisung aufgrund der Kostensteigerung zunächst negative Outputeffekte hervorruft. Sinkende klimabedingte Schäden im Produktionsprozess, die durch niedrigere CO2-Emissionen ausgelöst werden, materialisieren sich erst mittel- bis langfristig. Eine Grenzausgleichs-Besteuerung reduziert Carbon Leakage etwas, d.h. es wirkt der Tendenz entgegen, dass die Produktion „schmutziger“ Güter in Regionen ohne oder mit niedrigerer CO2-Bepreisung ausgelagert werden. Davon profitieren vor allem emissionsintensive Sektoren im Inland. Aus Sicht von Regionen, die ohnehin einen CO2-Preis einführen, ist es besser, wenn viele Regionen mitmachen. In diesem Fall ist die dadurch ausgelöste heimische Rezession kürzer, und die positiven langfristigen Effekte sind wegen der höheren weltweiten Emissionsreduktion größer. Die anderen Regionen haben jedoch nicht unbedingt einen Anreiz, bei einer globalen CO2-Bepreisung mitzumachen. Denn sie müssten auf Carbon Leakage-induzierte Handelsgewinne verzichten und wären höheren Produktionskosten ausgesetzt. Letztendlich könnte es aus ihrer Sicht vorteilhaft sein, sich nicht zu beteiligen. Die hohen Transformationskosten stehen somit einer globalen CO2-Bepreisung entgegen. Die globale Wohlfahrt könnte sogar sinken, es sei denn, dass, gemessen am Pro-Kopf-Einkommen, „reichere“ Regionen die „ärmeren“ Regionen unterstützen.

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Carbon Pricing, Border Adjustment and Climate Clubs: An Assessment with EMuSe*

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Abstract

In a dynamic, three-region **e**nvironmental **mu**lti-**se**ctor general equilibrium model (called *EMuSe*), 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, but it "protects" dirty domestic production sectors in particular. From the perspective of a region that introduces carbon pricing, the downturn is shorter 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 the costly transition, average world welfare may fall as a result of global carbon pricing unless "the rich" assist "the poor".

Keywords: Carbon Pricing, Border Adjustment, Climate Clubs, International Dynamic General Equilibrium Model, Sectoral Heterogeneity, Input-Output Matrix

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

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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. We do this within a three-region version of the **e**nvironmental **mu**lti-**se**ctor dynamic general equilibrium model *EMuSe* (see Hinterlang, Martin, Röhe, Stähler, and Strobel, 2021). 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, Rachedi, and Santoro (2021). In addition to their model, agents in our model also engage in international trade. Following Heutel (2012), Annicchiarico and Di Dio (2015) and Annicchiarico, Correani, and Di Dio (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, Carattini, Fischer, and Heutel, 2021, 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 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.[1]

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. Conversely, dirty domestic production sectors 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

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[1] It additionally reduces carbon leakage, which we discuss in the next paragraph.

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 a 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 prolonged downturn relative to our baseline simulations without price differentiation and transfers. However, 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. (2021). 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, Hassler, Krusell, and Tsyvinski, 2014). Others, such as Fischer and Springborn, 2011, Böhringer, Fischer, and Rosendahl, 2014, and Böhringer and Fischer, 2020, for example, analyse optimal pollution as a direct input. Because we rely on a multi-sector modelling framework in line with Hinterlang et al. (2021),[2] we implicitly incorporate this element through the input-output modeling structure, too. Specifically, firms determine their intermediate inputs and may avoid products from emissions-intensive sectors depending on their relative price. Concerning the effect of emissions on the economy, we follow Heutel (2012), Golosov et al. (2014) and Khan, Metaxoglou, Knittel, and Papineau (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, Chen, Shieh, and Lai (2009), Angelopoulos, Economides, and Philippopoulos (2013), Cai and Lontzek (2019) and Cai (2020).

There are several papers analysing 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. The effect of carbon pricing on trade spill-overs is investigated in Annicchiarico and Diluiso (2019) and Duan, Ji, Lu, and Wang (2021). Moreover, Annicchiarico et al. (2018) find that the environmental tax regime affects market structure and markups. 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 analyse carbon pricing in a multi-sector framework, at the cost of not being able to address the transition between steady states. Antosiewicz, Lewandowski, and Witajewski-Baltvilks (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. (2021) us a 54-sector model to compare different ways of energy and emissions taxation. 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, Zhao, and Wei (2020) provide an overview of the most recent literature on carbon leakage. The literature that tries to quantify carbon leakage can be divided into mainly two strands. The first one relies on econometric setups that use ex post

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[2] 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 modeling production networks regarding trade and tariffs. Similar models are currently applied to the Covid-19 crisis (Baqaee and Farhi, 2020), the fiscal policy response to the crisis (Hinterlang, Moyen, Röhe, and Stähler, 2021), as well as to assessing the government spending multiplier in general (Bouakez et al., 2021, and Devereux, Gente, and Yu, 2020). How the monetary transmission channel depends on heterogenous production structures with a focus on price rigidities is investigated in Pasten, Schoenle, and Weber (2020) and Bouakez, Cardia, and Ruge-Murcia (2014).

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, Grimm, and Reuter, 2020, relying on the European Emissions Trading System EU-ETS). The other strand uses CGE or partial equilibrium models to simulate the effects of carbon policies ex ante (see e.g. the meta study by Branger and Quirion, 2014). While the former strand typically finds no or limited carbon leakage when assessing existing carbon pricing schemes, the latter documents carbon leakage in some industries but only mixed evidence at the aggregate level. Comprehensive reviews by, for example, Felbermayr and Peterson (2020), Zachmann and McWilliams (2020) and Yu et al. (2020) also discuss that the amount of leakage depends on the regions considered or on specific model assumption made, such as, for example, substitution elasticities and/or trade structures. Our carbon leakage measures fall in the range of those presented in these studies.

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

The idea of a climate club, i.e. a larger group of countries introducing (similar) carbon prices dates back to Nordhaus (2015). Nachtigall, Ellis, Peterson, and Thube (2021) review CGE and IAM modelling studies regarding international coordination on carbon pricing. They find that international cooperation has positive economic and environmental effects. Moreover, these are larger (i.) when more countries participate and (ii.) when more emissions and sectors are covered. However, regions may have different reasons not to collaborate (as discussed in Weitzel et al., 2012). Additional incentives, such as transfers or price differentiation, may be necessary to reach international agreements (see Winkler, Peterson, and Thube, 2021, Peterson and Weitzel, 2016, Roolfs, Gaitan, and Edenhofer, 2021, and IMF, 2022). 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.

To put our simulation results into perspective, we should take notice of a debate

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

that started recently. Essentially, 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), however, 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, the question how fast lower carbon emissions improve the environment must be answered by natural scientists. However, the answer is important for economists because it determines optimal policies regarding, for example, the path of carbon prices, and also for interregional transfers.

3 The model

Our model is a multi-region extension of the multi-sector model *EMuSe* presented by Hinterlang et al. (2021). 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.[4] 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

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[4] 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.

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

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

The parameter σ denotes the inverse of the elasticity of intertemporal substitution for consumption, β is the discount rate. The inverse of the Frisch elasticity of labor supply is determined by ψ, $\kappa_{i,N}$ is the relative weight of the disutility of labor. Note that we allow only the latter parameter to be region-specific. $\mathbb{E}_0$ is the expectations operator at $t = 0$. Given the consumer price index (CPI) in region i, $P^C_{i,t}$, the choices of the representative household are subject to the real budget constraint

$$\begin{aligned}(1+\tau^c_{i,t})C_{i,t} + (1+\tau^I_{i,t})P^I_{i,t}I_{i,t} + nfa_{i,t} \quad &= \quad (1-\tau^w_{i,t})w_{i,t}N_{i,t} + r^k_{i,t}K_{i,t-1} + R_{i,t-1}nfa_{i,t-1} \\ &\quad +TR_{i,t} + \Pi_{i,t}, \end{aligned} \tag{2}$$

where $P^I_{i,t}$ 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 $r^k_{i,t}$ 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 $\tau^c_{i,t}$, on the investment bundle $\tau^I_{i,t}$, and the average labor tax rate is $\tau^w_{i,t}$. $TR_{i,t}$ 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. 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 $P^C_{i,t}$ and $P^I_{i,t}$, 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

$$\max_{X_{s,i,t}} (1+\tau^X_{i,t}) P^X_{i,t} X_{i,t} - \sum_{s=1}^{S} (1+\tilde{\tau}^X_{s,i,t}) P^X_{s,i,t} X_{s,i,t},$$

where $P^X_{s,i,t}$ 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. $\tilde{\tau}^X_{s,i,t}$ 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^K_t, 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

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

where $\varepsilon_{s,i,t}$ is total factor productivity, the α's determine factor intensity and $D_{s,i}\left(M_t\right)$ 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 $D_{s,i}\left(M_t\right) = \gamma_{0,s,i} + \gamma_{1,s,i} \cdot M_t + \gamma_{2,s,i} \cdot M_t^2$.[5]

Following Annicchiarico and Di Dio (2015), emissions are a by-product of production taking the form $Z_{s,i,t} = \kappa_{s,i} \cdot (1 - U_{s,i,t}) \cdot y_{s,i,t}$, where $\kappa_{s,i} \in [0, \infty)$ and $U_{s,i,t} \in [0,1)$ is costly abatement with an abatement cost function $C\left(U_{s,i,t}\right) = \phi_{1,s,i} \cdot U_{s,i,t}^{\phi_{2,s,i}} \cdot y_{s,i,t}$, 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

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[5] In the simulations presented below, we assume damage not to be sector nor region-specific due to the lack of reliable data (hence, the γ-parameters are assumed to be equal across regions and sectors). However, this is not likely to be true. Based on tentative simulations with different damage functions, we find that (welfare) losses (and gains) of highly damaged regions or sectors will be smaller (larger).

$\sigma_{H,s,i}$. These parameters may differ across sectors. The optimization problem is

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

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:

$$TR_{i,t} = \tau^w_{,it} \cdot w_{i,t} \cdot N_{i,t} + \tau^c_{i,t} \cdot C_{i,t} + \tau^I_{i,t} \cdot P^I_{i,t} \cdot I_{i,t} + \sum_{s=1}^{S} P^{em}_{s,i,t} \cdot Z_{s,i,t} + \sum_{s=1}^{S} \tau^H_{s,i,t} \cdot P^H_{s,i,t} \cdot H_{s,i,t}. \quad (5)$$

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, Sault, and Wallis (2000), is possible. For a discussion about the impact of using different fiscal instrument in our model, see also Hinterlang et al. (2021).

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

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

where $X \in \{C, I, H\}$.[6] 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

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

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[6] 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.

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.[7]

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

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

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, Huang, Ang, and Zhou (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.[8]

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[7] 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.

[8] 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

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.

To derive the product market clearing conditions, we follow Bouakez et al. (2021) and define CPI-deflated sectoral value added as

$$y^{va}_{s,i,t} = P_{s,i,t} \cdot y_{s,i,t} - (1 + \tau^E_{s,i,t}) \cdot P^H_{s,i,t} \cdot H_{s,i,t} - ec_{s,i,t} \cdot y_{s,i,t} + TB_{s,i,t},$$

for all sectors s and regions i, where the emission cost factor $ec_{s,i,t}$ is given by the sum of abatement costs and emission taxes, i.e. $ec_{s,i,t} = \left[\phi_{1,s,i} \cdot U^{\phi_{2,s,i}}_{s,i,t} + P^{em}_{s,i,t} \cdot \kappa_{s,i} \cdot (1 - U_{s,i,t})\right]$. Total value added is thus $Y^{va}_{co,t} = \sum_{s=1}^{S} y^{va}_{s,co,t}$, and it must hold that

$$Y^{va}_t = C_t + P^I_t \cdot I_t + TB_{i,t}. \tag{9}$$

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

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

$\rho^M \in (0, 1)$ 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. (2021). 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.[9] The United States (US), Canada, Mexico, Australia, Japan

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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).

[9] We would also include Iceland and Liechtenstein to this group. However, our main data source to calibrate the model does not include these countries individually.

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 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 to improve readability.

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 $\beta = 0.992$, which implies an annual interest rate of 3.3%. The intertemporal elasticity of substitution is set to a standard value of $\sigma_c = 2$. Following Coenen, Straub, and Trabandt (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 $\bar{N}_i = 0.33$. Capital depreciates at a typical annual rate of 10% (see, for example, Cooley and Prescott (1995)). 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. (2021) 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. (2021), 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 ($i \in \{a, b, c\}$).[10] 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).[11] 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

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[10] 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).

[11] Note, that in most cases only subsectors of these sectors fall under ETS. However, we lack more disaggregated data for calibration.

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, Dietzenbacher, Los, Stehrer, and De Vries (2015)).[12] 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 $\bar{i}$. To facilitate calculations, we normalize relative prices to one in the initial steady state.

Environmental parameters To calibrate sector-specific CO2 emissions per unit of output $\kappa_{s,i}$, we 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 sectoral emissions is available from 2000-2016. However, we are restricted to take values from 2014, since the WIOD series end in this period and carbon intensities are approximated by dividing emissions by gross output. 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). Following the recent DSGE literature, the parameters of the abatement cost function are equal across sectors with $\phi_{1,s} = 0.185$ and $\phi_{2,s} = 2.8 \, \forall s$ as in Nordhaus (2008) and Annicchiarico and Di Dio (2015). A critical discussion about different abatement cost functions and their parameterizations can be found in Cline (2011). Our parametrization for the damage function 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

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[12] Steady state values are calibrated such that they represent mean values over this period. Our calibration tool allows us to extract and aggregate WIOD data for a custom choice of years, country and sector specifications.

Financial System (NGFS; see NGFS, 2020, 2021a).[13] Due to the lack of data, we assume abatement cost and damage functions to be equal across sectors and regions. However, further research should focus on sectoral differences and the resulting implications. We abstract from this aspect in the present paper. As the values in the tables imply, region c, comprising countries like China or India, has the most carbon intensive production across sectors. The European region a produces least carbon per unit of output. Mining, quarrying & energy is the sector with the largest carbon intensity across regions, while IT and communication yields the lowest.

5 Baseline simulations

In this section, we will 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.

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 (and it remains at the initial steady-state level for the others).[14] 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

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[13] Choosing a lower economic damage from emissions would reduce the damage reduction and thereby reduce and 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.

[14] 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, theoretically, possible in our model. However, the results we present below remain unchanged qualitatively. Quantitatively, sector or regions with relatively higher (lower) emissions pricing are, unsurprisingly, affected more (less) relative to this simplified baseline scenario. Therefore, and because of the lack of reliable forecasts about how different carbon pricing will evolve regionally and sectorally, we simply assume the same price to hold in all regions for the simulations shown below.

2100, it will stay constant at the higher level. Based on calculations using the integrated assessment model REMIND,[15] 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 Figure 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,b,c, for details). Results presented below depend on these price developments.[16] 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.

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 $\tilde{i} = b, c$. This holds for all $s \in \mathcal{S}$, where $X \in \{C, I, H\}$.

Results The results of these policy scenarios are summarized in Figures 1 to 4 as well as Table 1. Figure 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). Figure 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 4 in case border adjustment is undertaken.[17] Figure 3 plots the effects for selected environmental variables. The results of the fifth simulation (all regions introduce carbon pricing) can be found in the appendix. Table 1 summarizes the long-run implications (including the fifth simulation), whereas Figure 4 brakes these down to different sectors.

Figure 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

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[15] See `https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind` for up-to-date details on the model.

[16] The NGFS provides paths for several other scenarios, some more ambitious (generating zero net emissions by 2050), other less ambitious but potentially containing more abrupt changes (called a hot house scenario). 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. Quantitatively, higher (lower) price hikes will, of course, increase (mitigate) both, losses (on impact) and gains (in the long run) that emerge from higher carbon pricing. For illustrative purposes, we show this by simulating the scenario with zero net emissions in the appendix. Which carbon price path will ultimately be established, is still unclear and subject to intense discussions (see Drupp, Nesje, and Schmidt, 2022, for an overview). Furthermore, note that the REMIND model is more elaborated regarding the environmental side, and additionally assumes (exogenous) technological progress (beyond mitigation efforts), which we do not. Therefore, it does not come as a surprise, that the price path of the REMIND model does not result in the same emissions reduction in our model.

[17] 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.

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 Figure 4).

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. As consumption and leisure are normal goods, hours worked increase (i.e. households try to partly compensate for the income loss by working more). Wages fall as labor supply rises. Capital interest also falls (not shown in the figures) because of the reduced marginal productivity of capital.

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 and faster it is, the stronger is the boom, and the earlier it starts. If only region a introduces carbon pricing, emissions reduction is rather small (see also Figure 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 allow to increase long-run output and consumption in most cases, materialize.[18]

The price-induced downturn followed by a productivity gain-induced upturn generates u-shaped output effects, which translate into u-shaped patterns for consumption and the capital stock. Given that consumption and leisure are normal goods, as described above, this yields inverse u-shaped employment patterns. The effects on factor prices are as we would expect (Figures 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 long-lasting 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 Figure 1).[19] The main reason is that products of region a become relatively more expensive such that the real exchange rate increases (see Figure 2). Hence, agents around the world

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[18] 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., 2021, for a more in-depth discussion).

[19] The very 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 the following effects described in this paragraph.

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. Even 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, too. This fosters carbon leakage. World emissions and thereby the emission stock fall only little (Figure 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 Figure 4). In the end, region a loses from introducing carbon pricing in terms of output and consumption.

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	-0.04	0.16	0.55	0.80	2.99
Consumption in a	-0.04	0.14	0.55	0.77	2.99
Hours in a	0.01	-0.06	-0.18	-0.27	-0.98
Wages in a	-0.06	0.18	0.73	1.02	4.00
Emissions in a	-9.07	-8.43	-8.43	-7.78	-5.78
Output in b	0.35	0.40	0.41	0.66	2.60
Consumption in b	0.35	0.40	0.41	0.65	2.61
Hours in b	-0.12	-0.13	-0.13	-0.22	-0.85
Wages in b	0.47	0.54	0.54	0.86	3.49
Emissions in b	0.42	0.43	-10.40	-9.73	-8.18
Output in c	0.40	0.42	1.04	1.08	2.16
Consumption in c	0.40	0.43	1.04	1.09	2.16
Hours in c	-0.13	-0.14	-0.34	-0.36	-0.71
Wages in c	0.54	0.58	1.39	1.46	2.89
Emissions in c	0.49	0.25	1.26	0.72	-13.21
World emission stock	-0.69	-0.78	-1.87	-2.06	-11.46

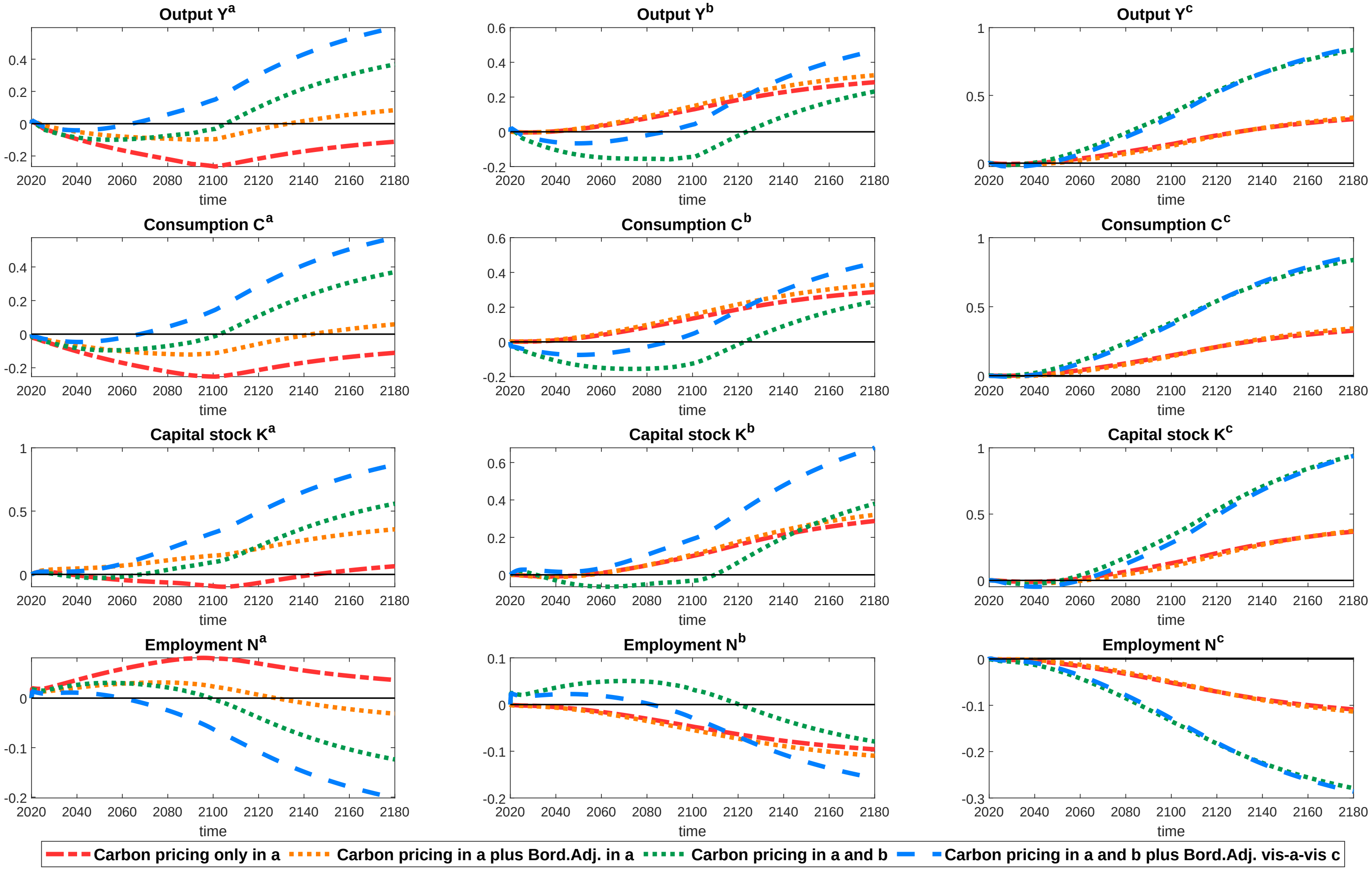
Notes: Table shows long-run effects on selected aggregate macro variables of different carbon pricing scenarios for regions a, b and c as well as for the world emissions stock, in percent deviations from initial steady state.

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 Figure 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. This is also true for output *gains* in the regions that do not introduce carbon pricing, 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 baseline simulation, the negative effects in a are overcompensated for by the positive effects of border adjustment in the long run (see Table 1). Additionally introducing border adjustment subsidies to exporting firms further improves the situation for the region that introduces carbon pricing. Carbon leakage is reduced further, but still not prevented entirely (in Appendix A, we show how we introduce border adjustment subsidies for exporters formally; simulation results can be found in Appendix C).

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 shorter is the economic downturn for those regions that introduce carbon pricing anyway. The reason is simple. The more regions price carbon emissions, the larger is emissions reduction. Thus, productivity gains are larger and materialize earlier. 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 (relatively long lasting) 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 (see red dotted-dashed lines with the green solid lines in Figure 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.

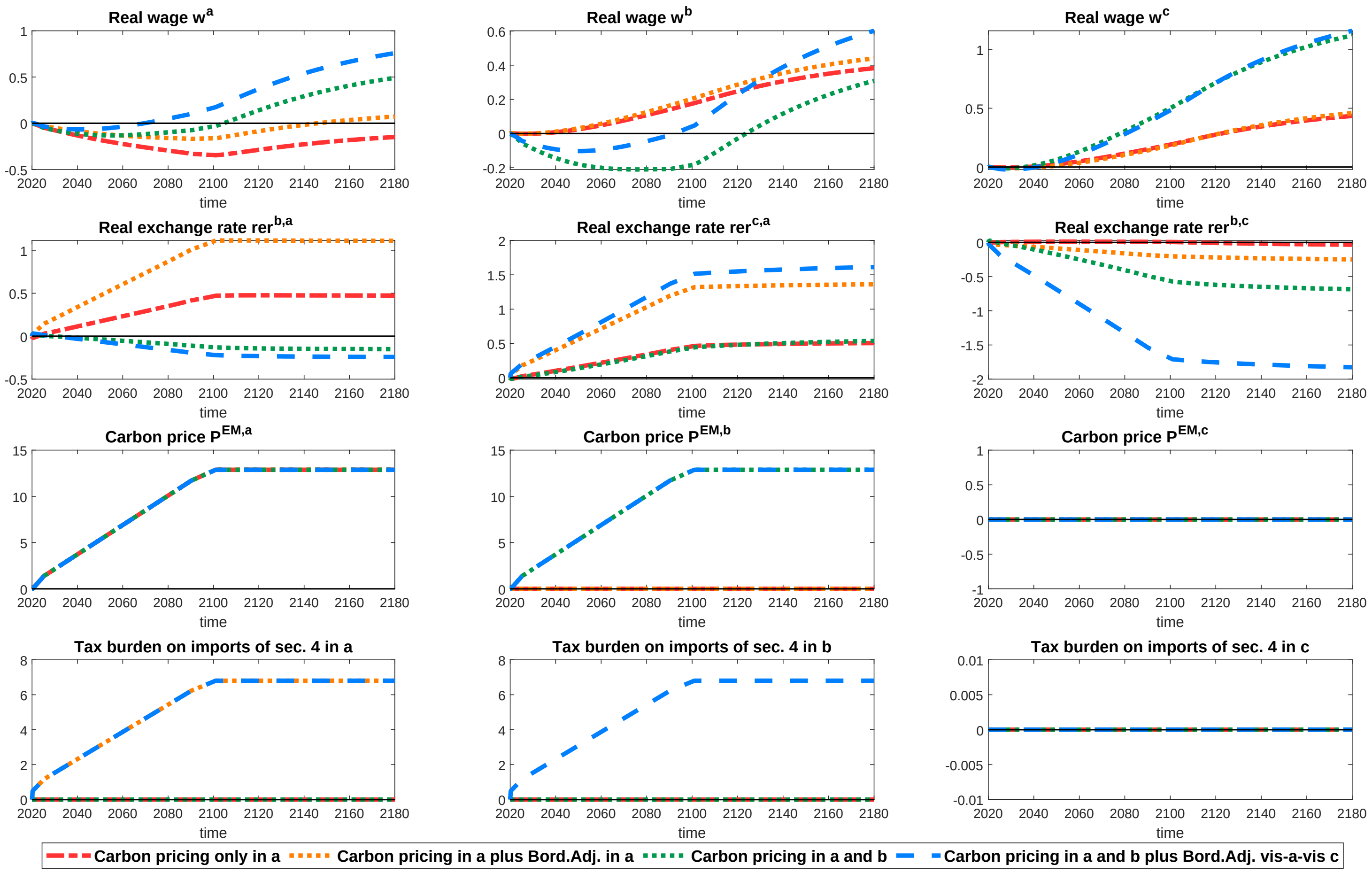
Before getting there, however, we want to address our last main finding, which again relates to border adjustment. Such a mechanism positively affects emissions reduction and aggregate macroeconomic performance of the region introducing it. However, this does not necessarily hold for all sectors alike. Taxing imports according to their emissions content, as described above, increases the import costs of emissions-intensive sectors disproportionately. In our simulations, this is especially the case for the mining and energy sector. If the import tax prevents domestic agents from importing these goods (because of a relatively high tax increase), it is this sector that gains domestically, while other sector may still lose (albeit to a lesser extent; see Figure 4 for the simulations in which either region a or regions a and b introduce border adjustment). In regions that do not introduce carbon pricing, the corresponding sector loses. 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, Figure 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. Generally, those sectors and regions with a cleaner production tend to benefit disproportionately.

Figure 1: Implications of carbon pricing for selected key macroeconomic variables



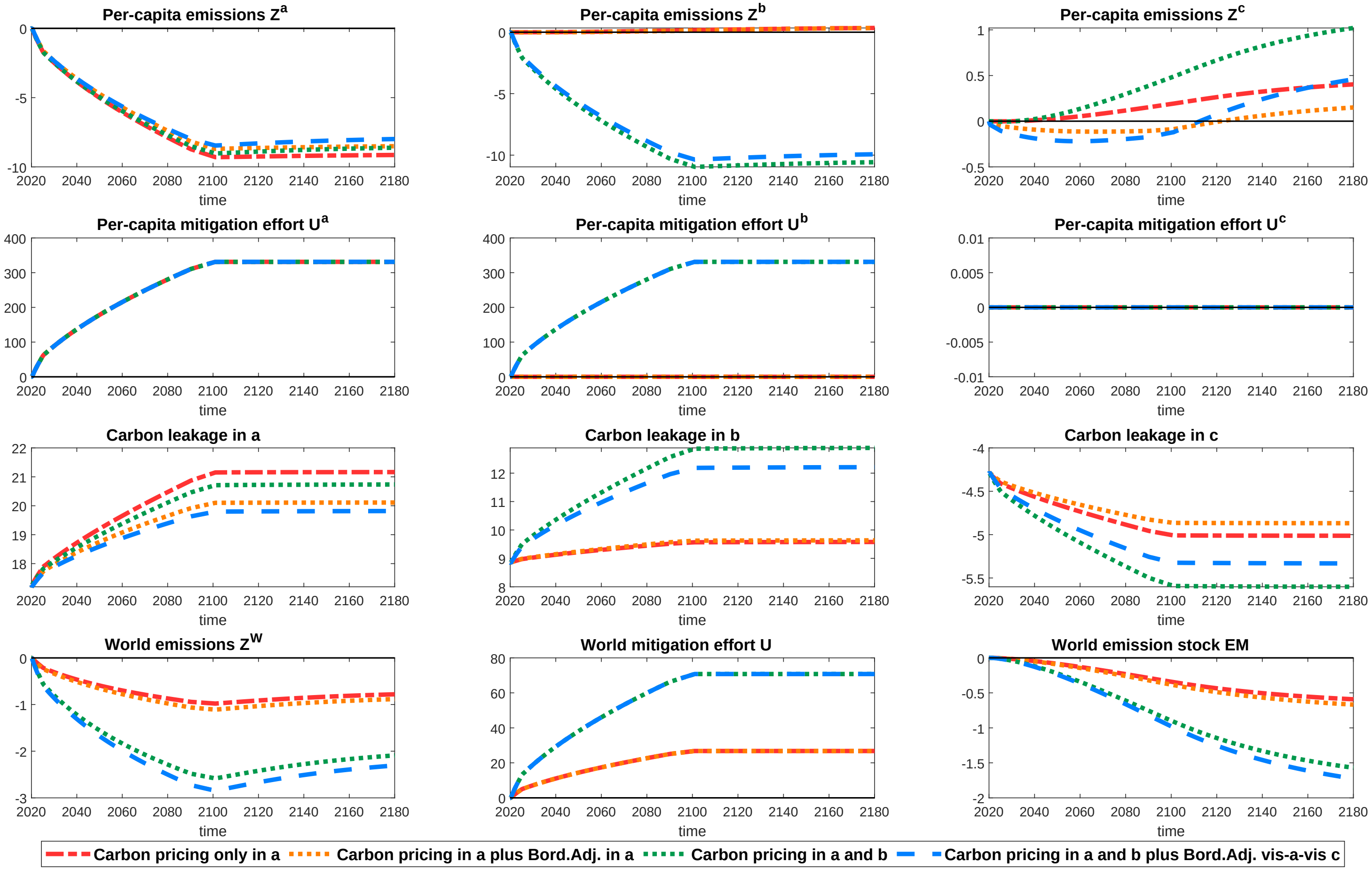
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment 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.

Figure 2: Implications of carbon pricing for selected factor/relative prices



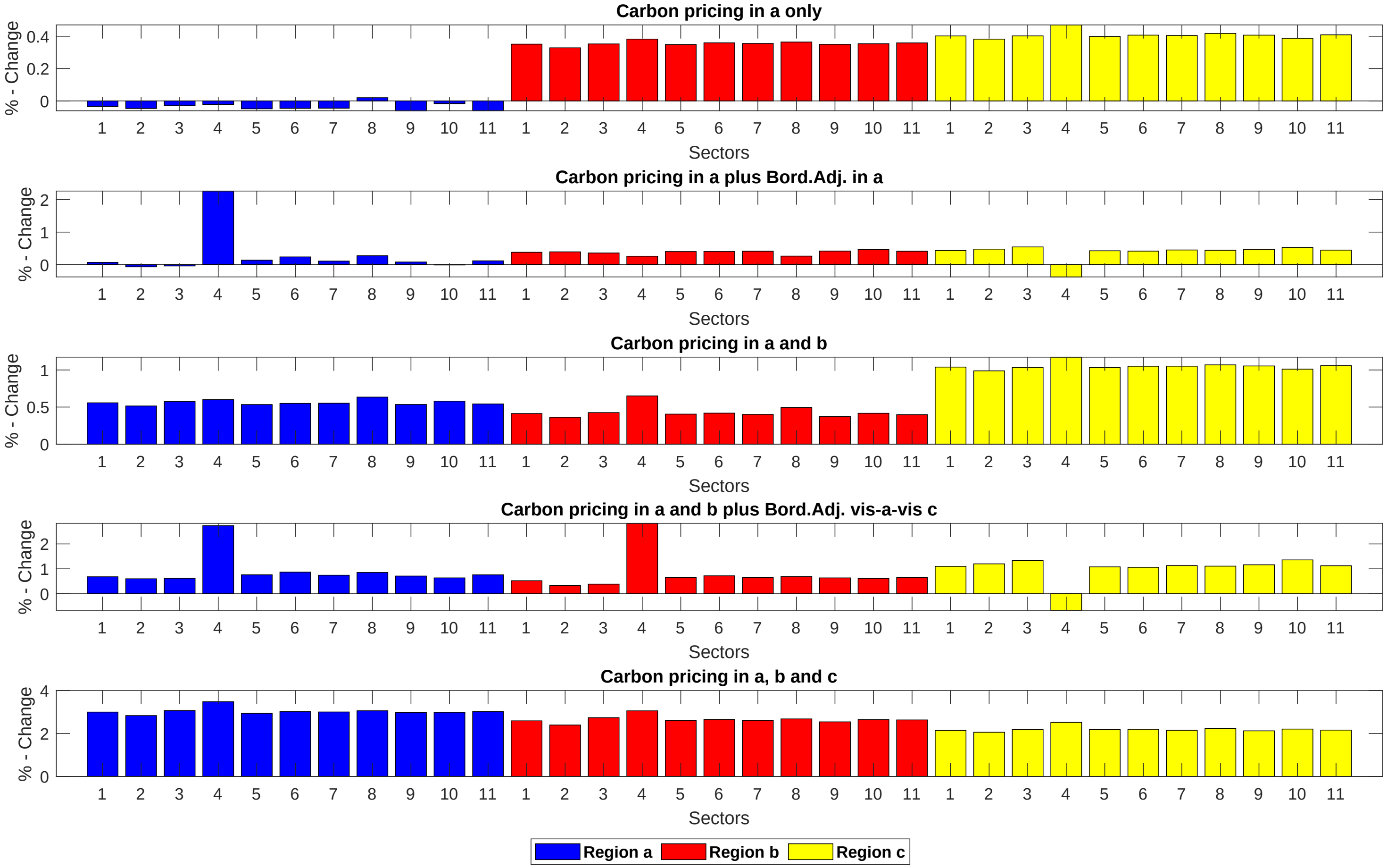
Notes: Figure plots (projected) implications of carbon pricing for selected factor/relative prices in percentage(point) deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region *a* only. Carbon prices in *a* with border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

Figure 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.

Figure 4: Long-run changes in total sectoral output 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.

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 equation (1). The alternative region-i welfare function is given by

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

where the bar indicates initial steady-state values. If we equate this equation with equation (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. Figure 5 shows the per-period evolution of welfare along the transition.

Table 2: Welfare 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 $i=a,b,c$
Steady state...					
...in a	-0.05	0.18	0.68	0.97	3.74
...in b	0.44	0.50	0.50	0.80	3.24
...in c	0.50	0.53	1.29	1.35	2.69
...globally	0.43	0.49	1.11	1.23	2.89
With transition...					
...in a	-0.15	-0.08	-0.06	0.01	0.35
...in b	0.05	0.06	-0.11	-0.04	0.22
...in c	0.05	0.04	0.13	0.12	-0.15
...globally	0.03	0.03	0.07	0.08	-0.04

Notes: Table shows welfare implications of different 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.

We can make 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 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 Figure 5).

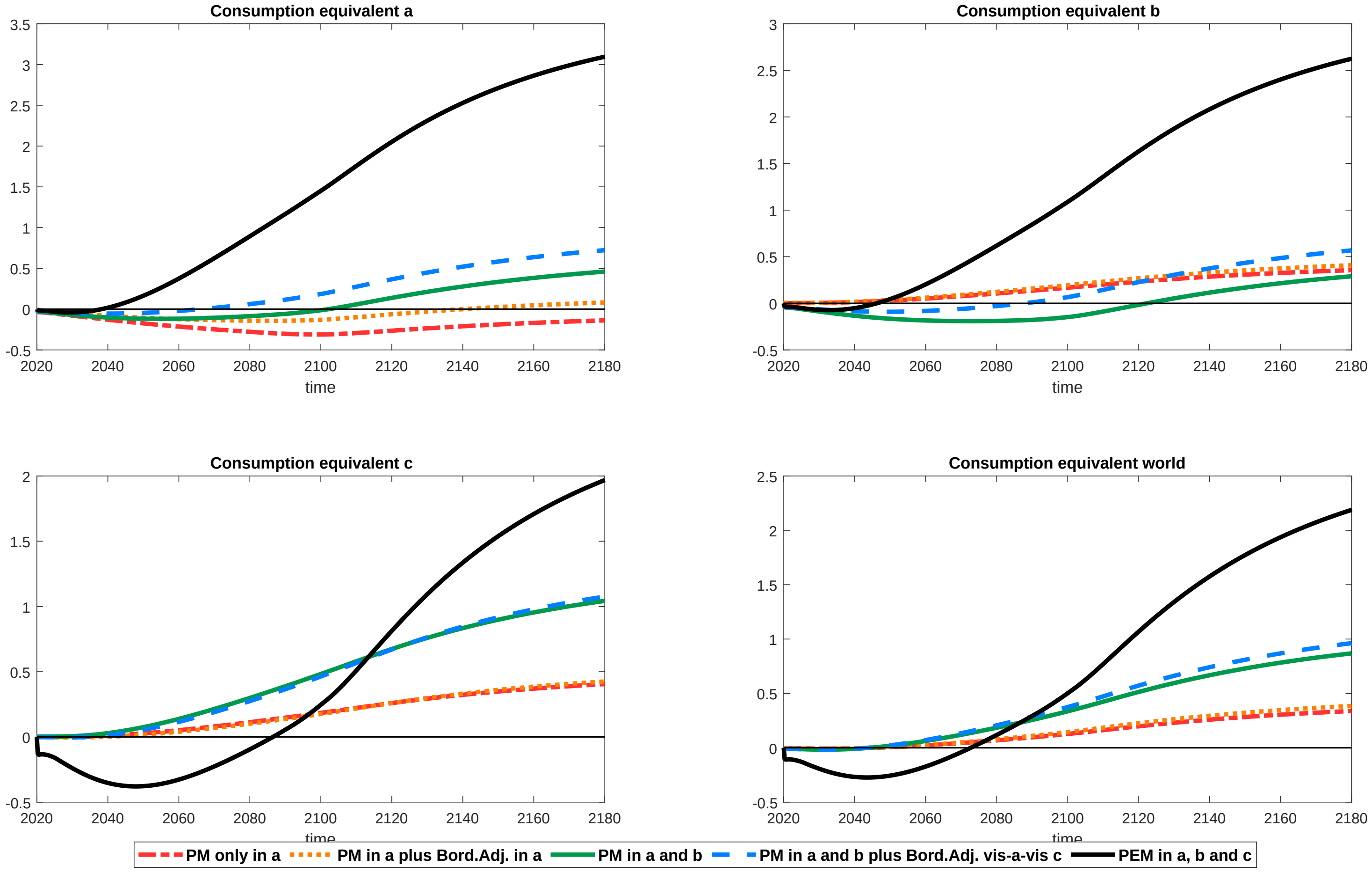
Before turning to the second observation, some words of caution related to this finding seem warranted, however. In our model, benefits from carbon taxation are generated by a reduction in emissions-induced damage. As already stressed in Section 4, its calibration is loosely tied to Kalkuhl and Wenz (2020) and to the damages calculated by the NFGS. Gillingham, Nordhaus, Anthoff, Blanford, Bosetti, Christensen, McJeon, and Reilly (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. 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. Still, 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.

Second, carbon border adjustment taxation significantly reduces welfare losses for the regions introducing carbon pricing. There are two effects of this environmental trade policy that are sources of welfare improvements for this region (besides reducing the environmental externality). The first is a positive term-of-trade effect: the region with border adjustment will import foreign goods at lower prices, especially when it is a large economy. This is because, then, a restrictive trade policy on imports will reduce world demand for polluting goods produced in the exporting regions. The border price will go down, and region a will benefit from this decrease. The other effect is related to the existence of imperfectly competitive markets. The border carbon pricing adjustment may allow extracting monopoly rents from imperfectly competitive foreign firms, which is again welfare improving. Again, additional border adjustment subsidies to exporting firms further improve the situation (a bit), but they are no significant game-changer.

The third important observation we can make in Table 2 is that, when one or more regions introduce carbon pricing, it is generally not beneficial for the remaining regions to join. This already holds for a steady-state comparison (except for the situation in which all regions participate). It is due to the increase in production costs and foregone trade benefits. When taking into account the transition paths, this becomes even more relevant.

Especially for regions characterized by low per-capita income in the initial steady state, such as region c in our model, 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).

Figure 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.

Fourth, 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. Figure 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, Flachsland, Jakob, and Lessmann (2015), Kornek, Steckel, Lessmann, and Edenhofer (2017) and Kornek and Edenhofer (2020). The analysis also shows that it is beneficial for economies that are going to introduce carbon pricing anyway if other regions also participated. 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.[20] Our model provides a suitable laboratory to simulate such scenarios.

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

Scenario:	Price differentiation	Transfers	Price diff. and transfers	Baseline
With transition...				
...in a	0.09	-0.11	0.05	0.35
...in b	-0.07	-0.33	0.05	0.22
...in c	0.02	0.29	0.03	-0.15
...globally	0.02	0.16	0.03	-0.04

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.

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 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

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[20] 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.

amounts to 80% of a, and c, with a price amounting to 45% of the price in a. Furthermore, regions a and b pay a transfer to c amounting to 15% 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. This is especially true for regional carbon price discrimination. In terms of welfare, a prolonged recession increases the duration for the rich region to face welfare losses, but losses are even higher when providing transfers to the poor. Aggregate welfare effects 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, also when including transition. Transfers from the rich to the poor regions remain below 0.5% of GDP in all simulated scenarios.[21]

7 Conclusions

In a dynamic, three-region **e**nvironmental **mu**lti-**se**ctor general equilibrium model (called *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 in particular. From the perspective of a region that introduces carbon pricing, the downturn is shorter 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 that should also be borne in mind 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 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. 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, Klenert, Edenhofer, and Fleurbaey, 2021).

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[21] Considering the results, it has to be borne in mind that the overall cost to achieve the reduction in the emissions stock may be higher due to an inherent cost inefficiency of carbon price discrimination. It is likely that this will be an issue for policy debates. Nevertheless, it goes beyond the scope of this paper to find the optimal carbon price and transfer mechanism. In practice, they certainly strongly depend on regionally differentiated damage and abatement cost functions for each sector. Future research should certainly address such a differentiation and focus on optimal international agreements in this direction.

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 partly 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, Aghion, Bursztyn, and Hemous, 2012, and Lilliestam, Patt, and Bersalli, 2020), or help industries to get rid of climate-damaging production technologies faster (as discussed in Kalkuhl, Edenhofer, and Lessmann, 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) as it could mitigate the negative effects of carbon pricing today by making those who benefit from the reforms pay tomorrow. We leave the analysis of these – and probably many more – questions to future research.

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Appendix A: First-order conditions and further model details

In this appendix, we provide some more model details and the first-order conditions of the above mentioned maximization problems.

From the standard intratemporal first-order conditions for household consumption and labor (see also Section 3.1), it follows that the marginal utility of consumption is denoted by $\lambda_{i,t} = C_{i,t}^{-\sigma}/(1+\tau_t^c)$, while labor supply is determined by $\kappa_{i,N} N_{i,t}^{\psi} = \lambda_{i,t}(1-\tau_{i,t}^w)w_{i,t}$. The optimal intertemporal savings decision is characterized by

$$1 = \beta \cdot \mathbb{E}_t \left\{ \frac{\lambda_{i,t+1}}{\lambda_{i,t}} \cdot \frac{r_{i,t+1}^k + (1-\delta_i)\cdot(1+\tau_{i,t+1}^I)\cdot P_{i,t+1}^I}{(1+\tau_{i,t}^I)\cdot P_{i,t}^I} \right\} = \beta \cdot \mathbb{E}_t \left\{ \frac{\lambda_{i,t+1}}{\lambda_{i,t}} \cdot R_{i,t} \right\}. \tag{A.1}$$

Taking into account the bundling technology described in Section 3.2, we get the following first-order condition for $X \in \{C, I\}$:

$$X_{s,i,t} = \psi_{X,s} \left(\frac{(1+\tilde{\tau}_{s,i,t}^X)P_{s,i,t}^X}{(1+\tau_{i,t}^X)} \right)^{\left(-\frac{1}{1-\sigma_{X,i}}\right)} X_{i,t} \quad \forall s \in \mathcal{S} \quad \textit{and} \quad i \in \{a,b,c\}. \tag{A.2}$$

Plugging this expression into the constant elasticity of substitution aggregator of consumption/investment goods shows that $P_{i,t}^X$ is equal to the weighted sectoral consumption/investment-good prices. We obtain the following relation:

$$(1+\tau_{i,t}^X)\cdot P_{i,t}^X = \left[\sum_{s=1}^{S} \psi_{X,i,s} \left((1+\tilde{\tau}_{s,i,t}^X) P_{s,i,t}^X \right)^{-\frac{\sigma_{X,i}}{(1-\sigma_{X,i})}} \right]^{-\frac{(1-\sigma_{X,i})}{\sigma_{X,i}}}, \tag{A.3}$$

where the aggregate tax rate on consumption is determined by

$$(1+\tau_{i,t}^X) = \frac{\left[\sum_{s=1}^{S} \psi_{X,i,s} \left((1+\tilde{\tau}_{s,i,t}^X) P_{s,i,t}^X \right)^{-\frac{\sigma_{X,i}}{(1-\sigma_{X,i})}} \right]^{-\frac{(1-\sigma_{X,i})}{\sigma_{X,i}}}}{\left[\sum_{s=1}^{S} \psi_{X,i,s} \left(P_{s,i,t}^X \right)^{-\frac{\sigma_{X,i}}{(1-\sigma_{X,i})}} \right]^{-\frac{(1-\sigma_{X,i})}{\sigma_{X,i}}}} \tag{A.4}$$

as in Blazquez, Galeotti, Manzano, Pierru, and Pradhan (2021).

The maximization problem of the labor and capital agency (Section 3.3) leads to the following first-order condition characterizing the sector specific demand for labor/capital

$$X_{s,i,t} = \omega_{X,i,s} \left(\frac{\tilde{p}_{s,i,t}}{\tilde{p}_{i,t}} \right)^{-\left(\frac{1}{1-\nu_{X,i}}\right)} X_{i,t} \quad \forall s \in \mathcal{S} \quad \textit{and} \quad i \in \{a,b,c\}, \tag{A.5}$$

where $X \in \{N, K\}$ and $\tilde{p} \in \{w, r^k\}$. After plugging this expression into the CES aggregator of labor goods, we obtain the aggregate wage index

$$\tilde{p}_{i,t} = \left[\sum_{s=1}^{S} \omega_{X,i,s} \tilde{p}_{s,i,t}^{-\frac{\nu_{X,i}}{\left(1-\nu_{X,i}\right)}} \right]^{-\frac{\left(1-\nu_{X,i}\right)}{\nu_{X,i}}} . \tag{A.6}$$

Variety demand by a sectoral final goods producer (Section 3.4)is given by the standard first-order conditions

$$y_{s,i,t}(z) = \left[\frac{P_{s,i,t}(z)}{P_{s,i,t}} \right]^{-\theta^P_{s,i}} Y_{s,i,t}, \tag{A.7}$$

and the (CPI-deflated) producer price of the sectoral bundle as

$$P_{s,i,t} = \left[\int_0^1 P_{s,i,t}(z)^{1-\theta^P_{s,i}} \, dz \right]^{\frac{1}{1-\theta^P_{s,i}}} \quad \forall s \in \mathcal{S} \quad and \quad i \in \{a, b, c\}. \tag{A.8}$$

For the intermediate goods producers, factor demand is given by

$$\begin{aligned} w_{s,i,t} &= \alpha_{H,s,i} \cdot \alpha_{N,s,i} \cdot mc_{s,i,t} \cdot \tfrac{y_{s,i,t}}{N_{s,i,t}}, & \text{(A.9)} \\ r^k_{s,i,t} &= \alpha_{H,s,i} \cdot (1 - \alpha_{N,s,i}) \cdot mc_{s,i,t} \cdot \tfrac{y_{s,i,t}}{K_{s,i,t-1}}, & \text{(A.10)} \\ (1 + \tau^H_{s,t}) P^H_{s,i,t} &= (1 - \alpha_{H,s,i}) \cdot mc_{s,i,t} \cdot \tfrac{y_{s,i,t}}{Hs,i,t}, & \text{(A.11)} \end{aligned}$$

where $\tau^H_{s,i,t}$ is the average tax rate on intermediate inputs in sector s and $P^H_{s,i,t}$ the CPI-deflated real price of these inputs. $mc_{s,i,t}$ are real marginal production costs in each sector. If emissions are priced at a (potentially sector and region-specific) price $P^{em}_{s,i,t}$, abatement is determined by

$$\phi_{1,s,i} \cdot \phi_{2,s,i} \cdot U_{s,i,t}^{\phi_{2,s,i}-1} = P^{em}_{s,i,t} \cdot \kappa_{s,i}. \tag{A.12}$$

For $P^{em}_{s,i,t} = 0$, it holds that $U_{s,i,t} = 0$ because firms do not take into account the pollution externality because it is costless from the individual firm perspective. Firms are price setters and charge a markup on their marginal production costs. Under flexible prices, it holds that

$$P_{s,i,t} = \tfrac{\theta^P_{s,i}}{\theta^P_{s,i}-1} \cdot \tilde{mc}_{s,i,t}, \tag{A.13}$$

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

$$\tilde{mc}_{s,i,t} = mc_{s,i,t} + \phi_{1,s,i} \cdot U_{s,i,t}^{\phi_{2,s,i}} + P^{em}_{s,i,t} \cdot \kappa_{s,i} \cdot (1 - U_{s,i,t}) \tag{A.14}$$

in the pricing equation. Marginal costs relevant for pricing also include abatement costs and emission taxes. They only equal marginal factor input costs whenever the price per emission is zero (and, thus, firms ignore these "extra costs"; see Annicchiarico and Di Dio, 2015, for details). Also note that, as $\theta^P_{s,i} \to \infty$, $P_{s,i,t} = \tilde{mc}_{s,i,t}$.

For the intermediate inputs, it is straightforward that we will get

$$H_{s,j,i,t} = \psi_{H,s,j,i} \left(\frac{(1+\tilde{\tau}^H_{j,i,t})P_{j,i,t}}{(1+\tau^H_{s,i,t})} \right)^{\left(-\frac{1}{1-\sigma_{H,s,i}}\right)} H_{s,i,t}, \tag{A.15}$$

$$(1+\tau^H_{s,i,t})P^H_{s,i,t} = \left[\sum_{j=1}^{S} \psi_{H,s,j,i} \left((1+\tilde{\tau}^H_{s,j,i,t})P_{j,i,t}\right)^{-\frac{\sigma_{H,s,i}}{\left(1-\sigma_{H,s,i}\right)}} \right]^{-\frac{\left(1-\sigma_{H,s,i}\right)}{\sigma_{H,s,i}}}, \tag{A.16}$$

and

$$(1+\tau^H_{s,i,t}) = \frac{\left[\sum_{j=1}^{S} \psi_{H,s,j,i} \left((1+\tilde{\tau}^H_{j,i,t})P_{j,i,t}\right)^{-\frac{\sigma_{H,s,i}}{\left(1-\sigma_{H,s,i}\right)}} \right]^{-\frac{\left(1-\sigma_{H,s,i}\right)}{\sigma_{H,s,i}}}}{\left[\sum_{j=1}^{S} \psi_{H,s,j,i} \left(P_{j,i,t}\right)^{-\frac{\sigma_{H,s,i}}{\left(1-\sigma_{H,s,i}\right)}} \right]^{-\frac{\left(1-\sigma_{H,s,i}\right)}{\sigma_{H,s,i}}}} \tag{A.17}$$

$\forall s, j \in \mathcal{S}$ and $i \in \{a, b, c\}$. The latter equation represents the implicit (aggregate/average) tax rate on (all) intermediate inputs of sector s in region i.

As discussed in Section 5, we also simulate a full border adjustment mechanism including export subsidies (in addition to border adjustment taxation). We assume that, under this scenario, the amount of goods exported is not subject to the carbon price. Formally, this implies that the effective carbon price that needs to be paid by a firm in sector s of region i reduces to

$$P^{eff,em}_{s,i,t} = P^{em}_{s,i,t} \cdot \left(1 - \frac{Exp_{s,i,t}}{y_{s,i,t}}\right), \tag{A.18}$$

where exports, $Exp_{s,i,t}$, are given by the first term on the right-hand-side of equation (6). Under the climate club scenario, exports from a to b (and vice versa) are, of course, not subsidized. When simulating this scenario, $P^{eff,em}_{s,i,t}$ substitutes $P^{em}_{s,i,t}$ in all the above equations. As a result, this reduces not only marginal costs, see equation (A.14), but also incentives to invest in mitigation technologies, see equation (A.12).

Appendix B: Calibration details

In this Appendix, we provide tables with detailed calibration parameters.

Table B.1: Choice of regions and sectors

Regions:	
a :	EU27, CHE, NOR, UK
b :	USA, AUS, CAN, JAP, MEX, KOR
c :	BRA, CHN, IDN, IND, RUS, TUR, TWN, ROW
Sectors:	
1)	Agriculture, forestry and fishing
2)	Manufacturing (ETS)
3)	Manufacturing (Non-ETS)
4)	Mining, quarrying & energy
5)	Water supply
6)	Construction
7)	Wholesale and retail trade, transport and storage (Non-ETS), accomodation & food
8)	Transport (ETS)
9)	IT and communication
10)	Prof., scient. and techn. & admin. and support services
11)	Arts, entertainment, recreation & oth. services

Notes: The table gives an overview of the modelled regions and sectors.

Table B.2: Baseline calibration of general parameters

Variable/Parameter	Symbol	Value
Relative population size, region a	ω^a	0.101
Relative population size, region b	ω^b	0.146
Relative population size, region c	ω^c	0.744
Relative value-added-per-capita, region a		1
Relative value-added-per-capita, region b		0.986
Relative value-added-per-capita, region c		0.389
Discount factor	β	0.992
Elasticity of intertemporal substitution	σ	2.000
Inverse of Frisch elasticity of lab. supply	ζ	2.000
Labor disutility scaling	$\kappa_{a,N}$	27.392
	$\kappa_{b,N}$	28.492
	$\kappa_{c,N}$	73.300
Capital depreciation rate	δ^k	0.025
Consumption tax rate	$\bar{\tau}_i^c$	0.200
AR(1) coefficients	ρ^x	0.8
Substitution elasticities:		
Elasticity of substitution, consumption	σ_C	1-1/0.9091
Elasticity of substitution, investment	σ_I	1-1/0.7511
Elasticity of substitution, labor	ν_N	2
Elasticity of substitution, capital	ν_K	2
Elasticity of substitution, intermediates	$\sigma_{H,z}$	1-1/0.3

Notes: The table shows calibrated values for general parameters as described in the main text.

Table B.3: Baseline calibration of sector-specific parameters

	$\alpha_{N,s,i}$	$\alpha_{H,s,i}$	$\omega_{N,s,i}$	$\omega_{K,s,i}$	$\psi_{C,s,i}$	$\psi_{I,s,i}$
Region $i = a$ (EU27, CHE, NOR, UK)						
1) Agriculture, forestry and fishing	0.649	0.455	0.081	0.064	0.039	0.004
2) Manufacturing (ETS)	0.573	0.230	0.031	0.057	0.154	0.293
3) Manufacturing (Non-ETS)	0.636	0.325	0.184	0.173	0.065	0.007
4) Mining, quarrying & energy	0.257	0.445	0.013	0.101	0.050	0.007
5) Water supply	0.470	0.423	0.009	0.053	0.007	0.000
6) Construction	0.734	0.379	0.098	0.081	0.015	0.456
7) Wholesale and retail trade, transportation and storage (Non-ETS), accomodation & food	0.664	0.519	0.333	0.243	0.464	0.078
8) Transport (ETS)	0.539	0.288	0.005	0.017	0.019	0.001
9) IT and communication	0.566	0.507	0.038	0.060	0.076	0.074
10) Prof., scient. and techn. & admin. and support services	0.678	0.547	0.149	0.104	0.037	0.074
11) Arts, entertainment, recreation & oth. services	0.702	0.585	0.058	0.047	0.073	0.005
Region $i = b$ (USA, AUS, CAN, JAP, MEX, KOR)						
1) Agriculture, forestry and fishing	0.494	0.468	0.068	0.057	0.020	0.001
2) Manufacturing (ETS)	0.378	0.290	0.024	0.070	0.129	0.274
3) Manufacturing (Non-ETS)	0.583	0.350	0.148	0.163	0.072	0.004
4) Mining, quarrying & energy	0.232	0.576	0.011	0.175	0.040	0.024
5) Water supply	0.496	0.551	0.005	0.024	0.003	0.000
6) Construction	0.806	0.472	0.108	0.022	0.001	0.433
7) Wholesale and retail trade, transportation and storage (Non-ETS), accomodation & food	0.608	0.608	0.375	0.211	0.484	0.084
8) Transport (ETS)	0.521	0.397	0.005	0.019	0.018	0.001
9) IT and communication	0.502	0.553	0.043	0.138	0.080	0.092
10) Prof., scient. and techn. & admin. and support services	0.673	0.629	0.149	0.085	0.051	0.086
11) Arts, entertainment, recreation & oth. services	0.737	0.610	0.063	0.036	0.101	0.001
Region $i = c$ (BRA, CHN, IDN, IND, RUS, TUR, TWN, ROW)						
1) Agriculture, forestry and fishing	0.845	0.627	0.445	0.093	0.174	0.012
2) Manufacturing (ETS)	0.380	0.216	0.032	0.124	0.156	0.288
3) Manufacturing (Non-ETS)	0.456	0.242	0.139	0.228	0.051	0.007
4) Mining, quarrying & energy	0.311	0.424	0.019	0.165	0.046	0.005
5) Water supply	0.933	0.417	0.001	0.015	0.008	0.000
6) Construction	0.605	0.302	0.080	0.044	0.003	0.605
7) Wholesale and retail trade, transportation and storage (Non-ETS), accomodation & food	0.539	0.569	0.193	0.162	0.395	0.048
8) Transport (ETS)	0.477	0.362	0.006	0.026	0.025	0.003
9) IT and communication	0.370	0.575	0.012	0.046	0.054	0.022
10) Prof., scient. and techn. & admin. and support services	0.648	0.506	0.017	0.026	0.027	0.010
11) Arts, entertainment, recreation & oth. services	0.775	0.512	0.057	0.072	0.062	0.000

Notes: The table shows calibrated values for sector-specific parameters as described in the main text. The values were computed by the authors based on the World Input-Output Database, taking an average over the years 2000-2014.

Table B.4: Input-Output matrix, $\psi_{H,s,j,i}$

	Consumer s										
Producer j	1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)
Region $i = a$											
1)	32.8	0.8	0.6	0.2	0.2	0.2	1.3	0.2	0.1	0.3	0.5
2)	10.6	49.5	8.4	8.5	15.2	22.7	10.1	9.9	14.5	8.7	10.8
3)	17.1	16.1	36.9	6.5	9.9	15.1	6.7	17.0	3.5	3.5	4.8
4)	4.3	2.3	24.9	58.2	14.9	2.1	3.8	0.9	1.9	1.8	4.7
5)	0.8	0.1	0.3	0.4	12.0	0.1	0.2	0.1	0.1	0.1	0.7
6)	2.1	1.0	1.1	3.4	8.6	32.5	3.6	1.4	2.1	2.5	3.7
7)	21.9	16.8	18.7	11.9	13.2	12.6	43.6	42.6	13.4	13.6	15.7
8)	0.2	0.4	0.4	0.7	0.3	0.2	1.7	9.2	0.6	2.1	1.1
9)	1.1	2.1	1.3	2.1	5.3	1.7	6.5	3.3	36.8	12.4	10.7
10)	8.5	10.4	6.8	7.6	19.1	12.3	20.9	14.8	23.8	52.8	24.3
11)	0.6	0.5	0.4	0.6	1.6	0.5	1.5	0.7	3.2	2.3	23.0
Region $i = b$											
1)	40.0	1.0	0.5	0.1	0.1	0.4	1.5	0.0	0.0	0.2	0.6
2)	8.6	51.0	7.2	7.4	11.8	32.6	14.7	6.9	13.2	11.6	18.7
3)	19.0	20.7	37.9	13.9	12.5	20.8	9.6	28.4	3.2	5.0	7.9
4)	3.7	1.9	34.0	36.8	17.3	3.6	4.5	1.7	1.2	1.9	5.3
5)	0.5	0.1	0.2	0.2	20.7	0.1	0.3	0.1	0.1	0.2	0.9
6)	1.5	0.4	0.7	5.6	9.2	5.8	1.9	0.3	0.9	0.7	2.2
7)	20.5	13.4	11.9	16.0	13.1	21.2	30.0	23.3	12.0	15.7	20.9
8)	0.8	0.5	0.6	1.1	0.8	0.4	1.2	16.1	1.1	2.3	0.9
9)	0.8	1.9	0.8	2.7	3.7	2.3	7.5	2.9	36.3	17.7	8.8
10)	4.2	8.7	5.7	15.3	9.8	11.9	26.6	19.9	28.1	41.3	24.0
11)	0.5	0.4	0.3	0.8	0.9	0.8	2.2	0.4	3.7	3.2	9.8
Region $i = c$											
1)	40.0	1.0	0.5	0.1	0.1	0.4	1.5	0.0	0.0	0.2	0.6
2)	8.6	51.0	7.2	7.4	11.8	32.6	14.7	6.9	13.2	11.6	18.7
3)	19.0	20.7	37.9	13.9	12.5	20.8	9.6	28.4	3.2	5.0	7.9
4)	3.7	1.9	34.0	36.8	17.3	3.6	4.5	1.7	1.2	1.9	5.3
5)	0.5	0.1	0.2	0.2	20.7	0.1	0.3	0.1	0.1	0.2	0.9
6)	1.5	0.4	0.7	5.6	9.2	5.8	1.9	0.3	0.9	0.7	2.2
7)	20.5	13.4	11.9	16.0	13.1	21.2	30.0	23.3	12.0	15.7	20.9
8)	0.8	0.5	0.6	1.1	0.8	0.4	1.2	16.1	1.1	2.3	0.9
9)	0.8	1.9	0.8	2.7	3.7	2.3	7.5	2.9	36.3	17.7	8.8
10)	4.2	8.7	5.7	15.3	9.8	11.9	26.6	19.9	28.1	41.3	24.0
11)	0.5	0.4	0.3	0.8	0.9	0.8	2.2	0.4	3.7	3.2	9.8

Notes: This table reports the share of total intermediates (in expenditure terms and %) used by the consuming sector that comes from the producing sector. (For example, 8.4% of the total intermediates used by the third sector stem from the second sector in region $i = a$.) The shares were computed by the authors based on the World Input-Output Database, taking an average over the years 2000-2014.

Table B.5: Preference biases, consumption and investment, $hb_{X,s,i,\bar{i}}$

Region $i = a$	$hb_{C,s,a,a}$	$hb_{C,s,a,b}$	$hb_{C,s,a,c}$	$hb_{I,s,a,a}$	$hb_{I,s,a,b}$	$hb_{I,s,a,c}$
1) Agriculture, forestry and fishing	0.910	0.011	0.079	0.989	0.002	0.010
2) Manufacturing (ETS)	0.844	0.052	0.104	0.838	0.077	0.085
3) Manufacturing (Non-ETS)	0.926	0.018	0.057	0.949	0.016	0.035
4) Mining, quarrying & energy	0.971	0.004	0.024	0.975	0.004	0.022
5) Water supply	1.000	0.000	0.000	0.986	0.000	0.014
6) Construction	0.991	0.000	0.008	1.000	0.000	0.000
7) Wholesale and retail trade, transportation and storage (Non-ETS), accomodation & food	0.979	0.006	0.015	0.987	0.005	0.009
8) Transport (ETS)	0.903	0.043	0.054	0.961	0.009	0.031
9) IT and communication	0.952	0.036	0.012	0.959	0.007	0.034
10) Prof., scient. and techn. & admin. and support services	0.929	0.030	0.041	0.978	0.012	0.009
11) Arts, entertainment, recreation & oth. services	0.977	0.004	0.018	0.994	0.001	0.004

Region $i = b$	$hb_{C,s,b,a}$	$hb_{C,s,b,b}$	$hb_{C,s,b,c}$	$hb_{I,s,b,a}$	$hb_{I,s,b,b}$	$hb_{I,s,b,c}$
1) Agriculture, forestry and fishing	0.009	0.905	0.086	0.003	0.996	0.001
2) Manufacturing (ETS)	0.084	0.782	0.134	0.077	0.790	0.133
3) Manufacturing (Non-ETS)	0.022	0.928	0.050	0.027	0.915	0.058
4) Mining, quarrying & energy	0.001	0.995	0.004	0.004	0.939	0.058
5) Water supply	0.000	0.999	0.001	0.006	0.980	0.014
6) Construction	0.021	0.950	0.029	0.000	1.000	0.000
7) Wholesale and retail trade, transportation and storage (Non-ETS), accomodation & food	0.004	0.991	0.005	0.013	0.984	0.003
8) Transport (ETS)	0.032	0.915	0.053	0.024	0.946	0.031
9) IT and communication	0.008	0.978	0.014	0.001	0.996	0.003
10) Prof., scient. and techn. & admin. and support services	0.028	0.894	0.078	0.002	0.996	0.003
11) Arts, entertainment, recreation & oth. services	0.002	0.995	0.003	0.006	0.990	0.004

Region $i = c$	$hb_{C,s,c,a}$	$hb_{C,s,c,b}$	$hb_{C,s,c,c}$	$hb_{I,s,c,a}$	$hb_{I,s,c,b}$	$hb_{I,s,c,c}$
1) Agriculture, forestry and fishing	0.007	0.005	0.988	0.007	0.005	0.988
2) Manufacturing (ETS)	0.021	0.032	0.947	0.021	0.032	0.947
3) Manufacturing (Non-ETS)	0.015	0.021	0.965	0.015	0.021	0.965
4) Mining, quarrying & energy	0.037	0.041	0.923	0.037	0.041	0.923
5) Water supply	0.002	0.000	0.997	0.002	0.000	0.997
6) Construction	0.001	0.000	0.998	0.001	0.000	0.998
7) Wholesale and retail trade, transportation and storage (Non-ETS), accomodation & food	0.013	0.003	0.984	0.013	0.003	0.984
8) Transport (ETS)	0.013	0.022	0.965	0.013	0.022	0.965
9) IT and communication	0.027	0.002	0.971	0.027	0.002	0.971
10) Prof., scient. and techn. & admin. and support services	0.046	0.020	0.935	0.046	0.020	0.935
11) Arts, entertainment, recreation & oth. services	0.010	0.003	0.987	0.010	0.003	0.987

Notes: This table reports parameter values for the sector-specific preference biases $hb_{X,s,i,\bar{i}}$, $X \in C, I$ of region i towards goods produced in region $\bar{i}$. These were computed for region $i = a, b$ by the authors based on the World Input-Output Database, taking an average over the years 2000-2014. Parameters for region $i = c$ were used to close the model.

Table B.6: Preference biases, intermediate inputs, $hb_{H,s,i,\bar{i}}$

	Consumer s										
Producer j	1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)
Region $i = a$											
$\bar{i} = a$											
1)	0.932	0.917	0.911	0.945	0.931	0.925	0.922	0.925	0.936	0.917	0.920
2)	0.931	0.884	0.932	0.917	0.909	0.928	0.913	0.890	0.836	0.902	0.882
3)	0.845	0.871	0.862	0.851	0.872	0.930	0.862	0.821	0.904	0.888	0.876
4)	0.917	0.931	0.589	0.836	0.937	0.758	0.946	0.905	0.969	0.961	0.964
5)	0.998	0.978	0.981	0.970	0.956	0.992	0.984	0.944	0.994	0.988	0.996
6)	0.994	0.993	0.985	0.990	0.994	0.993	0.993	0.992	0.993	0.992	0.994
7)	0.973	0.969	0.852	0.797	0.966	0.965	0.964	0.878	0.944	0.955	0.962
8)	0.876	0.851	0.845	0.840	0.893	0.889	0.838	0.834	0.845	0.810	0.828
9)	0.946	0.939	0.946	0.954	0.954	0.956	0.957	0.958	0.955	0.953	0.951
10)	0.947	0.911	0.951	0.951	0.960	0.960	0.951	0.941	0.895	0.955	0.953
11)	0.984	0.975	0.969	0.960	0.966	0.946	0.966	0.954	0.971	0.949	0.983
$\bar{i} = b$											
1)	0.008	0.006	0.004	0.006	0.009	0.019	0.012	0.012	0.014	0.012	0.011
2)	0.031	0.048	0.027	0.033	0.040	0.026	0.035	0.071	0.059	0.039	0.042
3)	0.042	0.036	0.041	0.033	0.033	0.018	0.030	0.036	0.029	0.033	0.037
4)	0.008	0.008	0.024	0.012	0.005	0.017	0.006	0.027	0.005	0.006	0.005
5)	0.000	0.006	0.006	0.013	0.024	0.002	0.006	0.012	0.002	0.005	0.002
6)	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000
7)	0.011	0.012	0.008	0.008	0.009	0.009	0.012	0.036	0.030	0.012	0.009
8)	0.044	0.061	0.059	0.064	0.041	0.043	0.069	0.074	0.073	0.082	0.077
9)	0.034	0.030	0.025	0.021	0.021	0.023	0.020	0.016	0.021	0.025	0.026
10)	0.029	0.057	0.026	0.026	0.021	0.022	0.025	0.026	0.066	0.023	0.023
11)	0.004	0.007	0.004	0.007	0.003	0.006	0.004	0.007	0.007	0.006	0.002
$\bar{i} = c$											
1)	0.060	0.077	0.084	0.049	0.060	0.056	0.066	0.063	0.050	0.070	0.069
2)	0.038	0.068	0.042	0.050	0.052	0.046	0.052	0.039	0.105	0.059	0.076
3)	0.113	0.093	0.097	0.117	0.095	0.053	0.107	0.142	0.067	0.079	0.087
4)	0.075	0.061	0.387	0.152	0.058	0.224	0.048	0.068	0.025	0.032	0.032
5)	0.002	0.016	0.013	0.017	0.020	0.006	0.009	0.044	0.004	0.007	0.003
6)	0.006	0.006	0.015	0.010	0.006	0.006	0.007	0.007	0.006	0.007	0.006
7)	0.016	0.019	0.140	0.194	0.025	0.025	0.024	0.086	0.026	0.033	0.029
8)	0.080	0.088	0.096	0.095	0.066	0.068	0.093	0.092	0.083	0.108	0.095
9)	0.020	0.031	0.030	0.025	0.025	0.020	0.023	0.026	0.024	0.021	0.023
10)	0.023	0.032	0.022	0.024	0.019	0.018	0.024	0.033	0.039	0.022	0.024
11)	0.012	0.017	0.028	0.032	0.031	0.048	0.030	0.039	0.022	0.045	0.015
Region $i = b$											
$\bar{i} = a$											
1)	0.004	0.005	0.005	0.013	0.008	0.007	0.005	0.046	0.028	0.008	0.006
2)	0.058	0.037	0.047	0.075	0.039	0.036	0.036	0.075	0.029	0.033	0.039
3)	0.050	0.041	0.035	0.033	0.033	0.032	0.027	0.028	0.030	0.045	0.034
4)	0.008	0.006	0.016	0.013	0.006	0.022	0.004	0.004	0.007	0.008	0.004
5)	0.001	0.004	0.010	0.006	0.000	0.005	0.004	0.034	0.004	0.004	0.003
6)	0.002	0.012	0.004	0.002	0.001	0.004	0.003	0.010	0.006	0.012	0.002
7)	0.008	0.013	0.011	0.006	0.007	0.007	0.004	0.008	0.006	0.007	0.006
8)	0.055	0.085	0.080	0.080	0.075	0.069	0.074	0.096	0.083	0.075	0.078
9)	0.008	0.006	0.006	0.006	0.004	0.005	0.005	0.007	0.006	0.004	0.005
10)	0.022	0.013	0.012	0.017	0.013	0.014	0.014	0.024	0.017	0.016	0.014
11)	0.003	0.004	0.003	0.003	0.002	0.003	0.003	0.008	0.001	0.005	0.002
$\bar{i} = b$											
1)	0.932	0.872	0.898	0.927	0.941	0.949	0.933	0.880	0.922	0.959	0.940
2)	0.893	0.884	0.901	0.849	0.887	0.900	0.904	0.884	0.876	0.906	0.896
3)	0.861	0.873	0.880	0.856	0.846	0.891	0.894	0.872	0.909	0.881	0.881
4)	0.941	0.961	0.682	0.679	0.752	0.702	0.970	0.962	0.978	0.968	0.978
5)	0.997	0.991	0.976	0.976	1.000	0.989	0.994	0.882	0.993	0.993	0.996
6)	0.994	0.984	0.968	0.992	0.996	0.990	0.993	0.969	0.990	0.982	0.996
7)	0.985	0.974	0.917	0.932	0.948	0.981	0.986	0.977	0.974	0.967	0.980
8)	0.850	0.773	0.776	0.774	0.735	0.811	0.776	0.727	0.759	0.792	0.764
9)	0.977	0.973	0.976	0.968	0.974	0.982	0.982	0.975	0.986	0.981	0.982
10)	0.917	0.961	0.959	0.948	0.953	0.956	0.960	0.881	0.949	0.961	0.964
11)	0.988	0.983	0.981	0.986	0.990	0.985	0.986	0.958	0.993	0.967	0.984
$\bar{i} = c$											
1)	0.064	0.123	0.096	0.060	0.051	0.044	0.063	0.074	0.050	0.033	0.054
2)	0.049	0.080	0.051	0.077	0.073	0.065	0.060	0.041	0.095	0.061	0.065
3)	0.089	0.086	0.085	0.110	0.121	0.077	0.080	0.100	0.060	0.074	0.085
4)	0.051	0.033	0.303	0.308	0.242	0.276	0.027	0.033	0.015	0.024	0.018
5)	0.002	0.004	0.015	0.017	0.000	0.007	0.003	0.084	0.003	0.002	0.001
6)	0.004	0.004	0.028	0.007	0.002	0.006	0.004	0.021	0.005	0.006	0.002
7)	0.007	0.013	0.072	0.062	0.045	0.012	0.010	0.015	0.020	0.026	0.014
8)	0.095	0.142	0.144	0.145	0.190	0.120	0.150	0.177	0.158	0.133	0.158
9)	0.015	0.021	0.018	0.026	0.021	0.013	0.013	0.018	0.008	0.014	0.013
10)	0.061	0.027	0.029	0.035	0.034	0.030	0.026	0.095	0.034	0.023	0.021
11)	0.010	0.013	0.016	0.011	0.007	0.012	0.011	0.034	0.006	0.028	0.014
Region $i = c$											
$\bar{i} = a$											
1)	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.007
2)	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021

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	Consumer s										
Producer j	1)	2)	3)	4)	5)	6)	7)	8)	9)	10)	11)
3)	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
4)	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
5)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
6)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
7)	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
8)	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
9)	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
10)	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046
11)	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
$\bar{i} = b$											
1)	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
2)	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032	0.032
3)	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021
4)	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041	0.041
5)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
8)	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022	0.022
9)	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
10)	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
11)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
$\bar{i} = c$											
1)	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988	0.988
2)	0.947	0.947	0.947	0.947	0.947	0.947	0.947	0.947	0.947	0.947	0.947
3)	0.965	0.965	0.965	0.965	0.965	0.965	0.965	0.965	0.965	0.965	0.965
4)	0.923	0.923	0.923	0.923	0.923	0.923	0.923	0.923	0.923	0.923	0.923
5)	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997	0.997
6)	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998	0.998
7)	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984	0.984
8)	0.965	0.965	0.965	0.965	0.965	0.965	0.965	0.965	0.965	0.965	0.965
9)	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971	0.971
10)	0.935	0.935	0.935	0.935	0.935	0.935	0.935	0.935	0.935	0.935	0.935
11)	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987	0.987

Notes: This table reports parameter values for the sector-specific preference biases $hb_{H,s,i,\bar{i}}$, of region i towards goods produced in region $\bar{i}$. These were computed for region $i = a, b$ by the authors based on the World Input-Output Database, taking an average over the years 2000-2014. Parameters for region $i = c$ were used to close the model.

Table B.7: Calibration of environmental parameters

Variable/Parameter	Symbol	Value	
Pollution decay	$1 - \rho^{EM}$	0.9979	
Damage parameter (constant)	$\gamma_{0,s}$	0.59565	
Damage parameter (proportional)	$\gamma_{1,s}$	-8.72068e-03	
Damage parameter (quadratic)	$\gamma_{2,s}$	3.27547e-05	
Abatement cost parameter (proportional)	$\phi_{1,s}$	0.185	
Abatement cost parameter (potent)	$\phi_{2,s}$	2.8	
Carbon intensity:	$\kappa_{s,a}$	$\kappa_{s,b}$	$\kappa_{s,c}$
1) Agriculture, forestry and fishing	0.154	0.131	0.189
2) Manufacturing (ETS)	0.033	0.043	0.163
3) Manufacturing (Non-ETS)	0.101	0.157	0.440
4) Mining, quarrying & energy	0.859	1.757	3.377
5) Water supply	0.012	0.089	0.100
6) Construction	0.023	0.038	0.051
7) Wholesale and retail trade, transportation and storage (Non-ETS), accomod. & food	0.052	0.082	0.168
8) Transport (ETS)	0.657	1.158	1.989
9) IT and communication	0.005	0.010	0.012
10) Prof., scient. and techn. & admin. and support services	0.011	0.031	0.078
11) Arts, entertainment, recreation & oth. services	0.018	0.051	0.170

Notes: This table reports the calibrated environmental parameters of the model, described in the main text. Carbon intensities were computed by the authors based on the World Input Output Database and environmental accounts and refer to 2014.

Appendix C: Additional results for baseline simulations

In this appendix, we show

(i.) the evolution of selected key macroeconomic variables when neglecting economic emissions damage in Figure C.1,

(ii.) the evolution of variables when assuming that the entire world introduces carbon pricing (the fifth simulation mentioned in the main text) in Figures C.2 to C.4,

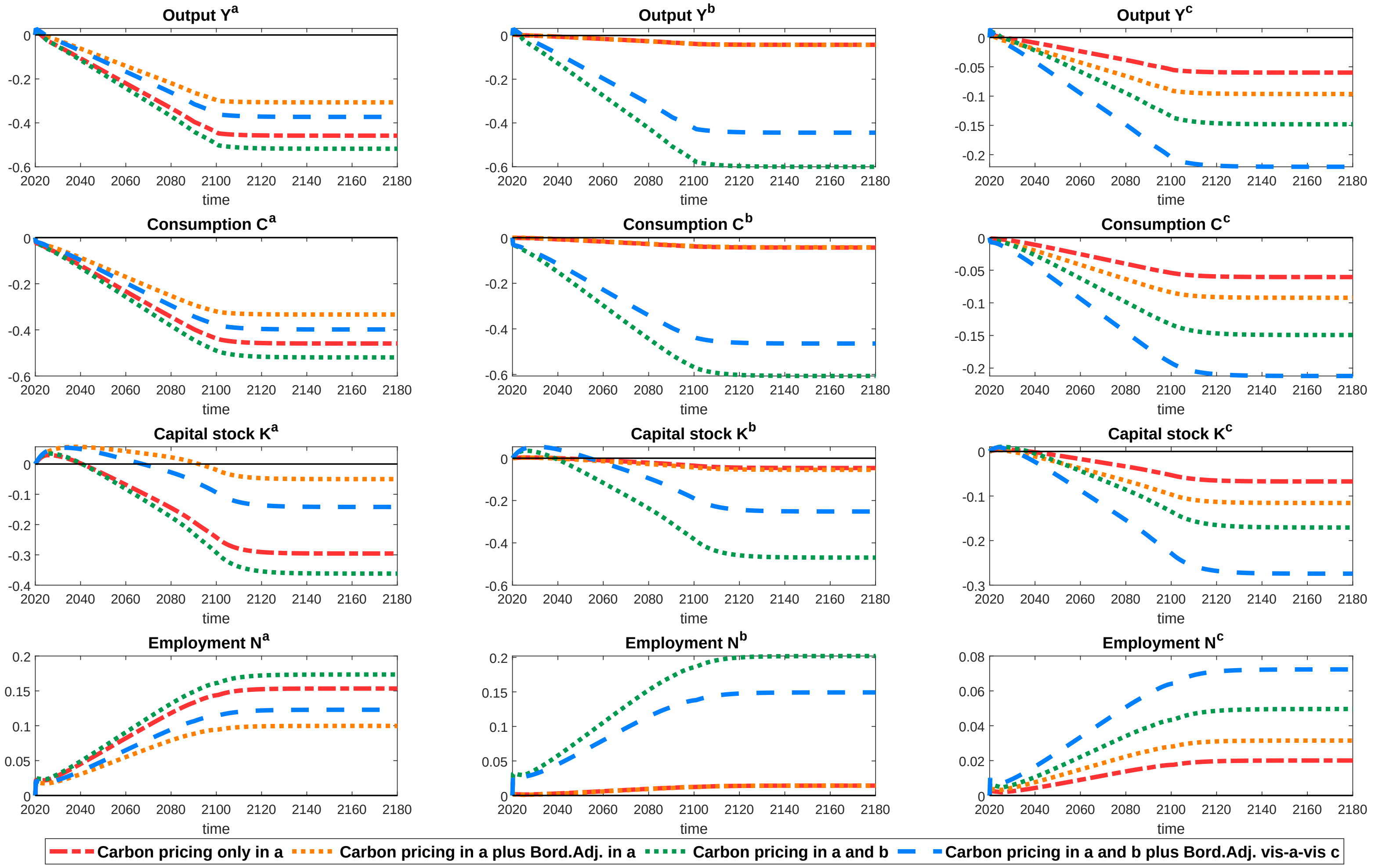
(iii.) the evolution of variables when either assuming the net zero price path or an EU ETS as mentioned briefly in the main text in Figure C.5,

(iv.) the evolution of variables when assuming a full border adjustment mechanism (including export subsidies) in Figure C.6,

(v.) and the evolution of key macro variables and welfare under the alternative simulations discussed in Section 6 in Figures C.7 and C.8.

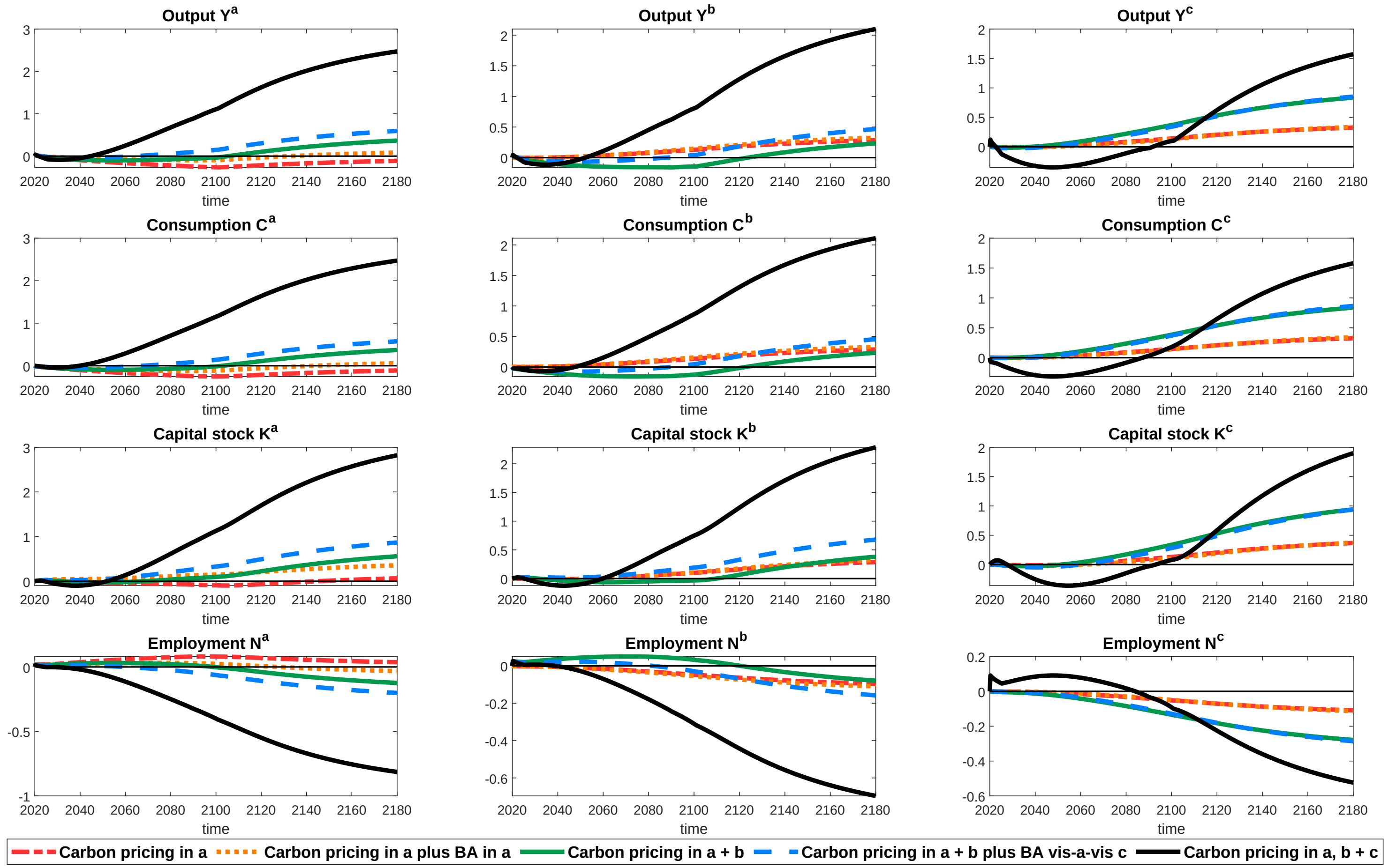
The evolution of regional and sector-specific macroeconomic variables in more detail can be sent upon request.

Figure C.1: Implications of carbon pricing for key macroeconomic variables (no damage)



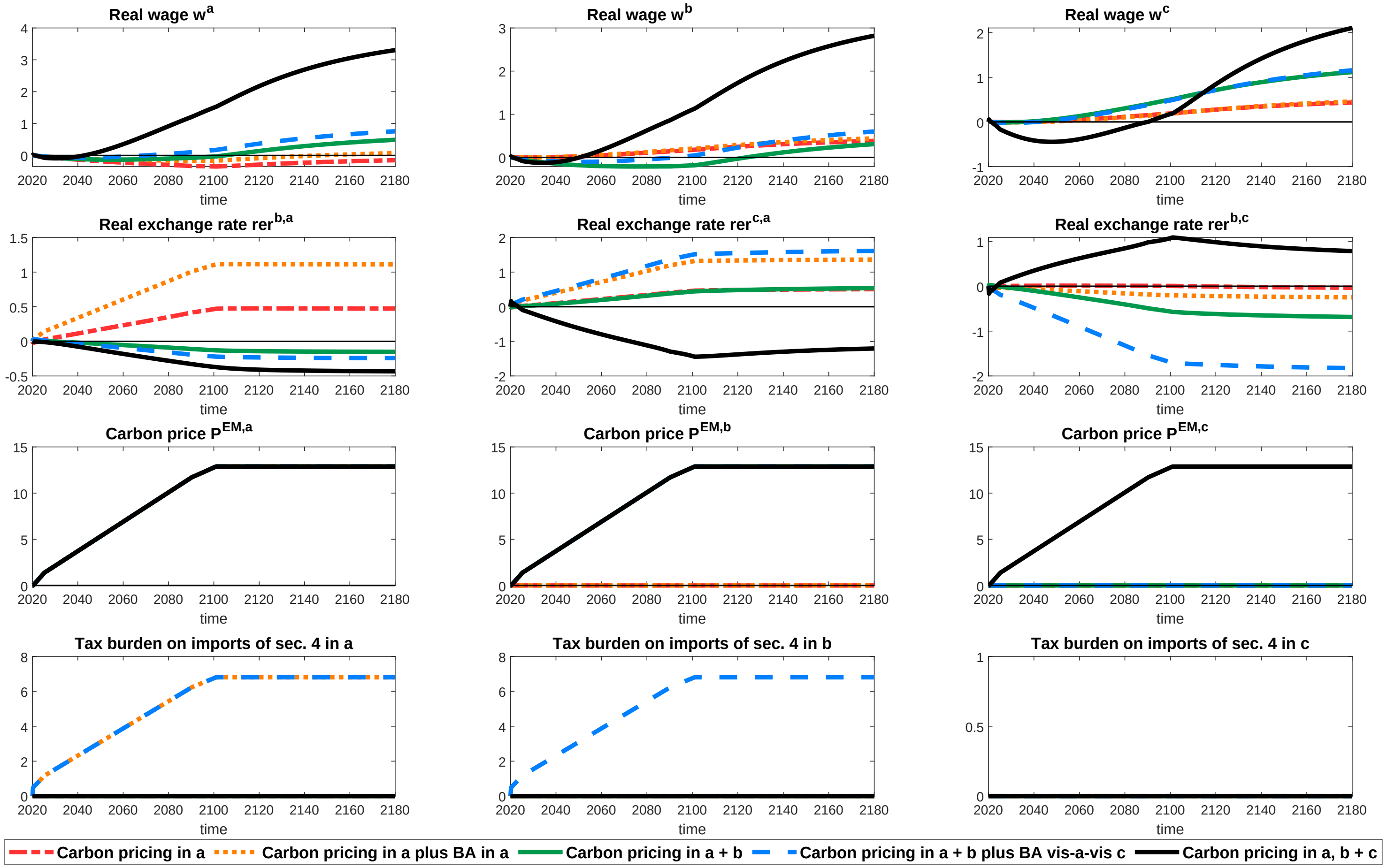
Notes: Figure plots (projected) implications of carbon pricing for key macroeconomic variables in percentage deviation from initial steady state, neglecting damage.

Figure C.2: Implications of carbon pricing for selected key macroeconomic variables (all scenarios)



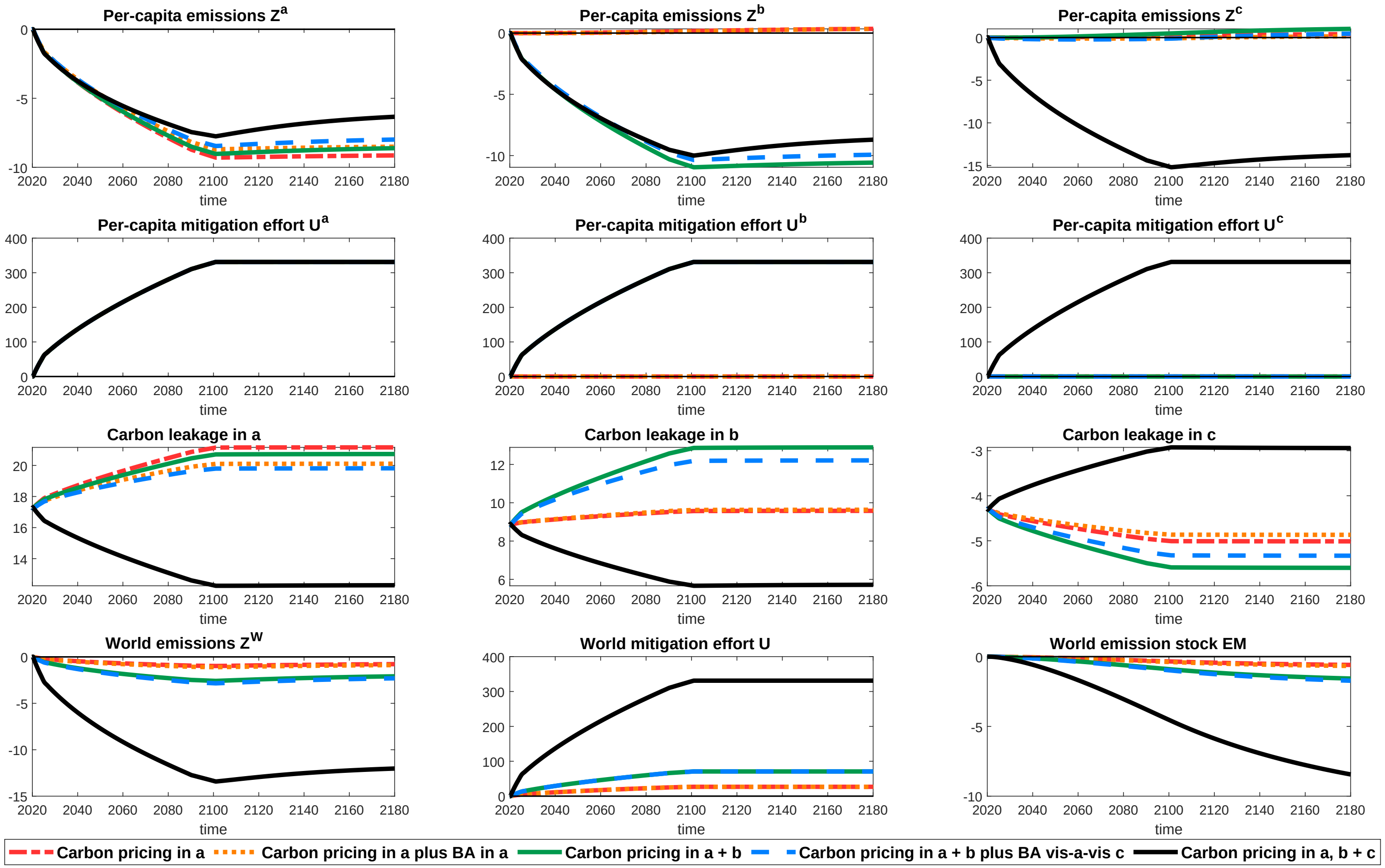
Notes: Figure plots (projected) implications of carbon pricing for selected key macroeconomic variables in percentage deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region *a* only. Carbon prices in *a* with border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

Figure C.3: Implications of carbon pricing for selected factor/relative prices (all scenarios)



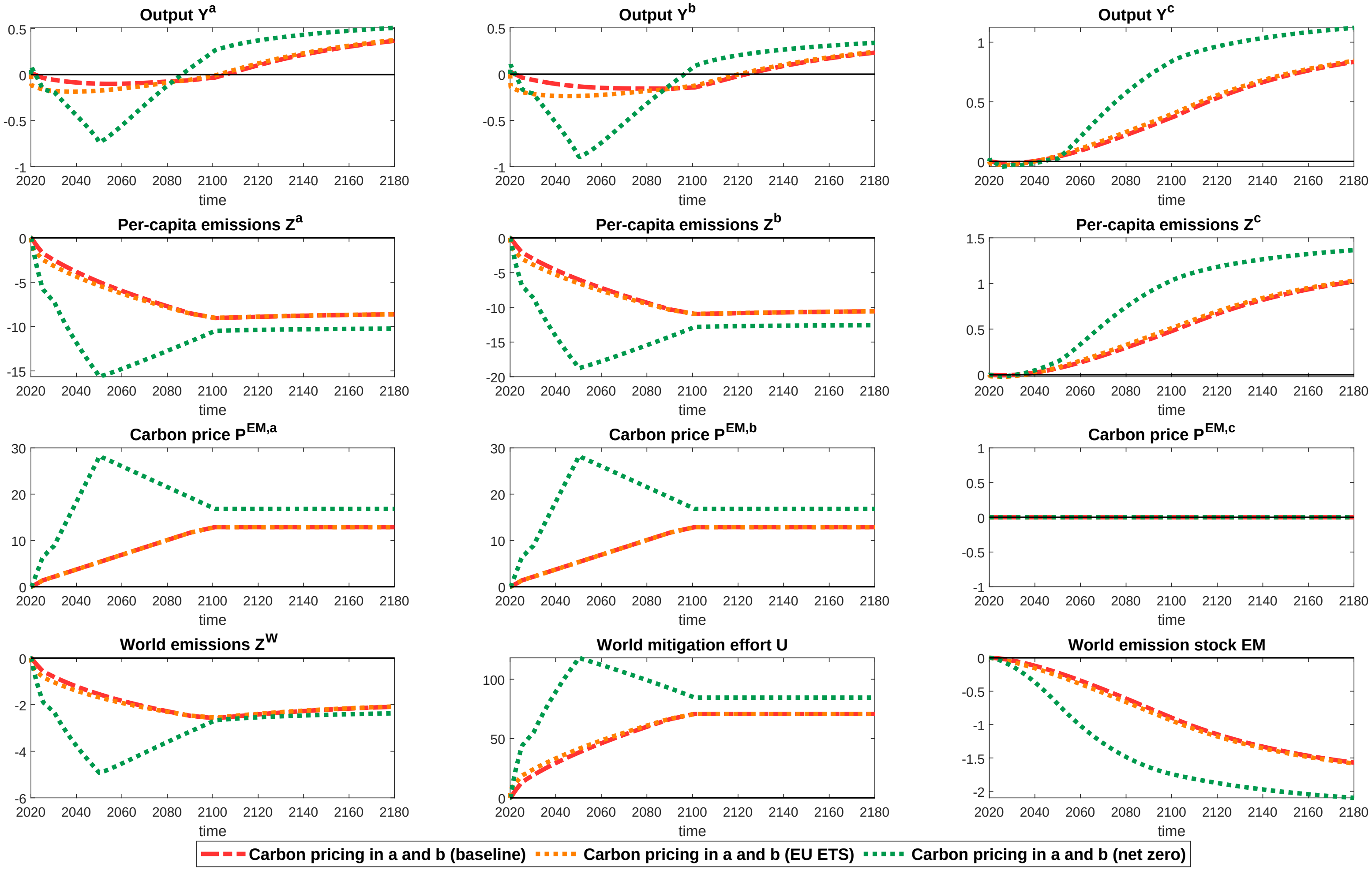
Notes: Figure plots (projected) implications of carbon pricing for selected factor/relative prices in percentage(point) deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment in a is depicted by the orange dotted line, carbon prices in a and b by the green straight line, 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.

Figure C.4: Implications of carbon pricing for selected environmental variables (all scenarios)



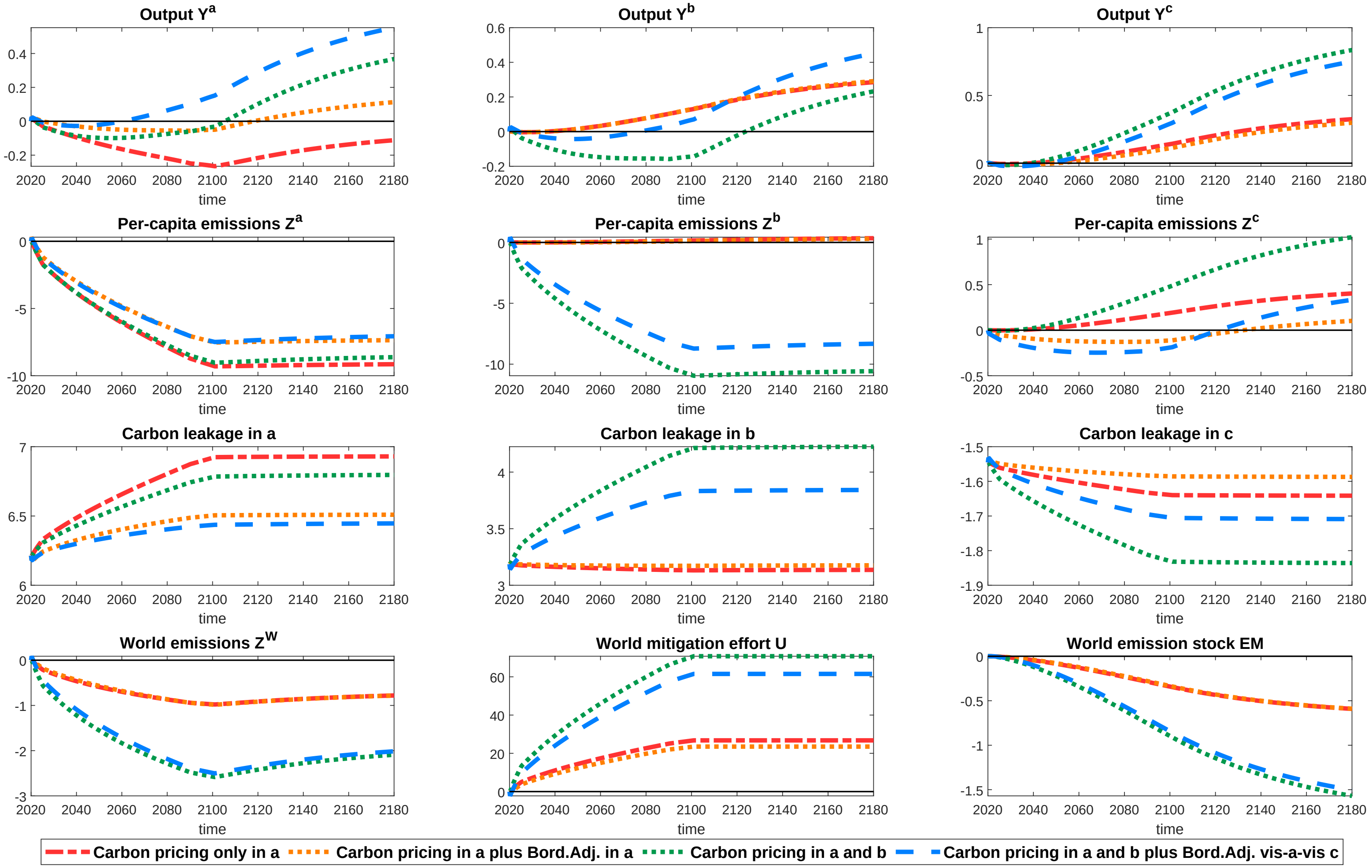
Notes: Figure plots (projected) implications of carbon pricing for selected environmental variables in percentage deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the variables for carbon prices in region a only. Carbon prices in a with border adjustment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

Figure C.5: Implications of carbon pricing for key macroeconomic variables under net zero or EU ETS scenarios



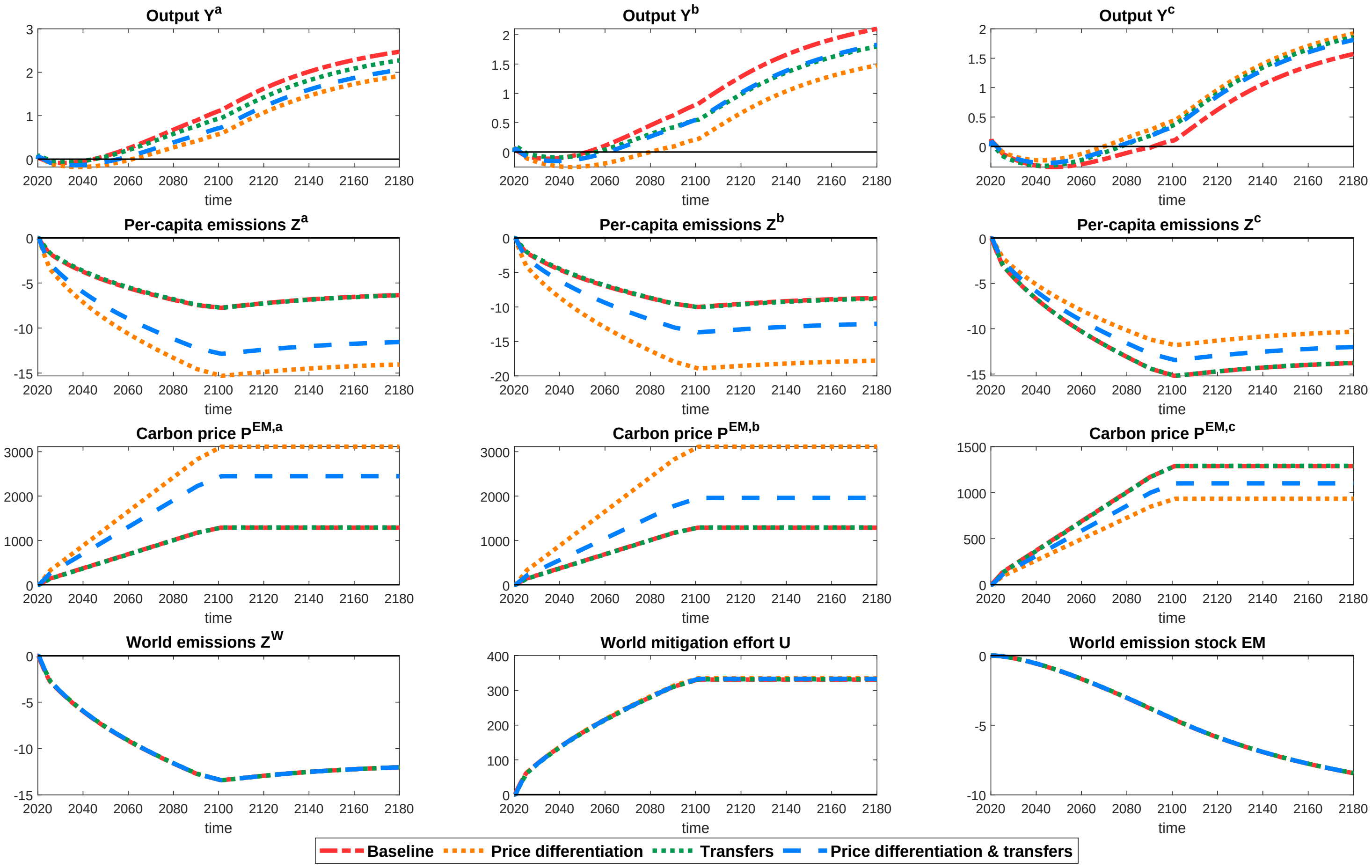
Notes: Figure plots (projected) implications of carbon pricing for key macroeconomic variables in percentage deviation from initial steady state under net zero or EU ETS scenarios, relative to our baseline scenario in the main text when assuming emissions pricing in regions a and b (we could choose any other benchmark scenario against which we compare the different pricing paths). Note that, under the EU ETS, the emissions price would have to be higher to re-produce the same emissions reduction because fewer sectors are affected.

Figure C.6: Implications of carbon pricing for key macroeconomic variables under full border adjustment mechanism



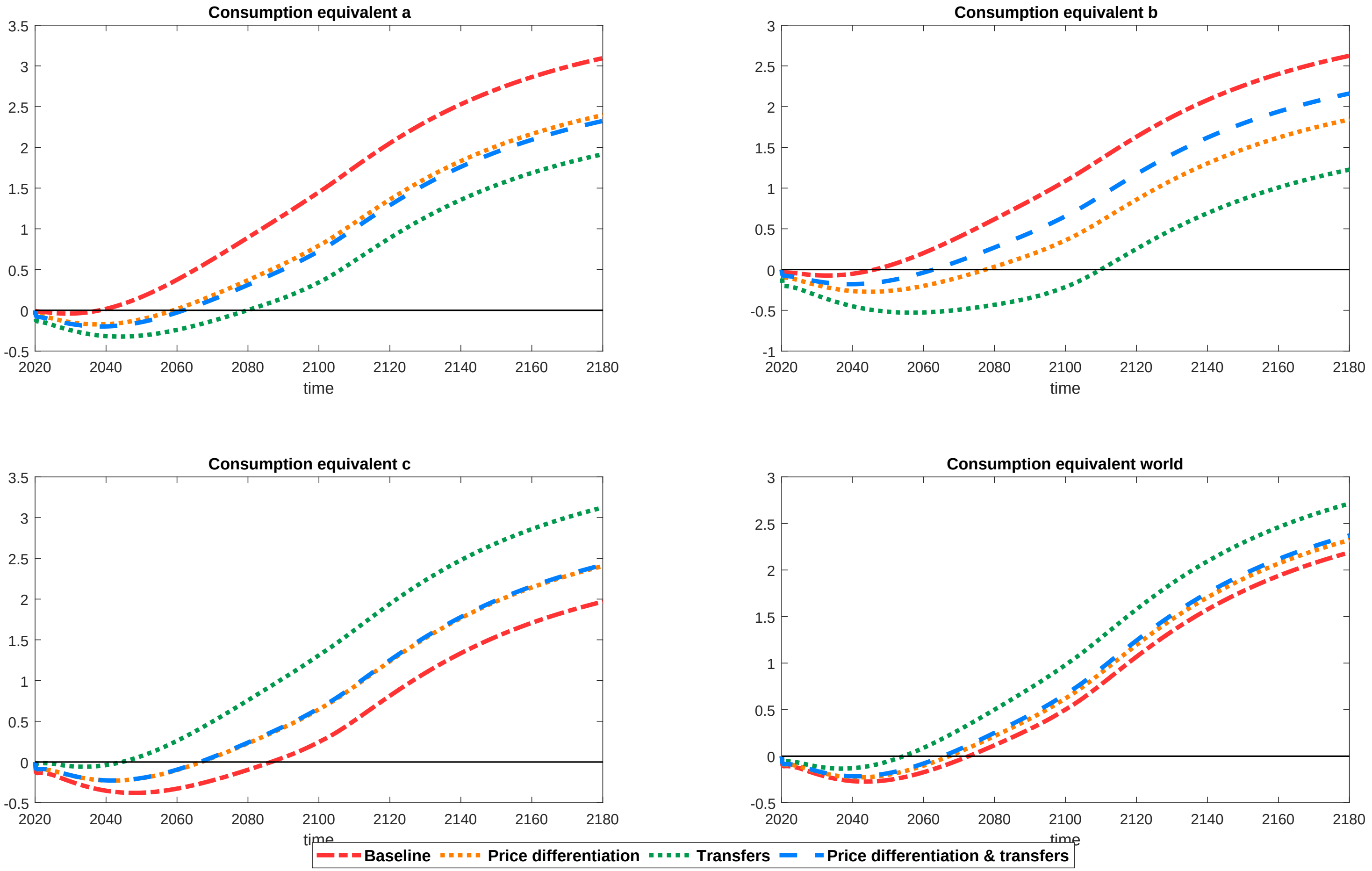
Notes: Figure plots (projected) implications of carbon pricing for key macroeconomic variables in percentage deviation from initial steady state under a full border adjustment mechanism (including export subsidies).

Figure C.7: Implications of world-wide carbon pricing for selected key macroeconomic variables under alternative regimes



Notes: Figure plots (projected) implications of world-wide carbon pricing for selected key variables in percentage deviation from initial steady state, taking into account damage. The red dotted-dashed lines show the baseline scenario described in the previous section. Regional carbon price differentiation is depicted by the orange dotted line, transfers from the rich to the poor by the green dotted line, and a combination of carbon price discrimination and transfers by the dashed blue line.

Figure C.8: Evolution of welfare implied by world-wide carbon pricing under alternative regimes



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 baseline scenario described in the previous section. Regional carbon price differentiation is depicted by the orange dotted line, transfers from the rich to the poor by the green dotted line, and a combination of carbon price discrimination and transfers by the dashed blue line.