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DOCTORAL THESIS

**Essays on Climate Change, Migration and
Labor Mobility**

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Chapter 1

Introduction

This dissertation consists of five papers that explore different themes from the fields of environmental and migration economics. The first two papers are concerned with the impacts of climate change and natural disasters on international as well as regional migration patterns. The following two articles investigate the distributional and regional effects of CO₂ pricing in Germany. The final paper analyzes differences in labor mobility across immigrant generations in the context of the European Debt Crisis.

The paper *“A Real-Options Analysis of Climate Change and International Migration”* (Chapter 2) investigates the “immobility paradox”, i.e. the observation that recent empirical research has largely failed to observe the large-scale international migration frequently predicted to occur as a result of climate change. The paper attempts to resolve this apparent paradox by applying a real-options framework to the relationship between climate change and international migration. This framework suggests that individuals may postpone their migration response to climate change in the face of uncertainty and only migrate once impacts of climate change have exceeded certain thresholds. This prediction is tested using semiparametric regression methods which allow for the empirical identification of the threshold effects implied by the real-options framework. However, the findings are generally inconsistent with such threshold effects. Rather, the results indicate that in low-income countries, individuals’ migration response is hampered by the existence of liquidity constraints. These are likely to become more binding due to climate change-induced decreases in agricultural productivity.

The second paper *“Climate-Related Natural Disasters and Regional Migration in Europe: A Spatial Econometric Analysis”* (Chapter 3), co-authored with Jarom Görtz, analyzes the impact of climate-related disasters on NUTS-2 region-level migration for the period 2000-2019. Employing spatial econometric methods, we find that experiencing a severe disaster leads to an increase in net out-migration of 0.9 individuals per 1000 inhabitants, followed by an increase in net in-migration of 0.6 individuals per 1000 inhabitants two years later. When using spatial Durbin models, we observe a negative spatial spillover effect of severe disasters on net migration, suggesting that neighboring regions may also be affected by the disasters, which may induce individuals in those regions to out-migrate. For less severe disaster events, no conclusive evidence is found that disasters are driving regional migration.

The paper *“The distributional effects of CO₂ pricing at home and at the border on German income groups”* (Chapter 4), co-authored with Michael Hübler, Malin Wiese and Johannes Damster, presents a step-by-step approach for incorporating distributional analysis into computable general equilibrium (CGE) models, with a focus on assessing the effects of climate policies on different income groups in Germany. We utilize a CGE model calibrated with the latest GTAP data from 2014 and adopt a

representative consumer framework for three income groups to evaluate the distributional consequences of CO₂ emissions reduction policies. Our findings indicate that the low-income group benefits the most from carbon pricing, especially due to per capita revenue redistribution and social transfer programs. Applying CO₂ pricing to imports at the EU border slightly reinforces these distributional effects and primarily benefits the low-income group. Expanding emissions trading through a “climate club” generates significant efficiency gains that are advantageous for both Germany and the EU.

The paper *“Regional Climate Policy Analysis in the EU Member Country Germany”* (Chapter 5), co-authored with Michael Hübler and Nils Keimes, analyzes the regional impacts of climate policy within Germany and across EU member states. Using a CGE model, we investigate the EU Emissions Trading System (EU ETS) in combination with the Carbon Border Adjustment Mechanism (CBAM), highlighting notable variation in policy effects both among EU countries and within Germany. Under a medium CO₂ reduction target, CBAM has a minimal average welfare impact on the EU as a whole, while effectively preventing carbon leakage caused by the EU ETS. With a less ambitious target, CBAM yields welfare gains for the EU; under a more ambitious target, it leads to welfare losses compared to the EU ETS alone. More stringent CO₂ targets enhance CBAM’s effectiveness in curbing carbon leakage and reducing global emissions.

The final paper *“Differences in Labour Mobility Between Immigrant Generations: Evidence From the European Debt Crisis”*, (Chapter 6), co-authored with Jarom Görts, studies how labor mobility patterns are passed on across immigrant generations in the European Union. Using household-level data from the European Labor Force Survey for the period 2007 to 2014, we compare mobility patterns of first- and 1.5-generation immigrants and natives. We observe that 1.5-generation immigrants have a significantly lower interregional and international mobility compared to first-generation immigrants but are more mobile than natives. The results thus suggest that not only first-generation immigrants but also their descendants contribute to labor market flexibility.

All five papers are separate works and presented as such. As the first, third and fifth paper are already published, they are included in the layout of the respective journals. The second and fourth paper are unpublished working papers.

Chapter 2

A Real-Options Analysis of Climate Change and International Migration

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RESEARCH ARTICLE

A real-options analysis of climate change and international migration

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Abstract

The potential impact of climate change on international migration patterns has recently received considerable attention, yet much of the empirical literature fails to find increases in international migration due to climate change. This paper attempts to resolve this “immobility paradox” by applying a real-options framework to the relationship between climate change and international migration. This framework suggests that individuals may postpone their migration response to climate change in the face of uncertainty and only migrate once impacts of climate change have exceeded certain thresholds. We test this prediction using semiparametric regression methods which allow us to empirically identify the threshold effects implied by the real-options framework. However, the findings are generally inconsistent with such threshold effects. Rather, the results suggest that in low-income countries, individuals’ migration response is hampered by the existence of liquidity constraints. These are likely to become more binding due to climate change-induced decreases in agricultural productivity.

Keywords: climate change; international migration; real-options; semiparametric methods

1. Introduction

In its 2014 assessment report, the Intergovernmental Panel on Climate Change (IPCC) notes that recent impacts of climate change “reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability” (Intergovernmental Panel on Climate Change, 2014: 40). One potentially important adaptation response which has recently received increasing attention in both the public and academic debate is migration, both within countries and across borders. Yet, much of the empirical literature fails to observe increases in international migration due to climate change (e.g., Millock, 2015; Burzynski *et al.*, 2019; Bertoli *et al.*, 2020; Hoffmann *et al.*, 2020). This finding is in contrast to the large-scale international movements frequently predicted to occur as a result of climate change (e.g., Myers, 2005; Stern, 2006).

The current paper attempts to resolve this “immobility paradox” (Beine *et al.*, 2021) by applying a real-options framework to the relationship between climate change and

international migration. First developed by Dixit (1992) and Dixit and Pindyck (1994), this framework has been applied extensively in the economic literature on migration (e.g., Burda, 1995; O'Connell, 1997; Anam *et al.*, 2008; Moretto and Vergalli, 2008; Gardner and Hendrickson, 2018; Mense, 2018) and suggests that migration is akin to an investment under uncertainty: migration (in particular across borders) is typically associated with large unrecoverable costs; in addition, future conditions in both origin and destination locations are often highly uncertain. As a result, it may be optimal to postpone the migration decision in order to acquire more information about the economic environment.

Applied to the context of climate change and migration, this framework suggests that individuals may postpone their migration response to climate change and only migrate once impacts of climate change have exceeded certain thresholds (Mense, 2018). Since such thresholds are likely much higher for international migration than for internal migration, the real-options framework potentially explains some of the empirical evidence indicating that climate change-induced international migration is relatively uncommon. In this regard, the current paper relates to a large literature that employs a real-options approach to analyze investments in climate change adaptation (Ginbo *et al.*, 2021).

In addition, the current paper contributes to a growing body of research which empirically investigates internal and international migration responses to climate change, with much of the literature focusing on developing countries (for a more extensive review see, e.g., Cattaneo *et al.*, 2019). One of the first studies to investigate the impact of changes in climatic conditions on internal migration is Barrios *et al.* (2006). Using cross-country panel data for Sub-Saharan Africa, the authors find that decreases in rainfall are associated with an increase in urbanization rates. More recently, using panel data for 32 African countries, Henderson *et al.* (2017) document a positive effect of declines in moisture on urbanization rates. Baez *et al.* (2017a, 2017b) find a similar effect for Latin American and Caribbean countries; in particular, they show that younger individuals have a higher propensity to migrate in response to droughts, hurricanes and prolonged heat exposure. Although some other studies only observe modest effects of certain climatic factors on internal migration (e.g., Gray and Mueller, 2012; Mueller *et al.*, 2014) for flooding in Bangladesh and Pakistan, respectively), the majority of studies find significant impacts of climate change on internal migration patterns.

However, empirical evidence on climate change-induced international migration is considerably more mixed. In their seminal paper, Marchiori *et al.* (2012) find that temperature and precipitation anomalies affect international migration in Sub-Saharan Africa through both their impact on amenities and on wages in the agricultural sector. Cattaneo and Peri (2016), using a larger sample of 115 non-OECD countries, observe a positive relationship between average temperature and emigration rates, but only for middle-income countries. For low-income countries, on the other hand, the authors find a negative effect of average temperature on emigration rates. Drabo and Mbaye (2015) study the effect of natural disasters related to climate change on emigration rates in developing countries. They report significant positive effects of natural disasters on emigration, but only for individuals with high levels of education, suggesting that developing countries may experience brain drain effects due to climate change.

In contrast, several other studies find no evidence that climatic factors influence international migration patterns. Ruysen and Rayp (2014), using panel data on migration flows between Sub-Saharan African countries, observe no significant impact of temperature anomalies on international migration. Beine and Parsons (2015) likewise find no

evidence of direct effects of climatic factors on international migration; however, their results suggest that natural disasters induce internal migration in developing countries. Gröschl and Steinwachs (2017), using decennial panel data on bilateral migration flows, also fail to find significant effects of natural disasters on international migration. Overall, the literature suggests that changes in climatic variables are primarily associated with internal migration, in particular in developing countries, but not with international migration.

In order to empirically assess the real-options framework, we follow Burda *et al.* (1998) and Basile and Lim (2006, 2017) and apply semiparametric regression methods developed by Hastie and Tibshirani (1986). More specifically, we estimate generalized additive models (GAMs), which provide a flexible estimation approach that allows us to identify the nonlinear relationship between climate change and international migration implied by the real-options framework. To the best of our knowledge, the current paper is the first to apply these methods to the climate-migration nexus. However, our findings are generally inconsistent with the real-options framework. Instead, the results are in line with the notion of “trapped populations” raised by recent literature (e.g., Cattaneo and Peri, 2016; Beine and Parsons, 2017; Gröschl and Steinwachs, 2017; Cui and Feng, 2020): particularly in developing countries, individuals are unable to move due to liquidity constraints, which are likely aggravated by negative impacts of climate change on agricultural productivity.

The rest of the paper is organized as follows. Section 2 provides a review of related literature and introduces a simple real-options framework of climate change and international migration. Section 3 describes the data and variables. Sections 4 and 5 present the empirical strategy and results, respectively. Section 6 shows some robustness checks, and section 7 concludes.

2. Background

2.1 Thresholds in the climate-migration relationship

While the existence of “tipping points” – that is, thresholds at which small perturbations may induce abrupt, long-term changes in the system – has been investigated in biophysical systems for some time (e.g., Lenton *et al.*, 2008), more recently, a growing body of literature has begun to analyze such nonlinearities in the adaptation of social systems to climate change. In this context and for the purposes of this paper, a threshold can be defined as “a situation where a significant change in collective social behaviour results” (Bardsley and Hugo, 2010: 243) because existing adaptation options to climate change are either no longer available or are perceived as insufficient to maintain valued objectives (Dow *et al.*, 2013).

One of the first attempts at conceptualizing thresholds in climate change adaptation is Adger *et al.* (2009), who discuss the social and individual factors which may limit adaptation responses. The authors argue that rather than being exogenously determined, limits to adaptation are inherently endogenous and are shaped by the values, risk perceptions and organizational arrangements present within a given society. Adger *et al.* (2009) conclude that these factors currently hamper adaptation capacities at the social and individual level but that these limits are mutable and could to some extent be overcome.

Once local adaptation measures cease to be effective, however, migration – either internally or internationally – may be undertaken as the most extreme form of adaptation to climate change. Such migration responses, in turn, are likely themselves characterized

by important thresholds and nonlinearities. Bardsley and Hugo (2010), for example., analyze thresholds in climate-related migration patterns using two case studies on Nepal and Thailand. They identify significant potential for nonlinear migration responses in the two countries, in particular due to increasing risk of flooding and sea level rise. The authors emphasize that more effective migration governance is necessary in order to address the fundamental changes in migration patterns that may occur as a result of climate change.

Building on the work of Adger *et al.* (2009) and Bardsley and Hugo (2010), McLeman (2018) develops a more refined conceptualization of thresholds in the climate-migration relationship. The author argues that with increasing severity of climate change impacts, multiple thresholds occur along the adaptation process: first, households adopt some initial adaptation strategies (e.g., irrigation). If these strategies cease to be effective, however, households may be required to explore other adaptation strategies (e.g., more drought-resistant crops), switch to other livelihood options entirely (e.g., off-farm employment) and ultimately migrate once local adaptation is no longer feasible. Finally, individual migration decisions may lead to large and nonlinear changes in aggregate migration patterns. McLeman (2018) notes, though, that these thresholds are highly context-specific and influenced by the social, economic and climatic factors of the human and natural systems at hand.

Relating the current paper to McLeman (2018), the focus of our theoretical and empirical analysis is the threshold between local adaptation and migration. We argue that by explicitly modelling the migration decision as an option to an (at least partially) irreversible investment under uncertainty, the real-options approach is a suitable framework for explaining such thresholds and accounting for the relative absence of climate change-induced international migration observed empirically.

Previous work has applied the real-options framework to both migration and climate change adaptation decisions. One of the earliest contributions from the migration literature is Burda (1995), who uses a real-options framework to explain the low migration rates from East to West Germany after the German reunification. O'Connell (1997) extends this framework to allow for return migration. More recently, Gardner and Hendrickson (2018) develop a real-options framework to explain why even in regions where the quality of labor market conditions is declining, outmigration rates tend to remain relatively low. Regarding climate change adaptation, the real-options framework has been used to model investment decisions on flood risk control (Abadie *et al.*, 2017; Kim *et al.*, 2018), water resources management (Erfani *et al.*, 2018) and agriculture and livestock adaptation (Narita and Quaas, 2014; Sanderson *et al.*, 2016).

The only previous paper applying the real-options approach to environmental migration is Mense (2018). Focusing on the issue of air pollution, the author develops a real-options framework to show that individuals may choose to wait and only migrate once environmental quality has decreased below some critical threshold. Our paper differs from Mense (2018) insofar as we are primarily concerned with slow-onset climate change and thus assume that the quality of climatic conditions declines on average over time. In addition, our paper contributes to the literature by attempting to empirically verify the implications of the real-options framework.

2.2 Theoretical framework

Based on recent work by Gardner and Hendrickson (2018) and Mense (2018), in this section we present a specific application of the real-options framework that illustrates

why it may be optimal for individuals to postpone their migration response to the impacts of climate change in the face of uncertainty. Consider a representative household who chooses whether to stay in their home country or migrate abroad. The quality of climatic conditions $c(t)$ with $c(0) = c_0$ evolves according to a geometric Brownian motion (GBM):

$$dc = c(\mu dt + \sigma dz), \tag{1}$$

where $\mu < 0$ is a drift parameter capturing the long-term trend of the GBM, σ is the standard deviation per unit of time and dz is the increment of a Wiener process of the form $z(t) = \varepsilon(t)\sqrt{dt}$ with $\varepsilon(t) \sim \mathcal{N}(0, 1)$. Eqn (1) implies that c changes gradually over time without discrete “jumps”, which may apply quite well to a range of slow-onset climatic events such as temperature increase, drought and sea level rise (Mense, 2018; Cattaneo *et al.*, 2019). The GBM is characterized by a negative long-term trend (indicated by $\mu < 0$) while there is uncertainty as to how c evolves in the short term, i.e., although climatic conditions are deteriorating on average over time, there is a positive probability that they will improve in the next period (Gardner and Hendrickson, 2018).

We assume that the household obtains a perpetual constant dividend w if they choose to emigrate. w could be thought of as an exogenous outside opportunity, reflecting the idea that households may lack accurate information about the prospective destination country (Burda, 1995). Migration is also associated with a fixed upfront cost $M > 0$, which encompasses both monetary and psychological cost.

The household’s Bellman equation can be expressed as

$$rV(c) = c + \frac{1}{dt}\mathbb{E}[dV], \tag{2}$$

where r is the real interest rate (Dixit and Pindyck, 1994: 101–105). If we apply Ito’s Lemma, substitute the right-hand side of equation (1) and take expectations, we obtain the following second-order partial differential equation:

$$\frac{1}{2}\sigma^2 c^2 V''(c) + \mu c V'(c) - rV(c) + c = 0. \tag{3}$$

The solution of this differential equation is given by

$$V(c) = A_1 c^{\gamma_1} + A_2 c^{\gamma_2} + V_p(c), \tag{4}$$

with $A_1 c^{\gamma_1}$ and $A_2 c^{\gamma_2}$ as homogenous solutions and $V_p(c)$ as the particular solution. A_1 and A_2 are constants, and γ_1 and γ_2 are the solutions of the characteristic equation $(\sigma^2/2)\gamma^2 + (\mu - \sigma^2/2)\gamma - r = 0$:

$$\begin{aligned} \gamma_1 &= \frac{1}{\sigma^2} \left[-\left(\mu - \frac{\sigma^2}{2}\right) - \sqrt{\left(\mu - \frac{\sigma^2}{2}\right)^2 + 2\sigma^2 r} \right] < 0 \\ \gamma_2 &= \frac{1}{\sigma^2} \left[-\left(\mu - \frac{\sigma^2}{2}\right) + \sqrt{\left(\mu - \frac{\sigma^2}{2}\right)^2 + 2\sigma^2 r} \right] > 0. \end{aligned} \tag{5}$$

The first two terms in equation (4) represent the option value of migrating abroad, whereas $V_p(c)$ represents the value of staying in the home country.

Following Gardner and Hendrickson (2018), we impose two boundary conditions on this solution in order to solve the model. The first condition requires that the option value of migrating be reduced to zero as c tends to infinity, i.e., there is no incentive to migrate if the quality of climatic conditions is sufficiently high:

$$\lim_{c \rightarrow \infty} [V(c) - V_p(c)] = 0. \quad (6)$$

Since γ_2 is positive, equation (6) implies that $A_2 = 0$. The second condition, also known as the “value-matching” condition, then requires that the value function $V(c)$ be equal to the present value associated with migrating abroad w/r less the cost of migration M :

$$\begin{aligned} V(c^*) &= A_1 c^{*\gamma_1} + V_p(c^*) = \frac{w}{r} - M \\ \iff A_1 &= (c^*)^{-\gamma_1} \left[\frac{w}{r} - M - V_p(c^*) \right], \end{aligned} \quad (7)$$

where c^* denotes the quality of climatic conditions at which it is optimal to migrate. Put differently, this condition implies that migration is optimal when the household is indifferent between migrating and staying. Substituting A_1 back into equation (4), we obtain

$$V(c) = \left(\frac{c}{c^*} \right)^{\gamma_1} \left[\frac{w}{r} - M - V_p(c^*) \right] + V_p(c). \quad (8)$$

Choosing a lower value of c^* , which implies that the household will on average have to wait longer before migrating, lowers the value of $V_p(c^*)$, thus increasing the present value of the net benefit of migration $V(c)$. On the other hand, a lower c^* increases the stochastic discount factor $(c/c^*)^{\gamma_1}$, thus reducing $V(c)$. The household therefore chooses c^* so as to maximize $V(c)$.

The first-order condition is given by

$$-\gamma_1 \left[\frac{w}{r} - M - V_p(c^*) \right] = c^* V_p'(c^*). \quad (9)$$

As previously noted, the particular solution represents the present discounted value of staying in the home country, i.e.,

$$V_p(c) = \frac{c}{r - \mu}. \quad (10)$$

c^* is thus given by

$$c^* = \left(\frac{\gamma_1}{\gamma_1 - 1} \right) (r - \mu) \left[\frac{w}{r} - M \right]. \quad (11)$$

The model provides two clear predictions: first, migration will only occur once the quality of climatic conditions falls below c^* , that is, once adverse impacts of climate change have exceeded certain thresholds. Second, c^* negatively depends on migration costs M . This implies that the higher the cost of migration, the lower the quality of climatic conditions the household is willing to endure before migrating. The intuition behind this prediction is the following (Mense, 2018; Ginbo *et al.*, 2021): because migration is costly and to a certain extent irreversible and information about climatic conditions is revealed gradually, it is valuable to postpone the migration decision; this incentive is greater the

higher the costs of migration are. However, once climatic conditions deteriorate past a critical level, the household will no longer be better off waiting and will choose to migrate instead.

A number of limitations of the model should be noted. First, as mentioned above, due to the nature of the GBM, the model only applies to gradual changes in climatic conditions and may thus not be suited to capture the effects of fast-onset climatic events such as storms, flooding or extreme heat on international migration. Such events may be modeled more appropriately using Poisson processes (as done, e.g., by Abadie *et al.* (2017)). Incorporating this type of process would present an interesting extension of the model; in the current paper, however, we will instead focus on slow-onset climatic events such as drought and temperature increase and leave these considerations for future research.

Second, the fact that climate-induced international migration appears to be relatively uncommon may also be consistent with a number of alternative explanations. In particular, as noted by Cattaneo and Peri (2016), this result may be generated by liquidity constraints faced by households in their countries of origin, i.e., households may simply lack the resources to finance the costs of migration. For now, the available data does not allow us to determine the exact mechanism behind a potential threshold effect. However, if households do make their migration decisions according to an option value of waiting rule, we should observe the corresponding threshold to be lower in low-income countries than in middle-income countries since liquidity constraints are likely more relevant in the former. Similarly, equation (11) implies that c^* is greater the lower the costs of migration, and thus we should expect the threshold level of quality of climatic conditions to be higher for migration to close destinations than to more distant ones.

3. Data

Data on bilateral international migration flows is taken from Abel and Sander (2014). Based on international migrant stock tables published by the United Nations' Department of Economic and Social Affairs (United Nations, 2013), the dataset provides information on bilateral migration flows between 196 countries over five-year intervals from 1990 to 2010. The dataset thus allows us to include middle- and low-income countries as both origins and destinations, which is an advantage over other datasets such as Ortega and Peri (2013), Vezzoli *et al.* (2014) and Wesselbaum and Aburn (2019) which only include OECD countries as destinations.

Information on GDP per capita is obtained from the World Development Indicators (World Bank, 2021), Penn World Tables (Feenstra *et al.*, 2015) and the World Economic Outlook Database (International Monetary Fund, 2021). The data on country population is taken from the World Development Indicators (World Bank, 2021). Drawing from the migration data, we compute bilateral migration rates as the ratio between the migration flow from origin country i to destination country j during five-year period t and the population of i at the beginning of t . Figure A1 in the online appendix shows the kernel density estimation for bilateral migration rates, which reveals that the distribution of this variable is heavily right-skewed.

Following Cattaneo and Peri (2016) and Beine and Parsons (2017), we only include non-OECD countries as countries of origin and distinguish between middle-income and low-income countries, where low-income countries are defined as those countries in the bottom quartile of the distribution of (purchasing power parity-adjusted) GDP per capita in the year 1990. The resulting final sample includes 138 countries of origin, 34 of which are classified as low-income countries according to the above definition, while

the remaining 104 are classified as middle-income countries (see the lists of low- and middle-income countries in the online appendix).

Data on monthly mean temperature and precipitation is taken from version 4.05 of the gridded climate dataset created by the Climatic Research Unit of the University of East Anglia (Harris *et al.*, 2020). The original data are gridded to a 0.5° latitude by 0.5° longitude grid and are then aggregated to area-weighted country-level averages. As argued by Beine and Parsons (2015, 2017), using absolute levels of temperature and precipitation is not appropriate because these variables would not adequately capture how individuals respond to deviations from standard climatic conditions. We follow their suggested approach and instead calculate standardized anomalies of temperature and precipitation as deviations from the respective long-run mean, divided by the respective long-run standard deviation.

However, in order to identify thresholds in the climate-migration relationship at a more granular level and also account for seasonal volatility, we first compute standardized monthly anomalies of temperature and precipitation and then take the average of these over the five-year periods, i.e.,

$$C_{i,t} = \frac{1}{60} \sum_{k=1}^5 \sum_{m=1}^{12} \frac{C_{level,i,t,k,m} - \mu_{i,m}^{LR}(C_{level})}{\sigma_{i,m}^{LR}(C_{level})}, \quad (12)$$

where $C_{level,i,t,k,m}$ is the level of temperature or precipitation in origin country i in five-year period t , year k and month m . $\mu_{i,m}^{LR}(C_{level})$ is the 1901–1970 mean of temperature or precipitation of origin country i for month m , and $\sigma_{i,m}^{LR}(C_{level})$ is the 1901–1970 standard deviation of temperature or precipitation of origin country i for month m . As an alternative measure of climatic anomalies, used as a robustness check, we follow Nawrotzki and Bakhtsiyarava (2017) and Nawrotzki and Bakhtsiyarava (2017) and calculate the share of months of five-year period t in which mean temperature was more than one standard deviation above and mean precipitation was more than one standard deviation below the 1901–1970 mean.

Figure A2 in the online appendix presents kernel density estimations for the standardized temperature and precipitation anomalies. Most notably, figures A2a and A2c indicate that temperature anomalies are not centered around zero in both low- and middle-income countries, and few countries experienced negative temperature anomalies in either sample. Moreover, the distributions of temperature anomalies in low-income countries and precipitation anomalies in middle-income countries appear to be characterized by some extreme positive and negative outliers, respectively. This finding is corroborated by respective excess kurtosis values of 0.38 and 1.14, suggesting that extreme anomalies occur more frequently than would be predicted by an otherwise equivalent normal distribution.

Across the sample period, five low-income countries experienced extreme positive temperature anomalies of more than two standard deviations above the low-income sample mean,¹ while three countries experienced extreme negative precipitation anomalies of less than two standard deviations below the sample mean.² These observations correspond to 5.88 and 2.21 per cent of the low-income sample, respectively. Likewise, among middle-income countries, extreme positive temperature anomalies were

¹They are Chad, Democratic Republic of Congo, Rwanda, South Sudan and Uganda.

²They are Guinea, Liberia and Sudan.

Table 1. Summary statistics.

Countries included in the sample Variable	Non-OECD middle-income countries			Non-OECD low-income countries			Welch <i>t</i> -test (<i>p</i> -value)
	Obs	Mean	Std. dev.	Obs	Mean	Std. dev.	
Bilateral migration rate (%)	81120	0.0129	0.1595	26520	0.0099	0.1813	0.0165
Temperature anomaly	416	1.0893	0.7073	136	1.0658	0.6569	0.0000
Precipitation anomaly	416	-0.0086	0.2611	136	-0.1198	0.2040	0.0000
Five-year period share of heat months	416	0.3148	0.1180	136	0.2983	0.1439	0.0000
Five-year period share of drought months	416	0.1764	0.1995	136	0.1879	0.2088	0.0000
GDP per capita	416	11201.76	15554.52	132	1860.45	2354.91	0.0000
Migration rate to neighboring countries (%)	1080	0.1351	0.5138	472	0.2479	1.1107	
Migration rate to non-neighboring countries (%)	80040	0.0112	0.1484	26048	0.0056	0.1006	
Migration rate to OECD countries (%)	13312	0.0217	0.1551	4352	0.0086	0.1022	
Migration rate to non-OECD countries (%)	67808	0.0111	0.1603	22168	0.0101	0.1931	

experienced by eight countries,³ and eight countries experienced extreme negative precipitation anomalies,⁴ corresponding to 3.13 and 1.92 per cent of the middle-income sample, respectively. We conduct robustness checks in section 6 in order to assess whether these outliers may affect the estimation results.

Table 1 presents summary statistics. We observe that middle-income countries have a higher average emigration rate than low-income countries. Consistent with previous literature (e.g., Oezden *et al.*, 2011), the majority of migration from non-OECD countries can be attributed to migration flows to other non-OECD countries, which account for 76.4 per cent of the migration flow volume between 1990 and 2010. In addition, although migration flows between neighboring countries comprise only 1.4 per cent of observations in the sample, they account for 28.8 per cent of the migration flow volume.⁵ This pattern is also reflected in the average migration rates to neighboring countries, which are an order of magnitude larger than migration rates to non-neighboring countries.

³They are Barbados, Costa Rica, Grenada, Indonesia, Malaysia, Maldives, Mauritius, Samoa.

⁴They are Botswana, Brunei, Mauritania, Mauritius, Philippines, Saudi Arabia, United Arab Emirates and Vanuatu.

⁵Information on geographic contiguity is obtained from version 3.2 of the Direct Contiguity dataset (Stinnett *et al.*, 2002).

4. Empirical strategy

To identify the nonlinear effects of climate on international migration implied by the real-options framework, we follow Burda *et al.* (1998) and Basile and Lim (2006, 2017) and estimate generalized additive models (GAMs). First developed by Hastie and Tibshirani (1986), GAMs are an extension of generalized linear models (GLMs) and provide a flexible empirical framework that is particularly well-suited for estimating nonlinear relationships. Unlike GLMs, in a GAM the explanatory variables are specified in terms of smooth nonparametric functions, thus requiring no restrictive a priori assumptions about any parametric functional form (Abe, 1999; Ferrini and Fezzi, 2012). Instead, the degree of nonlinearity is determined directly from the data using an automated smoothing selection criterion. Despite their flexibility, however, GAMs retain the interpretability of GLMs, and results can be interpreted in a straightforward manner using graphical representations of the estimated relationships.

Like GLMs, GAMs require the specification of the distribution of the response variable. In our specific case, online appendix figure A1 indicates a heavily right-skewed distribution of bilateral migration rates, and thus we choose to follow Basile and Lim (2017) and estimate a GAM with Gamma distribution:

$$g(\mathbb{E}(y_{ijt})) = \log(\mathbb{E}(y_{ijt})) = \beta_0 + s_1(T_{it}) + s_2(P_{it}) + \phi_i + \phi_j + \phi_t, \quad (13)$$

where y_{ijt} is the bilateral migration rate from origin country i to destination country j in five-year period t and is assumed to follow a Gamma distribution. To deal with the issue of zero observations in the bilateral migration rates, we apply a common solution used in the literature (e.g., Ortega and Peri, 2013; Cai *et al.*, 2016; Grimes and Wesselbaum, 2019) and add one to all migration flows before computing migration rates. $g(\mathbb{E}(y_{ijt})) = \log(\mathbb{E}(y_{ijt}))$ is the canonical log-link function, which relates the expected value of y_{ijt} to the explanatory variables. $s_1(T_{it})$ and $s_2(P_{it})$ are unknown smooth functions of the temperature and precipitation anomaly in origin country i in five-year period t , respectively, which are estimated using penalized cubic regression splines (Wood, 2017). As suggested by Wood (2011), smoothing parameters for the estimated functions $\hat{s}_1(T_{it})$ and $\hat{s}_2(P_{it})$ are selected using the restricted maximum likelihood (REML) method, which is implemented in the R package *mgcv* (Wood, 2001). ϕ_i and ϕ_j are sets of origin and destination country fixed effects, respectively, in order to control for unobserved heterogeneity at the origin and destination country level, and ϕ_t is a set of time fixed effects.

Following recent literature (Dell *et al.*, 2014; Cattaneo and Peri, 2016; Beine and Parsons, 2017; Cattaneo and Bosetti, 2017), we choose a parsimonious specification that includes fixed effects but no additional control variables such as GDP per capita, population, quality of institutions or probability of conflicts. As argued by these authors, those variables are likely themselves affected by changes in climatic conditions, and thus including them in the regression may result in an over-controlling problem, leading to biased estimates of the effects of climate on migration.

5. Results

5.1 Main results

Table 2 presents our main results. As a baseline exercise, we estimate a semiparametric GAM using our total sample before separately conducting estimations for low-income and middle-income countries. In each case, temperature and precipitation anomalies

Table 2. Climate change and international migration: main results.

Smooth terms	(1) Total sample <i>edf</i>	(2) Low-income countries <i>edf</i>	(3) Middle-income countries <i>edf</i>
s(T)	8.783 (0.007)	8.442 (0.000)	8.763 (0.001)
s(P)	7.170 (0.114)	8.914 (0.000)	8.517 (0.001)
REML score	-755939.7	-211053.8	-554627.1
AIC	-1512263	-422162.5	-1109584
N	107640	26520	81120
Pseudo-R ²	0.377	0.544	0.416

Note: Time period: 1990–2010. The dependent variable is the bilateral migration rate from country *i* to country *j* in five-year period *t*. *s*(T) and *s*(P) are smooth non-parametric functions of temperature and precipitation anomalies, respectively. Approximate *p*-values in parentheses. *edf*: effective degrees of freedom, REML: restricted maximum likelihood, AIC: Akaike information criterion.

enter via nonparametric smooth functions. Column 1 reports the effective degrees of freedom (*edf*) of the estimated smooth functions for the total sample, while columns 2 and 3 report the *edf* for low- and middle-income countries, respectively. The *edf* indicate the degree of nonlinearity or “wiggleness” of the function, with an *edf* of 1 corresponding to a linear relationship. However, the *edf* provide no information about the significance or magnitude of the estimated relationship, as smooth terms with high *edf* may not be statistically significant or vice versa. Instead, the estimation results are best understood by examining visual representations of *s*(T) and *s*(P). All models include origin, destination and time fixed effects.

For the total sample we find a significant and nonlinear effect of temperature anomalies but no significant effect of precipitation anomalies. When estimating GAMs separately for middle- and low-income countries, however, the effect of precipitation anomalies turns significant in both samples. These results are corroborated by χ^2 difference tests comparing the GAMs with corresponding GLMs: for both the total sample and low-income and middle-income countries, the χ^2 difference tests indicate that the GAM fits the data better than a linear specification.

Figure 1 shows the estimated effects of temperature and precipitation anomalies on the log of bilateral migration rates with 95 per cent Bayesian confidence intervals (Marra and Wood, 2012). For the total sample, Fig. 1(a) suggests a flat relationship between temperature anomalies and international migration for much of the data range. Regarding precipitation anomalies, we find an S-shaped relationship with slightly positive and negative effects at the upper and lower ends of the data range, respectively, but the relationship is not statistically significant. Estimated relationships for middle-income countries in figures 1(e) and 1(f) appear similar to those found for the total sample, with negative effects of precipitation anomalies below -0.5 being somewhat more pronounced than in the total sample. In contrast, figures 1(c) and 1(d) show rather different relationships for low-income countries: We observe a positive effect of temperature anomalies between 0.2 and 1.5 on migration, which then becomes negative for the remaining range of data. Figure 1(d), on the other hand, shows no clear relationship between precipitation anomalies and international migration for low-income countries.

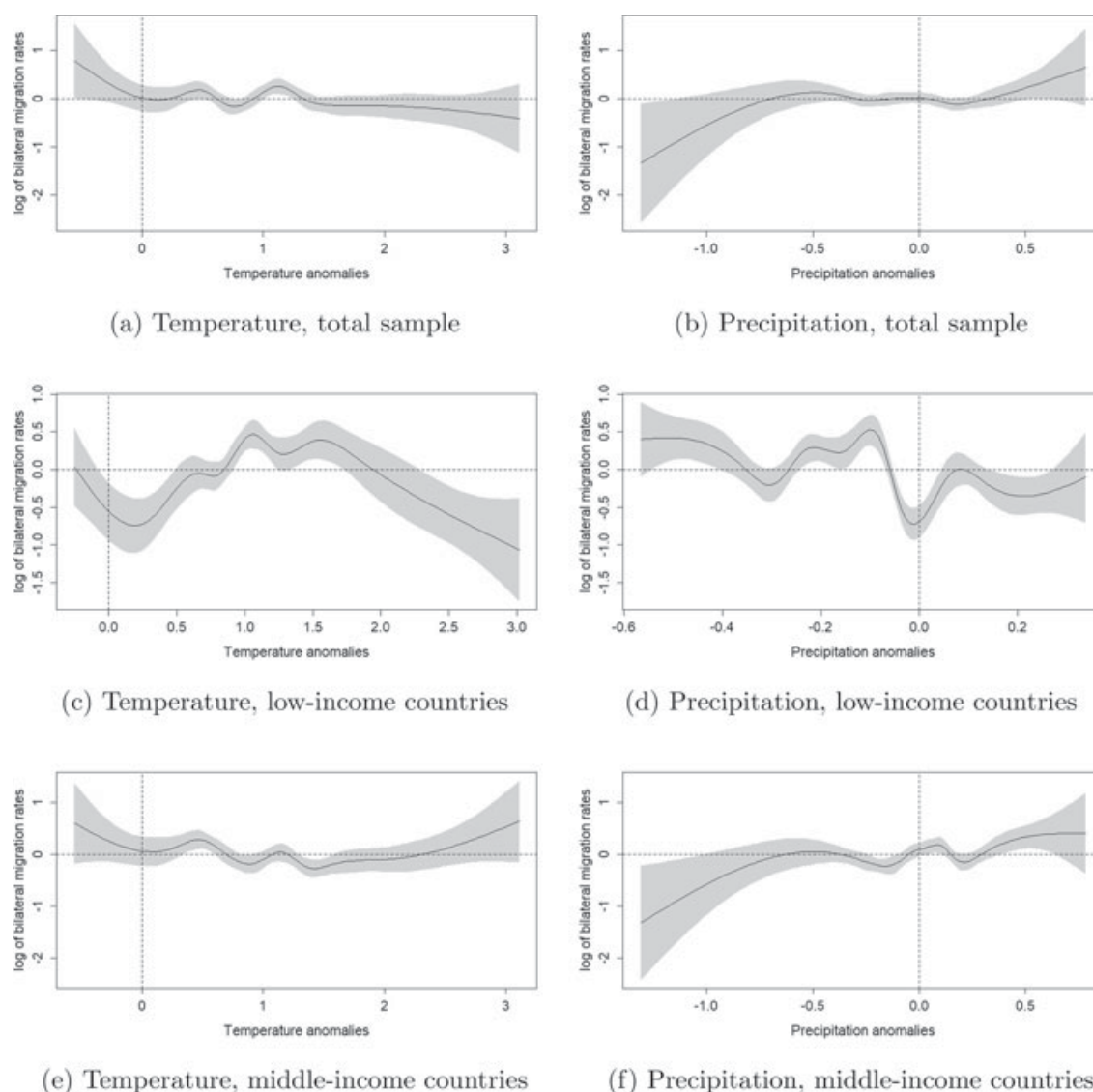


Figure 1. Nonlinear effects of temperature and precipitation anomalies on migration. (a) Temperature, total sample, (b) Precipitation, total sample, (c) Temperature, low-income countries, (d) Precipitation, low-income countries, (e) Temperature, middle-income countries, (f) Precipitation, middle-income countries.

Overall, the findings are not in line with the threshold effect suggested by the real-options framework, which would be verified empirically if the model estimated a flat relationship for low levels of climatic anomalies and a positive relationship past certain thresholds (Basile and Lim, 2017). Instead, the observed negative effect of temperature anomalies on migration in low-income countries is consistent with the role of liquidity constraints as emphasized by recent literature (e.g., Cattaneo and Peri, 2016; Beine and Parsons, 2017; Gröschl and Steinwachs, 2017; Cui and Feng, 2020): Increases in average temperature increase households' incentives to emigrate; past a certain threshold, however, tightening liquidity constraints due to worsening agricultural productivity dominate, as households are less able to afford the cost of migration, resulting in a negative effect on migration. The findings thus suggest that rather than employing a "wait and see" strategy, households in these countries may become "trapped" in place due to the adverse impacts of climate change.

5.2 Migration to neighboring countries

In the previous subsection, we demonstrated nonlinear relationships between temperature and precipitation anomalies and international migration that cannot be explained by the real-options framework but are in part consistent with the existence of liquidity constraints. However, such constraints should matter to a lesser extent for migration to nearby destinations (Beine and Parsons, 2017), and thus the real-options framework potentially does a better job at explaining migration to those destinations. Therefore, in this subsection we follow Beine and Parsons (2017) and interact our measures of climatic anomalies with a dummy variable indicating whether the origin and destination countries are contiguous (i.e., share a common border) or not, resulting in the following model:

$$g(\mathbb{E}(y_{ijt})) = \log(\mathbb{E}(y_{ijt})) = \beta_0 + s_1(T_{it}) + s_1(C_{ij}T_{it}) + s_2(P_{it}) + s_2(C_{ij}P_{it}) + \phi_i + \phi_j + \phi_t, \quad (14)$$

where C_{ij} is equal to one if i and j are contiguous and zero otherwise.

The results are reported in online appendix table A1. For low-income countries, we find significant effects of temperature and precipitation anomalies on migration to non-neighboring countries and a significant effect of temperature anomalies on migration to neighboring countries. Again, *edf* of about 8.7 and 8.9 for the respective smooth functions of temperature and precipitation anomalies indicate that the relationships are highly nonlinear. As for the interaction term between temperature anomalies and contiguity, on the other hand, an *edf* of close to 1 suggests a linear effect of temperature anomalies on migration to neighboring countries. For middle-income countries, we only find significant effects on migration to nonneighboring countries but not on migration to neighboring countries. Compared to the main results, pseudo- R^2 values for models (1) and (2) increase from 0.544 to 0.61 and from 0.416 to 0.496, respectively, suggesting that including interaction terms for contiguity increases the explanatory power of the GAM for both low- and middle-income countries.

Figures A3 and A4 in the online appendix plot the estimated effects for low- and middle-income countries, respectively. While the relationship between temperature anomalies and migration to nonneighboring countries shown in figure A3a appears similar to the one estimated in our main results – with migration decreasing with temperature anomalies greater than 1.5 – we observe a linear and negative effect on migration to neighboring countries (see figure A3b). This finding suggests that temperature anomalies constrain migration to both types of destinations, which is in contrast to Cattaneo and Peri (2016) who find that increases in temperature constrain migration from poor countries to distant destinations but not to close ones. Furthermore, similar to our main results, there is no clear relationship between precipitation anomalies and migration from low-income countries to both types of destinations (shown in figures A3c and A3d). Likewise, for middle-income countries the GAM estimates flat relationships between climatic anomalies and migration to both neighboring and nonneighboring countries (shown in figure A4).

5.3 Migration to OECD countries

The results presented in the previous subsection suggest that even for migration to neighboring countries, for which liquidity constraints should be less binding, the real-options framework does not explain migratory responses to climate change. In this subsection,

we further investigate specific emigration patterns by differentiating between emigration to OECD and non-OECD destination countries. Analogous to equation (14), we estimate the following model:

$$g(\mathbb{E}(y_{ijt})) = \log(\mathbb{E}(y_{ijt})) = \beta_0 + s_1(T_{it}) + s_1(OECD_j T_{it}) + s_2(P_{it}) + s_2(OECD_j P_{it}) + \phi_i + \phi_j + \phi_t, \quad (15)$$

where $OECD_j$ is a dummy variable that equals one if destination j is an OECD country and zero otherwise.

Online appendix table A2 presents the regression results. For low-income countries, relationships between climatic anomalies and migration show differing degrees of non-linearity for OECD and non-OECD destination countries: while *edf* of 8.4 and 8.9 for the respective smooth terms of temperature and precipitation anomalies are comparable to those found in the main results in table 2, *edf* for the corresponding OECD interaction terms are somewhat lower at 6.6 and 7.4, with the latter not being statistically significant. In contrast, all smooth terms for middle-income countries are statistically significant with *edf* between 8.4 and 8.9.

Figures A5 and A6 in the online appendix plot the estimated effects of climatic anomalies on migration to OECD and non-OECD destination countries for low- and middle-income countries, respectively. For low-income countries, the relationships between temperature and precipitation anomalies and migration to non-OECD countries in figures A5a and A5c, respectively, closely resemble the effects found in our main results (see figures 1(c) and 1(d)). This suggests that climate change-induced international migration from low-income countries occurs primarily to other low- and middle-income countries, which is consistent with recent literature (e.g., Hoffmann *et al.*, 2020). Figure A5b shows a similarly hump-shaped relationship between temperature anomalies and migration to OECD countries, although the negative effect of high levels of temperature anomalies is considerably less pronounced than in figure A5a. A possible interpretation of this difference is that migration from low-income countries to OECD countries in response to climate change is primarily undertaken by high-skilled individuals (Drabo and Mbaye, 2015; Kaczan and Orgill-Meyer, 2020) who are likely less affected by declines in agricultural income due to increasing temperatures.

Likewise, for middle-income countries the relationships between climatic anomalies and migration to non-OECD destination countries shown in figures A6a and A6c are similar to those estimated in our main results (see figures 1(e) and 1(f)). Interestingly, we find a pronounced negative effect of shortages in precipitation on migration to OECD countries (see figure A6d). This finding is in contrast to Cattaneo and Peri (2016) who find no effect of precipitation on migration from middle-income countries to OECD countries. Overall, the results again are inconsistent with the migration patterns predicted by the real-options framework.

6. Robustness checks

For our empirical analysis we followed Cattaneo and Peri (2016) and Beine and Parsons (2017) in defining countries in the bottom quartile of the GDP per capita distribution as “low-income countries”. Nevertheless, this delineation inevitably involves some arbitrariness since there is no clear definition of what a low-income country is, and thus a

potential concern is that varying the threshold between low- and middle-income countries may yield differing results. To address this concern, we repeat our analysis using the 20th and 30th percentile of the GDP per capita distribution as alternative thresholds.

The results are presented in online appendix table A3. For both alternative thresholds, the *edf* estimated by the GAM are of similar magnitude compared to the main results, and effects remain statistically significant. Turning to the plots of the estimated effects in online appendix figures A7 and A8, we find very similar relationships compared to the main results when using the 30th percentile of the income distribution as the threshold between low- and middle-income countries. The relationships estimated using the 20th percentile threshold are generally similar to the main results as well.

Another potential concern is that the results may be affected by the choice of the smoothing parameter selection method. While likelihood-based methods such as REML tend to exhibit faster convergence of smoothing parameters to their optimal values than prediction error-based methods such as generalized cross validation (GCV) (Wood, 2011), they have also been shown to have a tendency to undersmooth, i.e., to choose a too complex model (Wahba, 1985; Kauermann, 2005). Therefore, we reestimate equation (13) using GCV rather than REML. As shown in online appendix table A4 and figure A9, the results are very similar to our main findings.

Additional robustness checks are presented in the online appendix. In table A5 and figure A10, we test whether the negative effect of temperature anomalies on international migration in low-income countries is in fact driven by declines in agricultural productivity. For this purpose, we follow Cai *et al.* (2016: 149–150) and Cattaneo and Peri (2016: 134–135) and interact our measures of climatic anomalies with a factor variable indicating origin countries' quartile in the distribution of agricultural value added as a share of GDP. As shown in figure A10, we observe a negative effect of high positive temperature anomalies for all but the least agriculturally dependent countries. In fact, the results suggest that the higher the level of agricultural dependence, the lower the threshold beyond which the relationship becomes negative. This effect is particularly pronounced for the most agriculturally dependent countries (shown in figure A10 g), which exhibit a negative effect of temperature anomalies on migration across much of the data range. While these findings do not definitively prove that our results are driven by the existence of liquidity constraints, they do provide corroborative evidence of the transmission channel of agricultural productivity postulated by Cattaneo and Peri (2016).

Furthermore, to address potential concerns over omitted variable bias regarding our parsimonious main specification, in table A6 we include a number of control variables identified as important determinants of international migration in the literature (e.g., Ortega and Peri, 2013; Beine and Parsons, 2015). More specifically, we control for the log of the ratio of GDP per capita in origin and destination countries, whether origin-destination pairs share a common language, log distance between origin-destination pairs and the number of years per five-year period in which origin countries experienced civil war.⁶ Parametric estimates for the control variables are statistically significant and have the expected signs, and *edf* of smooth terms are similar in magnitude to the main results. Turning to the estimated relationships between climatic anomalies and international migration shown in figure A11, including the control variables appears to smooth

⁶Data on distance and common language are obtained from the CEPII Geographic and Bilateral Distance Database (Mayer and Zignago, 2011), and data on civil wars is taken from the Intra-State War Data (v5.1) of the Correlates of War project (Sarkees and Wayman, 2010).

out some of the “wiggleness” present in the relationships in [figure 1](#). Even so, we continue to observe a strong negative effect of high temperature anomalies on international migration for low-income countries.

Next, in [table A7](#) and [figure A12](#), we follow [Nawrotzki and Bakhtsiyarava \(2017\)](#) and [Nawrotzki and Bakhtsiyarava \(2017\)](#) and use five-year period shares of heat and drought months as alternative measures of climatic anomalies (see [section 2](#)). Again, *edf* of smooth terms are similar in magnitude to our main results, and effects remain statistically significant. For low-income countries, we find a hump-shaped relationship between heat month shares and international migration similar to [figure 1\(c\)](#). For middle-income countries, [figure A12c](#) suggests a slightly positive effect of high shares of heat months on international migration, but confidence intervals are quite large for this part of the sample.

Finally, to assess whether the results are driven by extreme outliers, we exclude observations with temperature anomalies more than two standard deviations above or precipitation anomalies more than two standard deviations below the respective sample mean. The results are presented in [table A8](#) and [figure A13](#). Compared to the main results, excluding outliers moderates the estimated relationships to an extent. Most notably, the negative effect of negative precipitation anomalies observed in [figure 1\(f\)](#) disappears. However, the remaining relationships are qualitatively similar to the main results.

7. Conclusions

The potential impact of climate change on international migration patterns has recently received considerable attention in both the public and academic debate. Yet, much of the empirical literature fails to find increases in international migration due to climate change. In light of this evidence, the current paper theoretically and empirically investigates why climate change-induced international migration appears to be relatively uncommon. Drawing on recent contributions by [Gardner and Hendrickson \(2018\)](#) and [Mense \(2018\)](#), the current paper presents an application of the real-options framework in which individuals may decide to postpone their migration response to climate change due to the fixed cost of migration as well as the option value of waiting. This framework implies that individuals choose a threshold level of quality of climatic conditions and migrate only once climatic conditions have deteriorated past this critical point.

We test this prediction empirically by estimating generalized additive models, which allow us to assess the threshold effects suggested by this theoretical framework. For low-income countries, we find a robust hump-shaped relationship between temperature anomalies and migration rates; this effect appears to be primarily driven by migration to other low- and middle-income countries. For middle-income countries, on the other hand, no robust effects of temperature and precipitation anomalies on migration rates can be observed.

We generally find no evidence of the threshold effects suggested by the real-options framework. Rather, consistent with recent literature (e.g., [Cattaneo and Peri, 2016](#); [Beine and Parsons, 2017](#); [Gröschl and Steinwachs, 2017](#); [Cui and Feng, 2020](#)), the findings suggest that in low-income countries, individuals’ migration response is hampered by the existence of liquidity constraints. These are likely to become more binding due to climate change-induced decreases in agricultural productivity.

A key implication of our findings is that instead of attempting to deter migration from areas increasingly affected by the impacts of climate change, policymakers should

focus on both fostering migration and assisting “trapped” populations by facilitating alternative adaptation strategies. Such strategies may include shifting planting dates and planting crop varieties with different maturation periods (McCord *et al.*, 2018), investing in irrigation systems (Benonnier *et al.*, 2019) as well as cash transfer and social protection programs (Chort and Rupelle, 2017; Mueller *et al.*, 2020).

Finally, a number of potential directions for future research emerge from our results. First, it should be noted that the aggregate nature of our analysis likely masks some considerable heterogeneity in local thresholds of climate-related migration. As pointed out by Adger *et al.* (2009) and McLeman (2018), such thresholds may be highly dependent on the social, economic and climatic context, and the measures of climatic anomalies used in this paper may only imperfectly capture the effects of climate change on local living conditions. Future research should thus consider applying the real-options framework to local and regional migration patterns as well as other aspects of the climate-migration relationship. This may include, for example, the impacts of fast-onset events such as flooding, storms and wildfire as well as the prevalence of infectious diseases (Marchiori *et al.*, 2012). Second, the current paper demonstrates how semiparametric estimation methods can be applied to assess nonlinearities in the relationship between climate and international migration. This methodology could be easily utilized by future research to investigate other determinants of international migration patterns.

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Conflict of interest. The author declares none.

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A real-options analysis of climate change and international migration

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ONLINE APPENDIX

Table A1. Specific emigration patterns: contiguity

	(1)	(2)
	Low-income countries	Middle-income countries
Smooth terms	<i>edf</i>	<i>edf</i>
s(T)	8.681*** (0.000)	8.727** (0.020)
s(T*contiguity)	1.085*** (0.002)	6.652 (0.892)
s(P)	8.860*** (0.000)	8.328*** (0.003)
s(P*contiguity)	6.681 (0.288)	6.560 (0.904)
REML score	-213916.7	-563102.4
AIC	-427922.9	-1126591
N	26520	81120
Pseudo-R ²	0.61	0.496

Note: Time period: 1990-2010. The dependent variable is the bilateral migration rate from country i to country j in five-year period t . $s(T)$ and $s(P)$ are smooth non-parametric functions of temperature and precipitation anomalies, respectively. Approximate p -values in parentheses. *edf*: effective degrees of freedom, REML: restricted maximum likelihood, AIC: Akaike information criterion. $*p < 0.1$, $**p < 0.05$, $***p < 0.01$.

Table A2. Specific emigration patterns: OECD destination countries

Smooth terms	(1)	(2)
	Low-income countries <i>edf</i>	Middle-income countries <i>edf</i>
s(T)	8.383*** (0.000)	8.849*** (0.000)
s(T*OECD destination)	6.590*** (0.007)	8.752*** (0.000)
s(P)	8.911*** (0.000)	8.755*** (0.001)
s(P*OECD destination)	7.368 (0.327)	8.467*** (0.000)
REML score	-211100.2	-555241
AIC	-422273.9	-1110878
N	26520	81120
Pseudo-R ²	0.546	0.422

Note: Time period: 1990-2010. The dependent variable is the bilateral migration rate from country i to country j in five-year period t . $s(T)$ and $s(P)$ are smooth non-parametric functions of temperature and precipitation anomalies, respectively. Approximate p -values in parentheses. *edf*: effective degrees of freedom, REML: restricted maximum likelihood, AIC: Akaike information criterion. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A3. Robustness checks: alternative definitions of low-income country

	Bottom 20 %		Bottom 30 %	
	(1) Low-income countries <i>edf</i>	(2) Middle-income countries <i>edf</i>	(3) Low-income countries <i>edf</i>	(4) Middle-income countries <i>edf</i>
Smooth terms				
s(T)	8.370*** (0.000)	8.846*** (0.003)	8.688*** (0.000)	8.540*** (0.005)
s(P)	8.895*** (0.000)	8.160* (0.054)	8.836*** (0.000)	8.789*** (0.000)
REML score	-170233.6	-593466.5	-249564.1	-518850.3
AIC	-340471.2	-1187273	-499236.2	-1038020
N	21060	86580	31980	75660
Pseudo-R ²	0.563	0.400	0.538	0.438

Note: Time period: 1990-2010. The dependent variable is the bilateral migration rate from country i to country j in five-year period t . $s(T)$ and $s(P)$ are smooth non-parametric functions of temperature and precipitation anomalies, respectively. Approximate p -values in parentheses. *edf*: effective degrees of freedom, REML: restricted maximum likelihood, AIC: Akaike information criterion. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A4. Robustness checks: smoothing parameter selection using GCV

Smooth terms	(1)	(2)
	Low-income countries <i>edf</i>	Middle-income countries <i>edf</i>
s(T)	8.712*** (0.000)	8.889*** (0.001)
s(P)	8.985*** (0.000)	8.704*** (0.001)
GCV score	5.492	6.033
AIC	-381587.4	-890441.9
N	26520	81120
Pseudo-R ²	0.544	0.416

Note: Time period: 1990-2010. The dependent variable is the bilateral migration rate from country i to country j in five-year period t . s(T) and s(P) are smooth non-parametric functions of temperature and precipitation anomalies, respectively. Approximate p -values in parentheses. *edf*: effective degrees of freedom, GCV: generalized cross validation, AIC: Akaike information criterion. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A5. Robustness checks: interacting climatic anomalies with quartiles of agricultural value added as a share of GDP

Smooth terms	Total sample <i>edf</i>
s(T*Q1)	8.597 (0.159)
s(T*Q2)	8.791*** (0.000)
s(T*Q3)	8.905*** (0.000)
s(T*Q4)	8.382*** (0.001)
s(P*Q1)	8.630 (0.158)
s(P*Q2)	8.814*** (0.000)
s(P*Q3)	8.907*** (0.000)
s(P*Q4)	7.917*** (0.000)
REML score	-705633.1
AIC	-1411848
N	99060
Pseudo-R ²	0.395

Note: Time period: 1990-2010. The dependent variable is the bilateral migration rate from country i to country j in five-year period t . $s(T)$ and $s(P)$ are smooth non-parametric functions of temperature and precipitation anomalies, respectively. Approximate p -values in parentheses. *edf*: effective degrees of freedom, REML: restricted maximum likelihood, AIC: Akaike information criterion. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A6. Robustness checks: including control variables

	(1)	(2)
	Low-income countries	Middle-income countries
Parametric terms	Estimate	Estimate
ln(GDP per capita ratio)	-0.040 (0.062)	0.156*** (0.043)
Common language	0.828*** (0.078)	1.041*** (0.048)
ln(Distance)	-3.028*** (0.041)	-1.960*** (0.021)
Civil war	0.072*** (0.028)	0.171*** (0.025)
Smooth terms	<i>edf</i>	<i>edf</i>
s(T)	8.438*** (0.000)	6.697** (0.039)
s(P)	8.589** (0.023)	8.558*** (0.002)
REML score	-191498.8	-519325.9
AIC	-383137.8	-1039129
N	23331	72114
Pseudo-R ²	0.709	0.691

Note: Time period: 1990-2010. The dependent variable is the bilateral migration rate from country i to country j in five-year period t . $s(T)$ and $s(P)$ are smooth non-parametric functions of temperature and precipitation anomalies, respectively. For parametric estimates, standard errors are reported in parentheses, while for smooth terms approximate p -values are reported in parentheses. *edf*: effective degrees of freedom, REML: restricted maximum likelihood, AIC: Akaike information criterion. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A7. Robustness checks: using five-year period shares of heat and drought months

	(1)	(2)
	Low-income countries	Middle-income countries
Smooth terms	<i>edf</i>	<i>edf</i>
s(Heat month share)	8.608*** (0.000)	8.812*** (0.000)
s(Drought month share)	8.884*** (0.000)	7.702* (0.069)
REML score	-211233.9	-554707.2
AIC	-422517.6	-1109729
N	26520	81120
Pseudo-R ²	0.548	0.416

Note: Time period: 1990-2010. The dependent variable is the bilateral migration rate from country i to country j in five-year period t . s (Heat month share) and s (Drought month share) are smooth non-parametric functions of five-year period heat and drought month shares, respectively. Approximate p -values in parentheses. *edf*: effective degrees of freedom, REML: restricted maximum likelihood, AIC: Akaike information criterion. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A8. Robustness checks: excluding extreme outliers

	(1)	(2)
Smooth terms	Low-income countries	Middle-income countries
	<i>edf</i>	<i>edf</i>
s(T)	8.647*** (0.000)	8.750** (0.012)
s(P)	8.770*** (0.000)	8.802*** (0.001)
REML score	-192912.9	-531276.5
AIC	-385852.6	-1062869
N	24375	77025
Pseudo-R ²	0.537	0.42

Note: Time period: 1990-2010. The dependent variable is the bilateral migration rate from country i to country j in five-year period t . s(T) and s(P) are smooth non-parametric functions of temperature and precipitation anomalies, respectively. Approximate p -values in parentheses. *edf*: effective degrees of freedom, REML: restricted maximum likelihood, AIC: Akaike information criterion. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

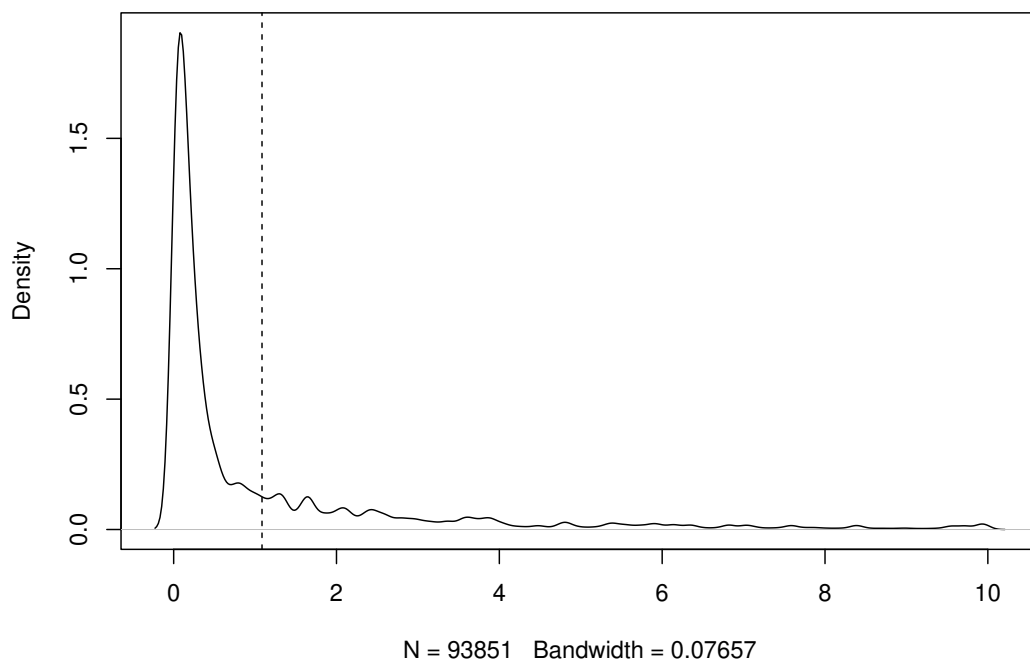
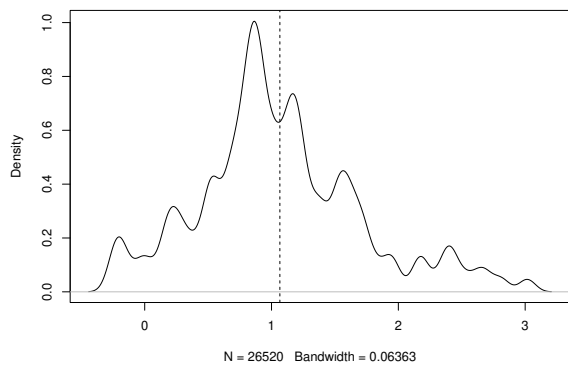
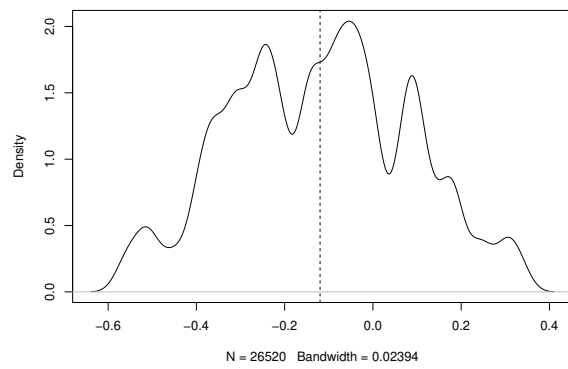


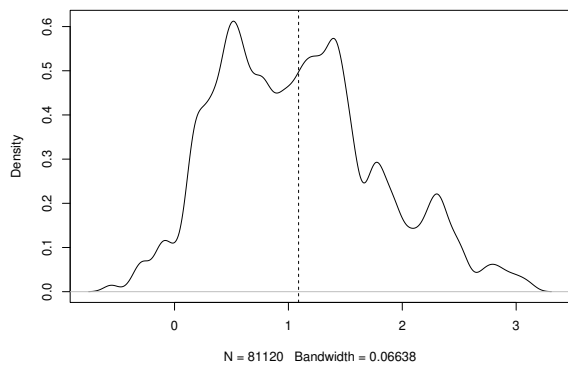
Figure A1. Kernel density estimation of bilateral migration rates. Only for the purpose of the kernel density estimation, we have scaled bilateral migration rates by a factor of 10^6 and excluded observations greater than 10.



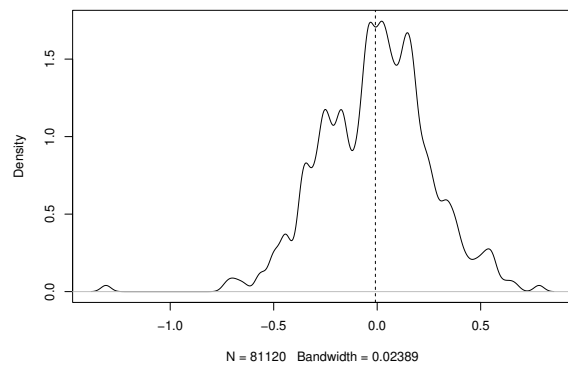
(a) Temperature, low-income countries



(b) Precipitation, low-income countries

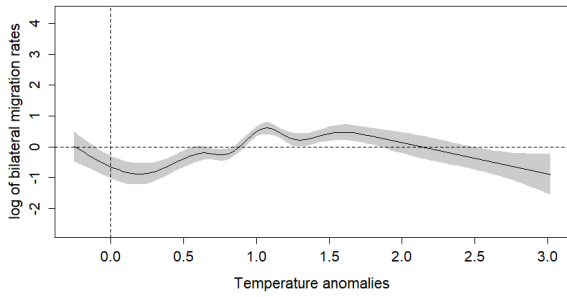


(c) Temperature, middle-income countries

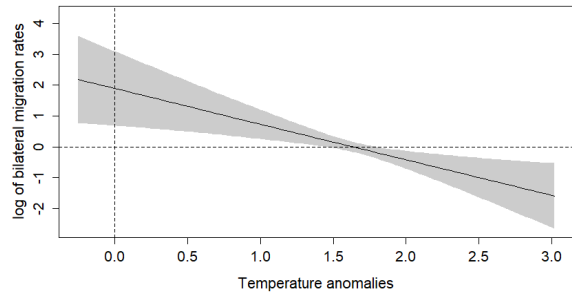


(d) Precipitation, middle-income countries

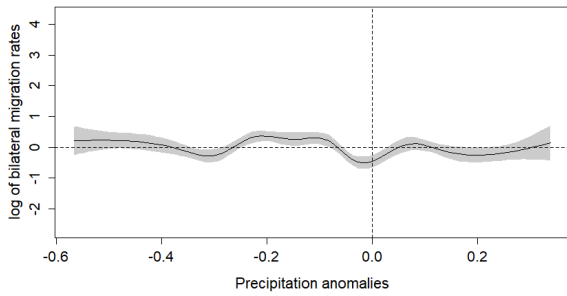
Figure A2. Kernel density estimations of temperature and precipitation anomalies for low- and middle-income countries.



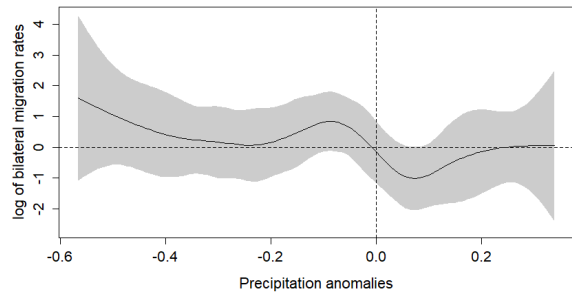
(a) Temperature and migration to nonneighboring countries



(b) Temperature and migration to neighboring countries

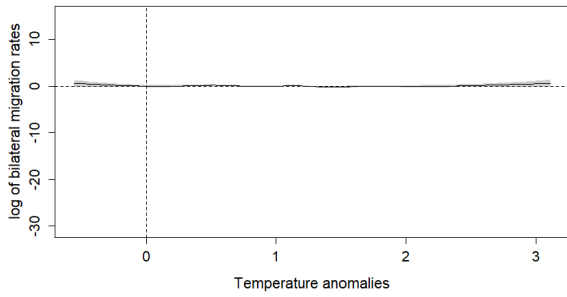


(c) Precipitation and migration to nonneighboring countries

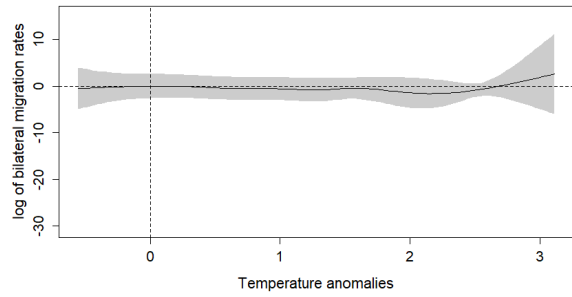


(d) Precipitation and migration to neighboring countries

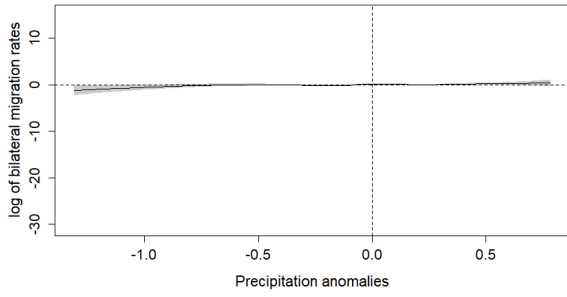
Figure A3. Nonlinear effects of temperature and precipitation anomalies on migration from low-income countries to neighboring and nonneighboring countries.



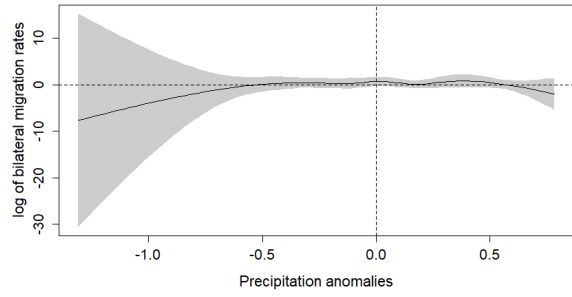
(a) Temperature and migration to nonneighboring countries



(b) Temperature and migration to neighboring countries

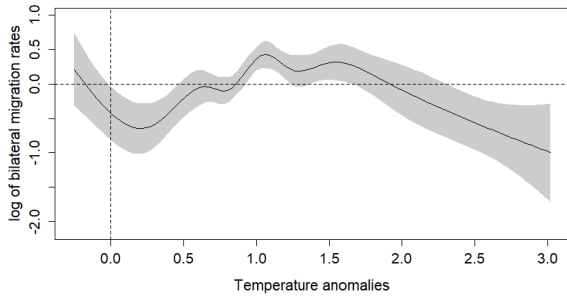


(c) Precipitation and migration to nonneighboring countries

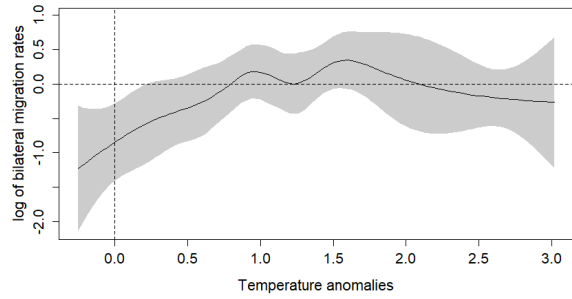


(d) Precipitation and migration to neighboring countries

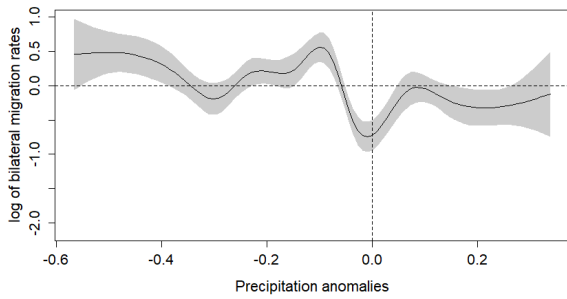
Figure A4. Nonlinear effects of temperature and precipitation anomalies on migration from middle-income countries to neighboring and nonneighboring countries.



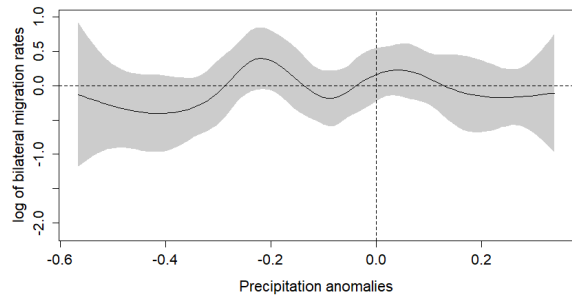
(a) Temperature and migration to non-OECD countries



(b) Temperature and migration to OECD countries

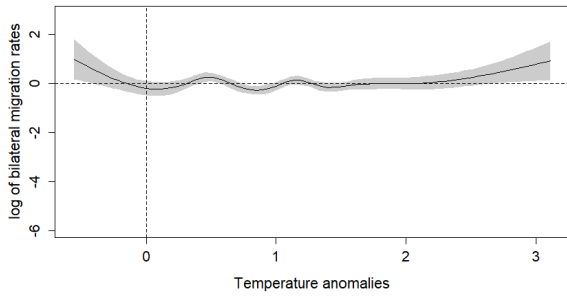


(c) Precipitation and migration to non-OECD countries

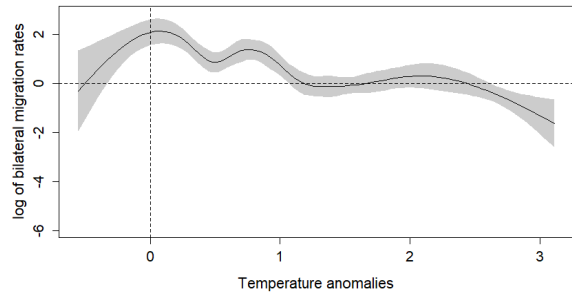


(d) Precipitation and migration to OECD countries

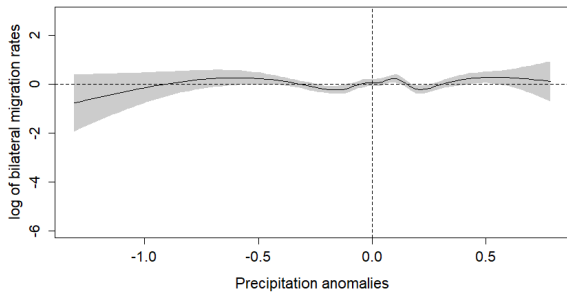
Figure A5. Nonlinear effects of temperature and precipitation anomalies on migration from low-income countries to OECD and non-OECD countries.



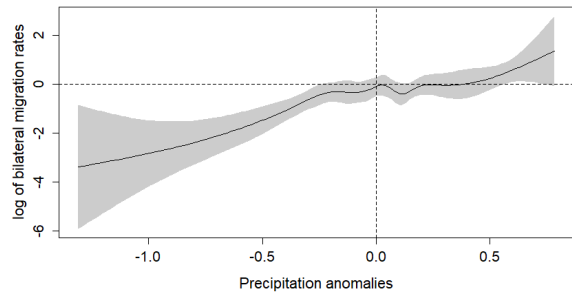
(a) Temperature and migration to non-OECD countries



(b) Temperature and migration to OECD countries

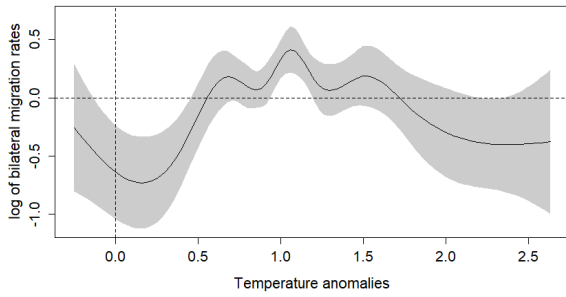


(c) Precipitation and migration to non-OECD countries

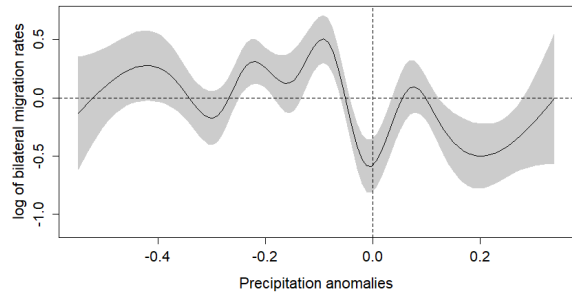


(d) Precipitation and migration to OECD countries

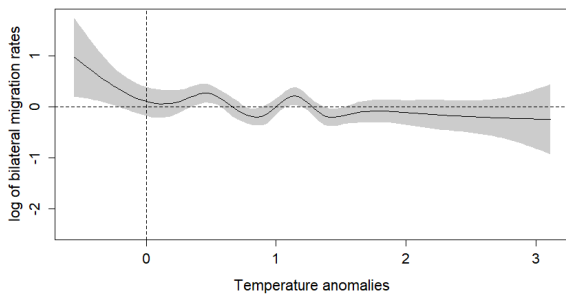
Figure A6. Nonlinear effects of temperature and precipitation anomalies on migration from middle-income countries to OECD and non-OECD countries.



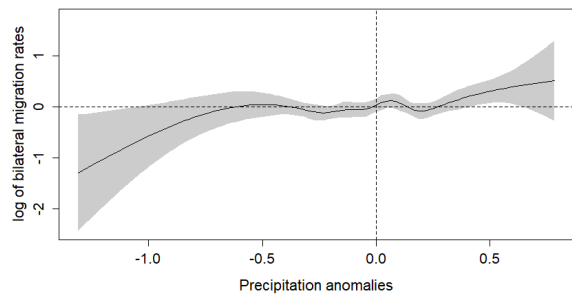
(a) Temperature, low-income countries



(b) Precipitation, low-income countries

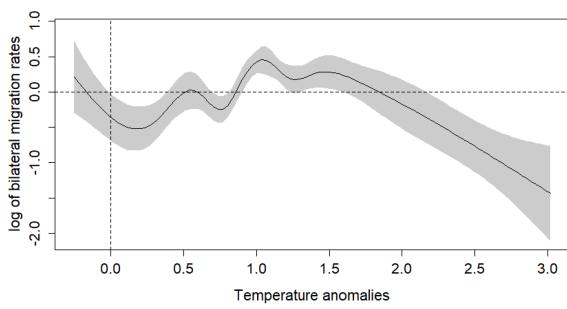


(c) Temperature, middle-income countries

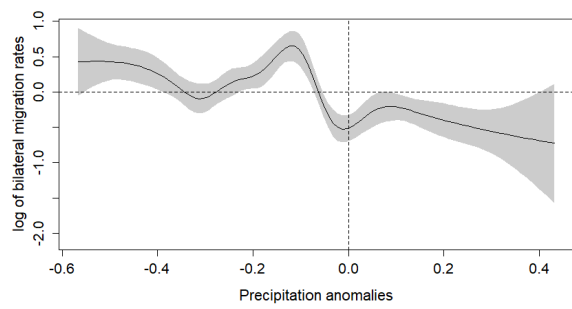


(d) Precipitation, middle-income countries

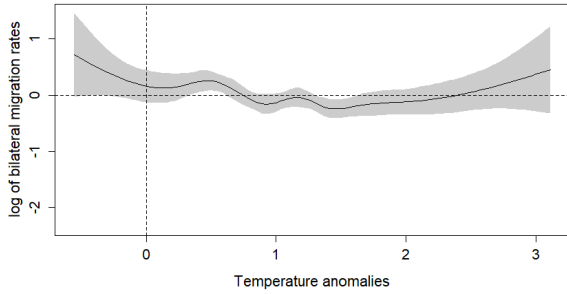
Figure A7. Nonlinear effects of temperature and precipitation anomalies on migration: defining the bottom 20% of the income distribution as low-income countries.



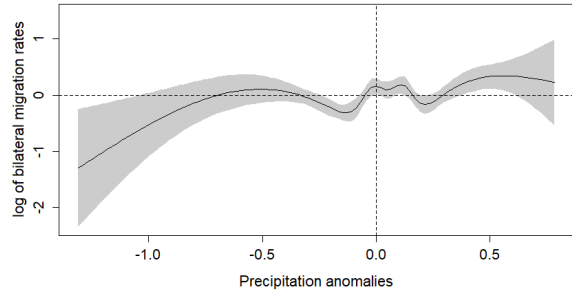
(a) Temperature, low-income countries



(b) Precipitation, low-income countries

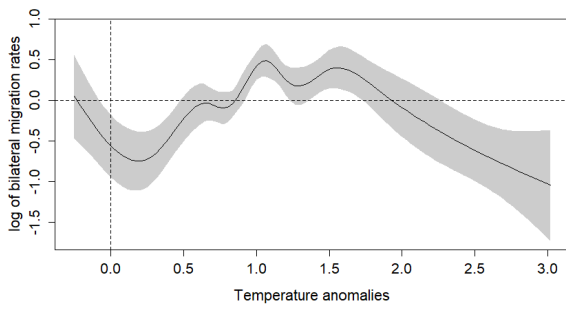


(c) Temperature, middle-income countries

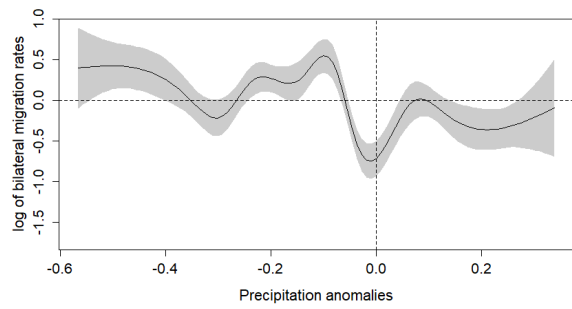


(d) Precipitation, middle-income countries

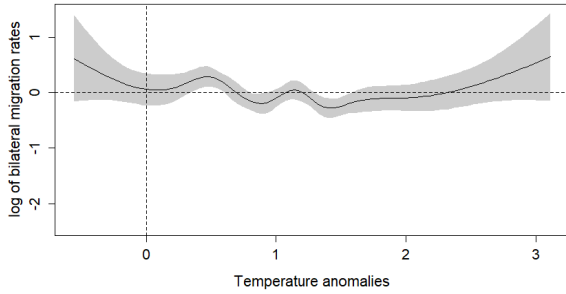
Figure A8. Nonlinear effects of temperature and precipitation anomalies on migration: defining the bottom 30% of the income distribution as low-income countries.



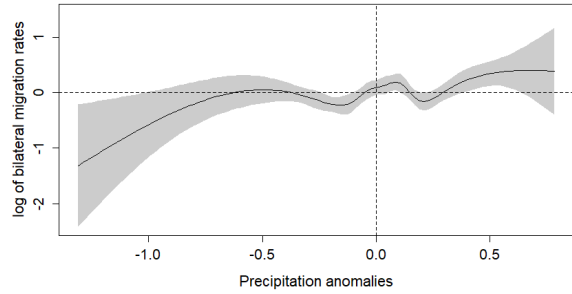
(a) Temperature, low-income countries



(b) Precipitation, low-income countries



(c) Temperature, middle-income countries



(d) Precipitation, middle-income countries

Figure A9. Nonlinear effects of temperature and precipitation anomalies on migration: smoothing parameter selection using GCV.

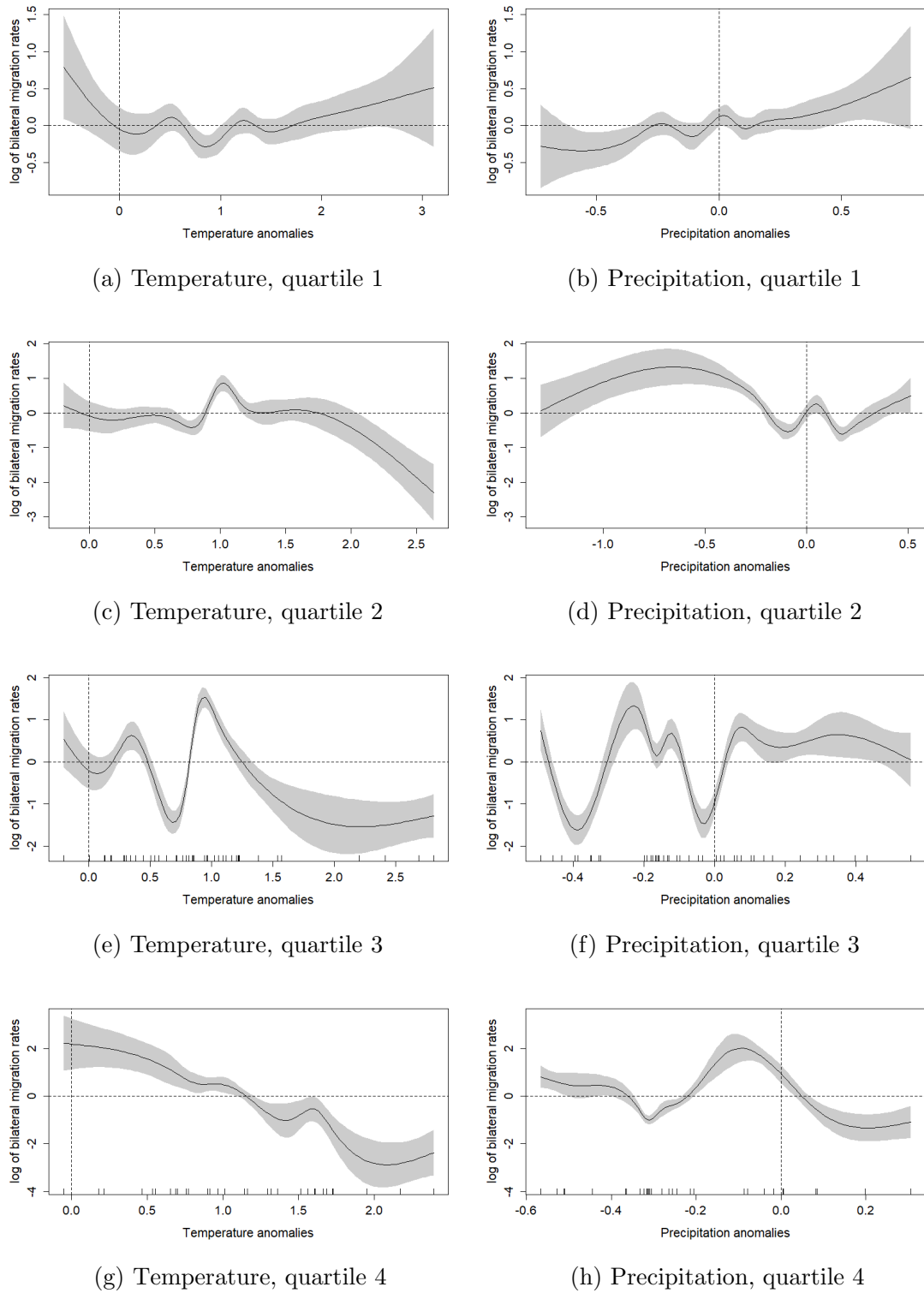
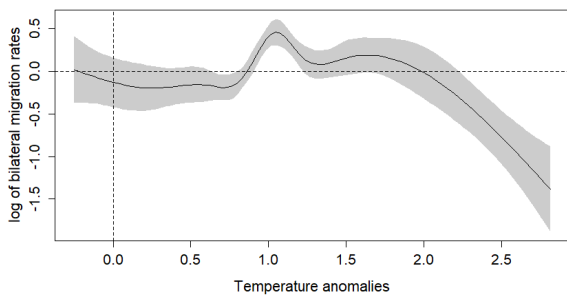
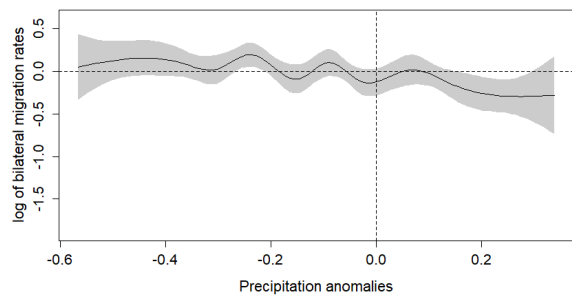


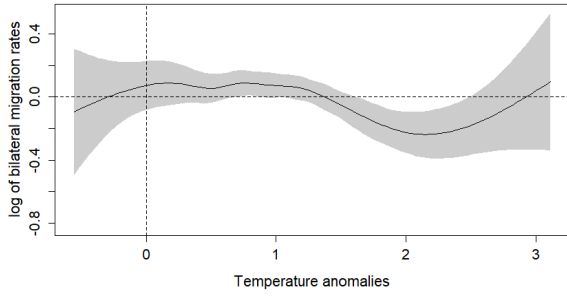
Figure A10. Nonlinear effects of temperature and precipitation anomalies on migration: interacting climatic anomalies with quartiles of agricultural value added as a share of GDP.



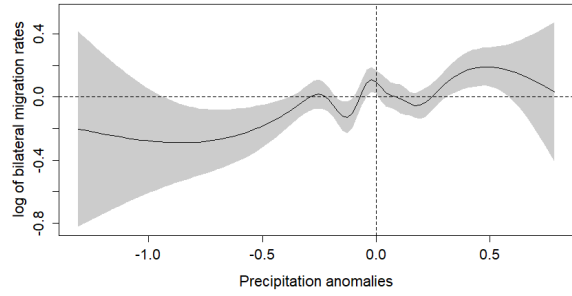
(a) Temperature, low-income countries



(b) Precipitation, low-income countries

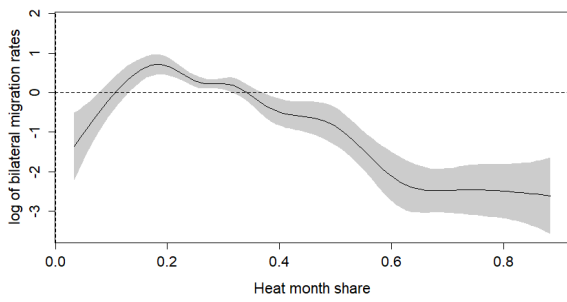


(c) Temperature, middle-income countries

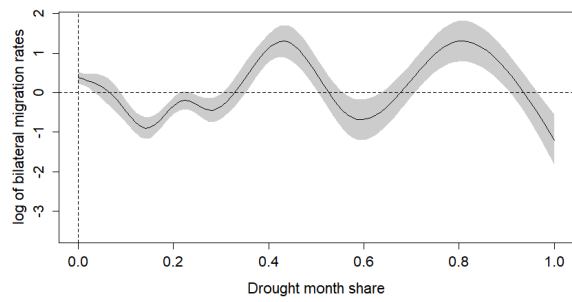


(d) Precipitation, middle-income countries

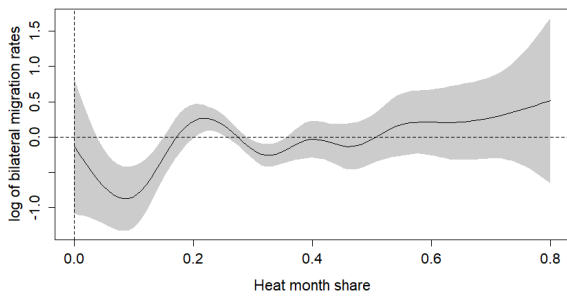
Figure A11. Nonlinear effects of temperature and precipitation anomalies on migration: including control variables.



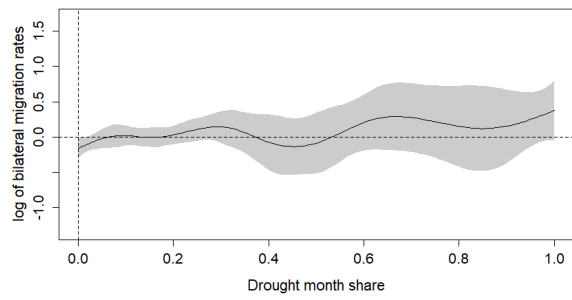
(a) Heat month share, low-income countries



(b) Drought month share, low-income countries

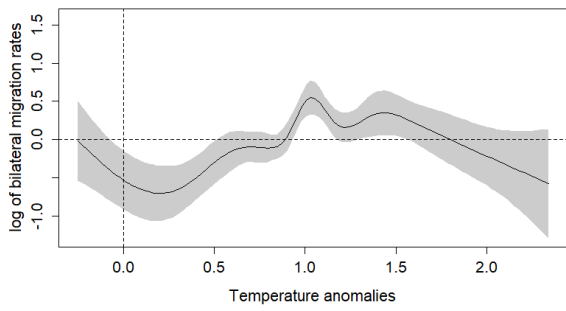


(c) Heat month share, middle-income countries

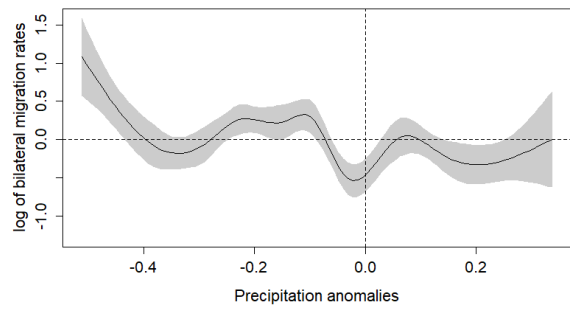


(d) Drought month share, middle-income countries

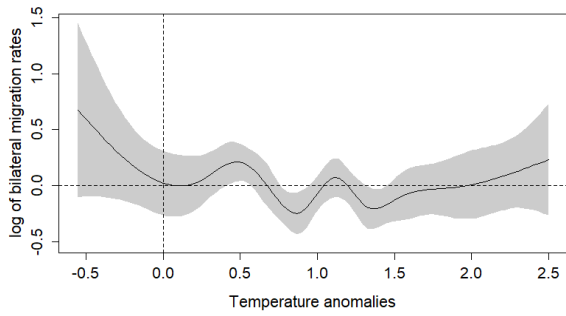
Figure A12. Nonlinear effects of temperature and precipitation anomalies on migration: using five-year period shares of heat and drought months.



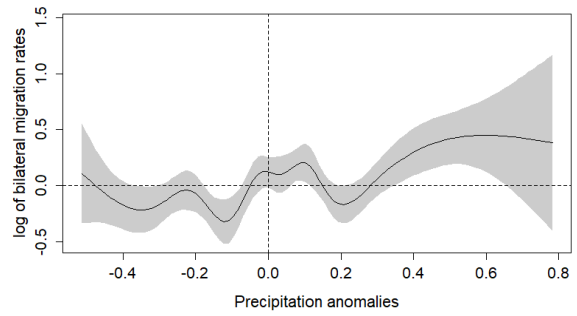
(a) Temperature, low-income countries



(b) Precipitation, low-income countries



(c) Temperature, middle-income countries



(d) Precipitation, middle-income countries

Figure A13. Nonlinear effects of temperature and precipitation anomalies on migration: excluding extreme outliers.

List of low-income countries

Bangladesh, Bosnia-Herzegovina, Burkina Faso, Burundi, Cambodia, Cape Verde, Central African Republic, Chad, China, Democratic Republic of Congo, Equatorial Guinea, Ethiopia, Guinea, India, Lesotho, Liberia, Madagascar, Malawi, Mali, Mozambique, Myanmar, Nepal, Niger, Rwanda, Sao Tome and Principe, Sierra Leone, South Sudan, Sudan, Syria, Tanzania, Togo, Uganda, Vietnam, Yemen

List of middle-income countries

Albania, Algeria, Angola, Argentina, Armenia, Azerbaijan, Bahamas, Bahrain, Barbados, Belarus, Belize, Benin, Bhutan, Bolivia, Botswana, Brazil, Brunei, Bulgaria, Cameroon, Comoros, Costa Rica, Croatia, Cyprus, Djibouti, Dominican Republic, Ecuador, Egypt, El Salvador, Fiji, Gabon, Gambia, Georgia, Ghana, Grenada, Guatemala, Guinea Bissau, Guyana, Haiti, Honduras, Hong Kong, Indonesia, Iran, Iraq, Ivory Coast, Jamaica, Jordan, Kazakhstan, Kenya, Kuwait, Kyrgyzstan, Laos, Lebanon, Libya, Macao, Macedonia, Malaysia, Maldives, Malta, Mauritania, Mauritius, Moldova, Mongolia, Montenegro, Morocco, Namibia, Nicaragua, Nigeria, Oman, Pakistan, Panama, Papua New-Guinea, Paraguay, Peru, Philippines, Puerto Rico, Qatar, Republic of Congo, Romania, Russia, Samoa, Saudi Arabia, Senegal, Serbia, Singapore, Solomon Islands, South Africa, South Korea, Sri Lanka, Suriname, Swaziland, Tajikistan, Thailand, Tonga, Trinidad and Tobago, Tunisia, Turkmenistan, Ukraine, United Arab Emirates, Uruguay, Uzbekistan, Vanuatu, Venezuela, Zambia, Zimbabwe

Chapter 3

Climate-Related Natural Disasters and Regional Migration in Europe: A Spatial Econometric Analysis

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Climate-Related Natural Disasters and Regional Migration in Europe: A Spatial Econometric Analysis

Marius Braun* Jarom Görts†

April 2025

Abstract

In recent decades, the European Union has experienced an increase in the frequency of climate-related natural disasters. While a large body of literature analyzing the impact of natural disasters on migration patterns in the U.S. and other areas has emerged, little research has been conducted for the European Union. In this paper, we attempt to close this gap in the literature and investigate the impact of climate-related disasters on NUTS-2 region-level migration for the period 2000-2019. Employing spatial econometric methods, we find that experiencing a severe disaster leads to an increase in net out-migration of 0.9 individuals per 1000 inhabitants, followed by an increase in net in-migration of 0.6 individuals per 1000 inhabitants two years later. When using spatial Durbin models, we observe a negative spatial spillover effect of severe disasters on net migration, suggesting that neighboring regions may also be affected by the disasters, which may induce individuals in those regions to out-migrate. For less severe disaster events, we find no conclusive evidence that disasters are driving regional migration.

Keywords: climate change, migration, natural disasters, spatial econometrics

JEL Classification: F22, R11, R23, Q54

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1 Introduction

The past decades have witnessed a significant increase in the frequency and severity of natural disasters attributed to anthropogenic climate change (Bednar-Friedl et al. 2022). Thus, regions around the world have experienced intensifying impacts of extreme weather events, such as storms, extreme heat, wildfires, floods, and droughts. When regions are struck by such events one potentially important adaptation strategy is to migrate away from the affected area.

Recently, a large body of literature analyzing the migration responses to slow- and fast-onset climatic events has emerged (for a review see, e.g., Cattaneo et al. 2019). This research has led to some considerable improvements in our understanding of the interaction between climatic factors and internal as well as international population movements. However, the literature has thus far predominantly focused on impacts in developing countries, which is typically justified on the basis that these countries are particularly vulnerable to adverse effects of climate change and have lower adaptation capacities compared to developed countries (Hunter 2018; Piguet, Kaenzig, and Guélat 2018).

With respect to developed countries, some research exists, predominantly analyzing the same climate change-migration nexus for the U.S. (e.g., Eyer et al. 2018; Fan, Klaiber, and Fisher-Vanden 2016; Fan, Fisher-Vanden, and Klaiber 2018; Boustan, Kahn, Rhode, and Yanguas 2020). The general finding of this research is that climate-related natural disasters have a significant impact on regional migration. However, empirical evidence in this regard remains relatively scant. In particular, virtually no research exists on climate change-induced internal migration in Europe (Hunter 2018), although the number of natural disasters has substantially increased over the last decades (see Figure 1). Considering this development and the findings for the U.S., a better understanding of the climate change-migration nexus in Europe seems highly relevant.

Therefore, this paper aims to provide a first assessment of impacts of natural disasters on migration patterns in the European Union for the period 2000-2019. To do so, we combine

data on natural disasters with data on net migration at the NUTS-2 region-level. Using spatial panel data models, we observe that experiencing a severe disaster leads to an increase in net out-migration of 0.9 individuals per 1000 inhabitants, followed by an increase in net in-migration of 0.6 individuals per 1000 inhabitants two years later. We also find a negative spatial spillover effect of severe disasters on net migration, suggesting that neighboring regions may also be affected by the disasters, which may induce individuals in those regions to out-migrate. For less severe disaster events, we find no conclusive evidence that disasters are driving regional migration.

The remainder of this paper is structured as follows: Section 2 presents a brief review of previous literature. Section 3 discusses our data and empirical strategy. Section 4 presents our results, while Section 5 provides robustness checks. Section 6 concludes.

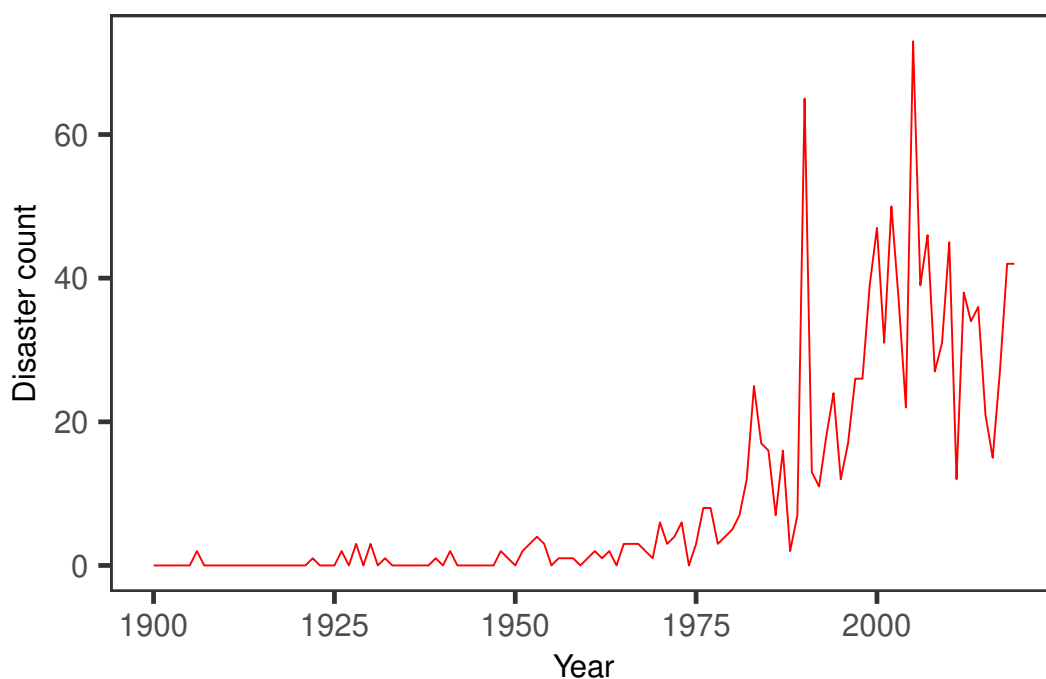


Figure 1: Annual disaster counts in the geographical area of the European Union, 1900-2019

2 Literature Review

Our paper contributes to two strands in the literature on climate change and migration. First, we contribute to an emerging body of literature investigating impact of climate change on migration patterns in developed countries. Second, our paper relates to previous work applying spatial econometric methods to analyze the relationship between climate change and migration.

Regarding the first strand of literature, existing work has primarily focused on the U.S. This literature builds on earlier work that emphasizes the role of environmental amenities to explain the migration patterns that have led to the higher population density in coastal areas that can be observed at the beginning of the 21st century (Rappaport and Sachs 2003; Partridge 2010). Interestingly, this literature finds that these high-amenity coastal areas are the same regions that are becoming increasingly vulnerable to the impacts of climate-related natural disasters.

Fan, Klaiber, and Fisher-Vanden (2016) use a residential sorting model to analyze the effect of extreme weather on interregional brain drain in the U.S. They find that high-skilled individuals are more likely to leave regions experiencing extreme weather events. In another paper, Fan, Fisher-Vanden, and Klaiber (2018) combine a residential sorting model with a computable general equilibrium model to investigate climate-related regional migration in the U.S. while taking into account wage and housing price feedbacks. They find that the magnitude of climate-related migration is reduced when wages and housing prices are endogenized. Nevertheless, the Midwestern and Southern are projected to experience significant out-migration due to climate change, whereas the Northeastern and Western regions as well as California may experience in-migration. These findings support the notion of amenity-based migration.

Eyer et al. (2018) assess which destinations attracted individuals relocating out of New Orleans in the wake of Hurricane Katrina in 2005. Using a gravity model, they find that out-migration occurred to nearby urban regions despite them being at a higher risk of being

struck by future hurricanes. The paper most closely related to ours is Boustan, Kahn, Rhode, and Yanguas (2020). The authors combine Census data from 1920 to 2010 with county-level disaster data to investigate the impact of climate-related natural disasters on migration. They find that severe disasters induce net out-migration. Additionally, the magnitude of the migration response to disasters has increased over time. One of the most recent papers related to ours is Winkler and Rouleau (2021), who analyze the relationship between wildfire and extreme heat and regional migration in the U.S. for the period 1990-2015. Their main finding is that wildfire and extreme heat reduce in-migration and increase out-migration. These effects are particularly pronounced in counties rich in environmental amenities, suggesting a gradual shift towards environmental disamenities due to climate change.

The second strand of literature builds on methods developed in the spatial econometrics literature (e.g., Burridge 1980; J. P. LeSage and R. K. Pace 2014).¹ For instance, Saldaña-Zorrilla and Sandberg (2009) employ spatial error and spatial Durbin models to analyze the effect of climate-related disasters on regional migration in Mexico during the 1990s. Ruysen and Rayp (2014) estimate a spatial Durbin model to investigate the impact of economic, sociopolitical and environmental conditions (including natural disasters and climatic anomalies) on bilateral international migration flows in Sub-Saharan Africa between 1980 and 2000. Zouabi (2021) studies the relationship between temperature and precipitation and regional migration in Tunisia using a spatial Durbin model. Finally, Conigliani, Costantini, and Finardi (2022) analyze spatial spillover effects of climate-related disasters on forced migration for a panel of South and Southeast Asia over the period 1990-2016.

¹For a comprehensive review see, e.g., Anselin (2003) and Elhorst (2010).

3 Data and Empirical Strategy

3.1 Data Description

For our empirical analysis, we use Eurostat (2023) NUTS-2 region-level data on net migration and population. Net migration is defined as the difference between the number of immigrants and the number of emigrants from a region during a given year. We compute regional net migration rates as the ratio between net migration during a given year and population at the beginning of the year. We consider all countries in the European Union over the period 2000-2019. The lowest net migration rates in our sample period can be observed in 2001 in Northern Central Bulgaria, Southern Central Bulgaria and West Romania with -4,5%, -4,2 % and -3,6 %, respectively. The highest net migration rates are observed in Lazio in 2013, North Aegean in 2018 and the Balearic Islands in 2002 with 5,7 %, 4,9 % and 4,2 %, respectively. These regions also account for the ten highest observed net migration rates in the sample period, which is in line with the literature documenting a significant immigration to amenity-rich coastal regions in the United States (Rappaport 2007; Partridge 2010; Winkler and Rouleau 2021).

Data on natural disasters is obtained from the International Disasters Database (EM-DAT) created by the Centre for Research on the Epidemiology of Disasters (CRED) (Guhapir, Below, and Hoyois 2023). Events are entered into the database if at least one of the following criteria is fulfilled: Ten or more people were reported as killed, 100 or more people were reported as affected, a state of emergency was declared by regional or national authorities, or international assistance was requested. When an event is entered into the database, information on locations affected by the event is provided as names of villages, cities, departments, provinces, districts and states. Generally, the geographical specification corresponds to the NUTS-2 level or lower, with the exception of Germany, where location information is only provided at the federal state level. We exclude Cyprus from our sample as no disasters data is available. To harmonize the disaster data with the NUTS-2 level

migration data, we geocode disasters using the R package `weed`.

In a next step, we construct region-year disaster counts by disaster type. Following the literature, we only focus on types of natural disasters which could potentially be driven by climate change (Saldaña-Zorrilla and Sandberg 2009; Drabo and Mbaye 2015; Conigliani, Costantini, and Finardi 2022). Additionally, we follow Boustan, Kahn, Rhode, and Yanguas (2020) and construct a severe disaster dummy that equals one if a region experienced a disaster resulting in 4 or more deaths, which is the median number of deaths for disasters with known fatality counts. As a robustness check, we also estimate a number of alternative specifications using different fatality thresholds. Table 1 presents summary statistics of the disaster types in our sample. The most common disaster types are floods and storms, which account for 71.5 % of the events in the sample period. Because only a very small number of events was reported for droughts and landslides in the sample period, we subsume these events as “Others”. The highest number of reported disasters in a region in a year are observed in Southern Central Bulgaria in 2007, Adriatic Croatia in 2003, North-Eastern Romania in 2004 and South Muntenia Romania in 2005, with six reported disasters each.

Spatial panel data models require balanced data. However, our data is slightly unbalanced, with information on net migration and employment missing for some regions, particularly toward the beginning of the sample period. Therefore, we follow the spatial econometrics literature (Belotti, Hughes, and Mortari 2017; Ma and Hofmann 2019) and use multiple imputation to create a balanced panel. Multiple imputation uses the distribution of the existing observations to simulate multiple sets of values for the missing observations. Estimates are adjusted to reflect uncertainty of missing data and then combined into overall estimates (Rubin 1996). More specifically, we employ Multiple Imputation by Chained Equations (MICE), which makes use of a sequence of univariate imputation methods with fully conditional specification of prediction equations (White, Royston, and Wood 2011).

Figure 2 shows disaster counts by NUTS-2 regions by type for the period 2000-2019. For some disaster types, disaster counts are geographically unevenly distributed, e.g., floods

occur predominantly in Southeastern regions of Europe, while heat waves and wildfires occur primarily in Central and Southern Europe.

Disaster type	(1) Event count	(2) Mean number of disasters, by region-year
Flood	282	0.162
Storm	205	0.174
Cold wave	73	0.094
Heat wave	44	0.052
Wildfire	44	0.022
Severe winter conditions	21	0.025
Other	12	0.014
Total disasters	681	0.543
Severe disasters	276	–

Note: Column 1 shows the number of individual disaster events in the EM-DAT dataset in the geographical area of the European Union for the period 2000-2019. Each event is counted once even if multiple regions are affected. Column 2 shows the mean number of disaster registered per region and year.

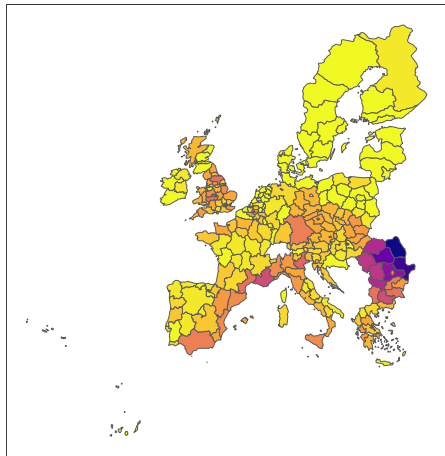
Table 1: Summary statistics

3.2 Econometric Model

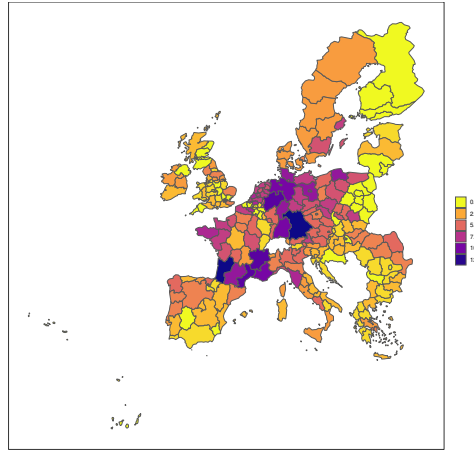
In a first step, we estimate the following baseline fixed effects model:

$$M_{i,t} = \beta_0 + D_{i,t,(t-1;t-3)}\beta_1 + \beta_2 EmplGrowth_{i,t-1} + \alpha_i + \mu_i t + \varepsilon_{i,t} \quad (1)$$

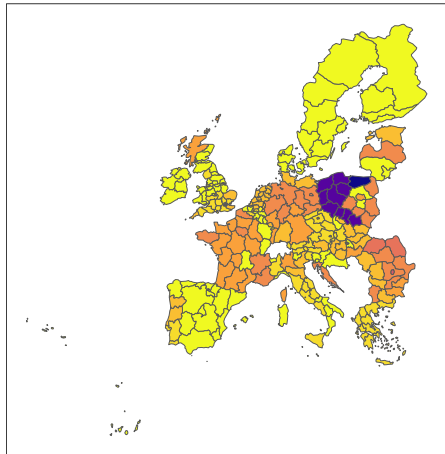
where $M_{i,t}$ is the net migration of region i in year t . $D_{i,t}$ is a vector of disaster counts of region i in year t . To examine potential delayed migration responses to disaster events, we include several time lags of disaster counts. α_i indicates region fixed effects to control for unobserved time-invariant heterogeneity. In addition, we include region-specific linear time trends to account for pre-existing regional migration trends (Roeckert and Kraehnert 2022). $\varepsilon_{i,t}$ is the error term. Because regional economic indicators are likely themselves affected by disaster events, including them in our specification may introduce an overcontrolling bias. Therefore, we follow Boustan, Kahn, Rhode, and Yanguas (2020) and include a measure of region-level employment growth as a proxy of local economic growth (Bartik (1991);



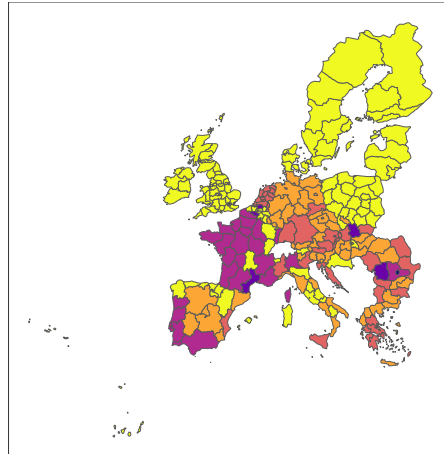
(a) Floods



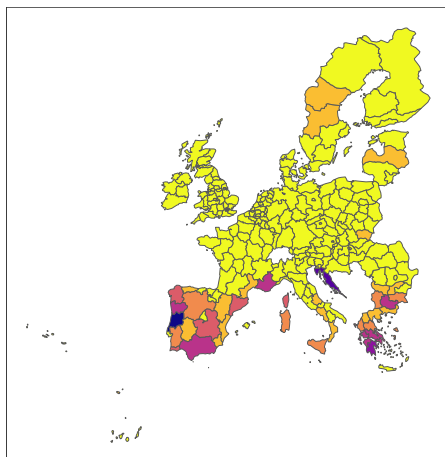
(b) Storms



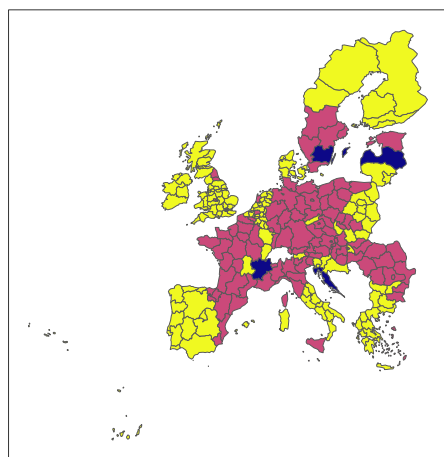
(c) Cold waves



(d) Heat waves



(e) Wildfires



(f) Severe winter conditions

Figure 2: Disaster counts by NUTS-2 region by type, 2000-2019

Blanchard and Katz (1992); Basso, D’Amuri, and Peri (2019)):

$$EmplGrowth_{i,t} = \sum_j \frac{E_{i,j,1999}}{E_{i,1999}} E_{c,j,t} \quad (2)$$

Thus, $EmplGrowth_{i,t}$ measures employment in country c in sector j in year t weighted by employment share of sector j in region i in 1999.

In a second step, we follow Saldaña-Zorrilla and Sandberg (2009) and Conigliani, Costantini, and Finardi (2022) and use our baseline model to test for the existence of spatial dependence. There are three types of spatial dependence that may potentially confound the estimation results (Elhorst 2010): The first type is spatial dependence of the error term, e.g., due to correlation of unobserved characteristics across neighboring regions. The second type is spatial dependence of the dependent variable, e.g., if net migration in region i is correlated with net migration in neighboring region j . The third type is spatial dependence of the independent variable, e.g. if there is a spatial clustering of regions affected by a natural disaster. While not controlling for the first type of spatial dependence may lead to inefficient estimates, not controlling for the second type may results in estimates that are both biased and inefficient. A full model accounting for all types of spatial dependence can thus be written as follows:

$$Y = \beta_0 + \rho WY + X\beta_1 + WX\theta + u \quad (3)$$

$$u = \lambda Wu + \varepsilon \quad (4)$$

Because our sample includes island regions, it is not possible to construct spatial lags using a contiguity-based weights matrix. Therefore, we use a row-standardized inverse distance-based weights matrix, indicated by W (J. LeSage and R. Pace 2009). As the full model is typically over-parameterized, we test for the first two types of spatial dependence using Lagrange multiplier (LM) tests. In addition, as suggested by the literature (Saldaña-Zorrilla

and Sandberg 2009; Ruysen and Rayp 2014; Zouabi 2021; Conigliani, Costantini, and Finardi 2022), we account for spatial spillover effects of natural disasters, i.e. disasters in region i affecting net migration in neighboring region j , and estimate spatial Durbin models (SDM). All spatial models are estimated via maximum likelihood using the `spm1` R package.

4 Results

Table 2 presents our baseline results. Column 1 estimates the effect of disaster events on net migration in the same period, while in columns 2, 3 and 4, disaster measures are lagged by 1, 2, and 3 periods, respectively. All models include region fixed effects and region-specific linear time trends. We find that experiencing a severe disaster event leads to a 0.09 percentage point decrease in the net migration rate in the same year, corresponding to an increase in net out-migration of 0.9 individuals per 1000 inhabitants. This result is consistent with the findings of Boustan, Kahn, Rhode, and Yanguas (2020) for the U.S., who observe a 1.5 percentage point decrease in net migration rates in response to severe disasters. In addition, column (3) indicates a positive migration response two years after a severe disaster event. A possible interpretation of this finding is that individuals who left the region in response to a severe disaster return after two years. Our findings thus support the general finding in the literature that natural disasters result in short-term relocation followed by return migration (Harper 2013; Cattaneo et al. 2019; Fussell and Castro 2022).

When comparing the effects of severe disasters with the effect of regional employment shocks on net migration, we find that the effects are similar in magnitude: A one standard deviation decrease in regional employment growth leads to an increase in net out-migration of 0.8 individuals per 1000 inhabitants. In this regard, our results differ from the findings of Boustan, Kahn, Rhode, and Yanguas (2020) for the U.S., who observe that the effect of severe disasters on net migration is about half as large as the effect of a large negative employment shock.

Furthermore, experiencing one additional storm event is associated with a 0.03 percentage point increase in net out-migration two years later. For cold waves, we find an increase in net in-migration three years later. Contrary to our expectations, we find positive effects of heat waves and wildfires on net migration in columns (1) and (2), which is in contrast to, e.g., Boustan, Kahn, Rhode, and Yanguas (2020) and Winkler and Rouleau (2021) who observe that these events encourage out-migration. However, column (1) suggests that flood events attract in-migrants in the same year they occur, which is in line with Boustan, Kahn, and Rhode (2012) and Boustan, Kahn, Rhode, and Yanguas (2020). Likewise, severe winter conditions are associated with net in-migration in the same year and net out-migration three years after an event.

To test for spatial dependence and determine the proper model specification, we follow Saldaña-Zorrilla and Sandberg (2009) and use the residuals from our baseline models to conduct LM tests for spatial lag and spatial error dependence. While both LM-error and LM-lag tests are statistically significant for all specifications, the LM-error test statistic is always larger than the LM-lag test statistic. In addition, when considering robust LM tests, the LM-error test is always significant while the LM-lag test is never significant. This indicates that the baseline model is misspecified and that the estimators are likely inefficient due to lack of stochastic independence between regions (Anselin 1988; Anselin et al. 1996). Therefore, the spatial error model should be used.

Table 3 shows the results of the spatial error model. The spatial autocorrelation coefficient of the error term λ is always positive and significant, indicating spatial autocorrelation of unobserved NUTS-2 region-level variables. We continue to find a positive effect of regional employment growth on net migration. Turning to the disaster events, we observe that the effects of severe disasters in columns (1) and (3) slightly decrease in magnitude but remain statistically significant. Additionally, the effects of floods, wildfires and cold waves in column (1), (2) and (4), respectively, remain unchanged. With respect to heat waves and storms, however, the effects on net migration in columns (1) and (3), respectively, are no longer

significant. Finally, the positive effect of severe winter conditions on net migration in the year an event occurred disappears; however, we continue to find a negative effect after three years.

While the results of the spatial error model account for the misspecification of our baseline model, they do not allow for any insight into potential spatial spillover effects of disaster events on net migration. Therefore, we also estimate a SDM which incorporates spatial lags of the dependent as well as the independent variables. The results are presented in Table 4. We observe that the spatial lag dependence parameter ρ is always positive and significant, which suggests a spatial clustering of NUTS-2 regions experiencing high or low levels of net migration. The effect of employment growth on net migration continues to be positive and significant. Likewise, results are unchanged for severe disasters.

When looking at severe disasters, we continue to find the same effects in columns (1) and (3). Interestingly, we observe a negative spatial spillover effect of severe disasters, i.e. severe disasters are associated with net out-migration in neighboring regions in the year they occur and the following year. Our interpretation of this finding is twofold: First, if region i is struck by a severe disaster, neighboring region $j \neq i$ may also be affected by the event, which may induce individuals in j to out-migrate. Second, individuals out-migrating from i in response to the severe disaster may prefer more distant, unaffected regions to neighboring and likely affected ones.

In contrast to the baseline and spatial error model results, we now find a negative effect of storms in the region the event occurred in (see column (1)) and positive spatial spillover effects in the year the event occurred in as well as the following year. This suggests that individuals tend to migrate to neighboring regions in response to storm events. This finding is consistent with e.g., the results of Eyer et al. (2018) and Loughran and Elliott (2019) who find that individuals primarily relocate to nearby counties.

Regarding the other disaster types, the effects on net migration in the same region stay largely unchanged. However, we find a number of spatial spillover effects that are difficult

to interpret with respect to their timing and/or direction: First, cold waves are associated with in-migration to neighboring regions after one year. Second, heat wave induce net in-migration in neighboring regions in the year they occur and the following year. Third, wildfires are associated with in-migration to neighboring regions only after three years but have no effect in previous periods. Fourth, we observe a positive effect of floods on net migration in neighboring regions after one year. Fifth, severe winter conditions induce in-migration to neighboring regions in the year they occur in. Finally, the spatial lag of the count of other disasters is positive after one year and negative after two and three years, while no effect can be observed in the region that the event was counted in.

5 Robustness Checks

In the previous sections, we employed variable definitions that follow previous literature. In particular, these include the construction of the severe disaster dummy variable (Boustan, Kahn, Rhode, and Yanguas 2020) and the choice of our spatial weights matrix (Saldaña-Zorrilla and Sandberg 2009; Conigliani, Costantini, and Finardi 2022). However, as the choice of these definitions involve some degree of arbitrariness, we conduct a number of robustness checks to asses whether our main findings remain unchanged for alternative variable definitions. The results are presented in the appendix.

First, in our main results we included a severe disaster dummy variable that equals one if a region experienced a disaster resulting in 4 or more deaths in a given year. In Table A1, we re-estimate our baseline results for different fatality thresholds. For fatality thresholds ranging from 2 to 7, we find a consistent negative effect of severe disasters on net migration

	<i>Dependent variable:</i>			
	Net migration rate			
	(1)	(2)	(3)	(4)
		Lag1	Lag2	Lag3
Severe disaster = 1	-0.089*** (0.022)	-0.008 (0.022)	0.061*** (0.020)	0.007 (0.020)
Storm count	-0.009 (0.016)	-0.017 (0.017)	-0.030** (0.015)	0.005 (0.015)
Cold wave count	-0.003 (0.022)	0.015 (0.022)	0.001 (0.020)	0.075*** (0.020)
Heat wave count	0.101*** (0.032)	0.041 (0.031)	-0.001 (0.028)	-0.005 (0.028)
Wildfire count	-0.015 (0.041)	0.082** (0.039)	0.022 (0.036)	0.018 (0.037)
Flood count	0.049*** (0.016)	0.011 (0.016)	-0.022 (0.015)	-0.0001 (0.015)
Severe winter conditions count	0.141*** (0.040)	0.038 (0.039)	-0.031 (0.036)	-0.118*** (0.036)
Other count	0.076 (0.058)	0.085 (0.053)	-0.073 (0.049)	-0.035 (0.052)
Employment growth lag1	0.049*** (0.004)	0.048*** (0.004)	0.054*** (0.003)	0.056*** (0.003)
Observations	4313	4313	4086	3859
R ²	0.320	0.316	0.377	0.377
Adjusted R ²	0.239	0.234	0.297	0.292
Region FE	Yes	Yes	Yes	Yes
Region FE * time trend	Yes	Yes	Yes	Yes
LM-error	436.96***	488.22***	262.8***	281.08***
LM-error, Robust	135.65***	158.04***	93.646***	107.86***
LM-lag	302.21***	332.97***	169.49***	173.69***
LM-lag, Robust	0.900	2.7928*	0.33166	0.470

Note: Baseline results using fixed effects estimations. The dependent variable is the net migration rate of region i in year t . The sample period is 2000 to 2019. LM indicates Lagrange multiplier test. In columns (2), (3) and (4), disaster counts are lagged by one, two and three years, respectively. Standard errors in parentheses. *p<0.1; **p<0.05; ***p<0.01.

Table 2: Baseline results

	<i>Dependent variable:</i>			
	Net migration rate			
	(1)	(2)	(3)	(4)
		Lag1	Lag2	Lag3
λ	0.813*** (0.028)	0.815*** (0.028)	0.774*** (0.034)	0.796*** (0.032)
Severe disaster = 1	-0.076*** (0.021)	-0.000 (0.002)	0.056*** (0.019)	0.002 (0.019)
Storm count	-0.028* (0.016)	-0.022 (0.016)	-0.025* (0.015)	-0.006 (0.015)
Cold wave count	0.019 (0.023)	0.017 (0.023)	0.015 (0.021)	0.097*** (0.021)
Heat wave count	0.045 (0.032)	0.015 (0.032)	0.010 (0.029)	0.017 (0.029)
Wildfire count	-0.030 (0.039)	0.086** (0.037)	0.032 (0.034)	0.003 (0.035)
Flood count	0.046*** (0.015)	0.004 (0.015)	-0.015 (0.014)	0.002 (0.014)
Severe winter conditions count	0.079 (0.048)	0.050 (0.048)	-0.081* (0.043)	-0.119*** (0.043)
Other count	0.063 (0.057)	0.038 (0.052)	-0.052 (0.048)	0.018 (0.051)
Employment growth lag1	0.052*** (0.004)	0.052*** (0.004)	0.055*** (0.004)	0.057*** (0.004)
Observations	4313	4313	4086	3859
Log likelihood	-13697.37	-13707.34	-12463.17	-11590.51
Region FE	Yes	Yes	Yes	Yes
Region FE * time trend	Yes	Yes	Yes	Yes

Note: Spatial error model results using maximum likelihood estimations.

The dependent variable is the net migration rate of region i in year t .

The sample period is 2000 to 2019. λ indicates the spatial error dependence parameter. In columns (2), (3) and (4), disaster counts are lagged by one, two and three years, respectively. Standard errors in parentheses. *p<0.1;

p<0.05; *p<0.01.

Table 3: Spatial error model results

	<i>Dependent variable:</i>			
	Net migration rate			
	(1)	(2) Lag1	(3) Lag2	(4) Lag3
ρ	0.752*** (0.029)	0.784*** (0.027)	0.717*** (0.035)	0.725*** (0.033)
Severe disaster = 1	-0.067*** (0.021)	0.005 (0.021)	0.055*** (0.019)	0.002 (0.019)
SL Severe disaster = 1	-0.313** (0.140)	-0.361*** (0.138)	0.023 (0.130)	0.125 (0.130)
Storm count	-0.035** (0.016)	-0.023 (0.016)	-0.023 (0.015)	-0.008 (0.015)
SL Storm count	0.220*** (0.074)	0.179** (0.071)	-0.027 (0.065)	0.035 (0.065)
Cold wave count	0.021 (0.023)	0.016 (0.023)	0.011 (0.021)	0.094*** (0.021)
SL Cold wave count	0.157* (0.084)	0.208** (0.082)	0.033 (0.077)	-0.103 (0.075)
Heat wave count	0.037 (0.033)	0.005 (0.032)	0.009 (0.029)	0.017 (0.029)
SL Heat wave count	0.263** (0.116)	0.225** (0.110)	-0.071 (0.103)	-0.162 (0.103)
Wildfire count	-0.031 (0.039)	0.089** (0.037)	0.033 (0.035)	0.000 (0.035)
SL Wildfire count	-0.111 (0.215)	-0.057 (0.202)	-0.150 (0.184)	0.415** (0.189)
Flood count	0.044*** (0.016)	-0.000 (0.015)	-0.010 (0.014)	0.005 (0.014)
SL Flood count	0.137 (0.102)	0.215** (0.099)	-0.161* (0.093)	-0.097 (0.092)
Severe winter conditions count	0.068 (0.049)	0.046 (0.049)	-0.082* (0.044)	-0.119*** (0.044)
SL Severe winter conditions count	0.224** (0.110)	0.143 (0.108)	-0.007 (0.100)	-0.097 (0.102)
Other count	0.049 (0.062)	-0.006 (0.055)	-0.018 (0.051)	0.065 (0.054)
SL Other count	0.455 (0.318)	0.864*** (0.298)	-0.612** (0.272)	-1.075*** (0.312)
Employment growth lag1	0.039*** (0.004)	0.040*** (0.037)	0.046*** (0.004)	0.049*** (0.004)
Observations	4313	4313	4086	3859
Log likelihood	-1777.906	-1785.075	-1279.646	-1133.11
Region FE	Yes	Yes	Yes	Yes
Region FE * time trend	Yes	Yes	Yes	Yes

Note: Spatial Durbin model results using maximum likelihood estimations. The dependent variable is the net migration rate of region i in year t . The sample period is 2000 to 2019. ρ indicates the spatial lag dependence parameter. SL indicates spatial lags. In columns (2), (3) and (4), disaster counts are lagged by one, two and three years, respectively. Standard errors in parentheses. *p<0.1; **p<0.05; ***p<0.01.

Table 4: Spatial Durbin model results

in the same year (column (1)). For thresholds larger than 7, we find that standard errors increase and estimates are generally no longer significant. However, the positive effect on net migration after two years found in our main results is not consistent across fatality thresholds (column (2)). Only for the fatality thresholds 4 and 6 we find a positive effect.

Second, we used a spatial weights matrix with inverse distance weights with no distance threshold in our spatial panel models. In Tables A2 to A5, we re-estimate our results using two alternative spatial weights matrices with distance thresholds at 1000 and 1500 km, i.e., weights for region-pairs with a distance greater than the respective threshold are set to zero (Elhorst 2014).² The results are very similar to our main findings.

Finally, we assess whether our results for severe disasters are driven by certain countries in the European Union by conducting a leave-one-out analysis. For each individual country, we re-estimate our baseline results excluding that country from the sample. The resulting effects of severe disasters on net migration by time lag are shown in Figure A1. Our findings remain statistically significant for all countries (see Figures A1a and A1c). Notably, the effects slightly decrease in magnitude when excluding Spain.

6 Conclusion

Recent decades have seen an increase in the frequency of climate-related natural disasters in the European Union. However, while a considerable number of studies have analyzed the relationship between natural disasters and migration for the U.S. and other areas, little research has been conducted for Europe (Hunter 2018; Piguet, Kaenzig, and Guélat 2018).

In this paper, we attempt to close this gap in the literature and investigate the impact of climate-related natural disasters on regional migration in the European Union during the period 2000-2019. Employing spatial econometric methods, we find that experiencing a severe disaster leads to a 0.09 percentage point decrease in the net migration rate at the

²For distance thresholds less than 1000 km the resulting spatial weights matrix would include rows and columns with only zeros for a number of island regions.

NUTS-2 region level, corresponding to an increase in net out-migration of 0.9 individuals per 1000 inhabitants. This effect is similar in magnitude to a large negative employment shock, which underlines that the impact of climate-related severe disasters is economically significant. In addition, we find a positive effect of severe disasters lagged by two years on net migration of 0.6 individuals per 1000 inhabitants, which we interpret as return migration of individuals who had relocated in response to a severe disaster event. Thus, our findings with regard to severe disasters are in line with the results of recent literature for the U.S. (Boustan, Kahn, Rhode, and Yanguas 2020).

When using spatial Durbin models, we observe a negative spatial spillover effect of severe disasters on net migration, suggesting that neighboring regions may also be affected by the disasters, which may induce individuals in those regions to out-migrate. For milder disaster events, we find no conclusive evidence that disasters are driving regional migration.

As the frequency and severity of climate-related natural disasters is projected to increase in the coming decades, the costs of adaptation and mitigation measures are likely to increase. Policymakers should take migration as an adaptation response into account when designing such measures. Finally, one limitation of our paper is that our data does not allow us to capture heterogeneity in migration responses across different socio-economic groups. Thus, future research should investigate how migration responses differ across age, skill and income levels as well as factors such as risk perception, loss aversion and social networks.

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Appendix

Severe disaster fatality thresholds	<i>Dependent variable:</i>			
	(1)	Net migration rate		
		(2) Lag1	(3) Lag2	(4) Lag3
2	-0.062*** (0.023)	-0.024 (0.022)	0.032 (0.021)	0.034 (0.021)
3	-0.060*** (0.022)	-0.026 (0.022)	0.036* (0.020)	0.024 (0.020)
4	-0.089*** (0.022)	-0.008 (0.022)	0.061*** (0.020)	0.007 (0.020)
5	-0.092*** (0.021)	-0.015 (0.021)	0.027 (0.020)	-0.011 (0.020)
6	-0.059*** (0.022)	-0.010 (0.022)	0.054*** (0.020)	-0.048** (0.020)
7	-0.069*** (0.022)	-0.006 (0.022)	0.023 (0.021)	-0.041** (0.021)
8	-0.039* (0.023)	-0.007 (0.023)	0.029 (0.021)	-0.009 (0.021)
9	-0.027 (0.024)	0.055** (0.023)	0.042* (0.022)	-0.049** (0.022)
10	-0.033 (0.023)	0.014 (0.023)	-0.026 (0.022)	-0.075*** (0.022)
20	0.042 (0.030)	0.048* (0.029)	-0.012 (0.026)	0.018 (0.027)
30	-0.004 (0.032)	-0.082*** (0.031)	-0.020 (0.028)	-0.035 (0.029)
40	-0.055* (0.032)	-0.044 (0.031)	-0.028 (0.028)	-0.016 (0.029)
50	-0.063** (0.032)	-0.069** (0.031)	-0.019 (0.029)	-0.013 (0.029)

Note: Baseline estimations for alternative severe disaster fatality thresholds. Events are classified as severe disasters if the total number of deaths is equal to or greater than the threshold in each row. The dependent variable is the net migration rate of region i in year t . The sample period is 2000 to 2019. In columns (2), (3) and (4), disaster counts are lagged by one, two and three years, respectively. Standard errors in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table A1: Robustness checks: alternative severe disaster fatality thresholds

	<i>Dependent variable:</i>			
	Net migration rate			
	(1)	(2)	(3)	(4)
		Lag1	Lag2	Lag3
λ	0.690*** (0.030)	0.698*** (0.029)	0.649*** (0.033)	0.670*** (0.033)
Severe disaster = 1	-0.071*** (0.020)	0.002 (0.020)	0.058*** (0.019)	0.003 (0.019)
Storm count	-0.021 (0.016)	-0.020 (0.016)	-0.031** (0.015)	-0.008 (0.015)
Cold wave count	0.021 (0.023)	0.025 (0.023)	0.009 (0.021)	0.086*** (0.021)
Heat wave count	0.041 (0.032)	0.010 (0.031)	-0.001 (0.028)	0.013 (0.028)
Wildfire count	-0.026 (0.039)	0.0873** (0.037)	0.025 (0.034)	0.004 (0.035)
Flood count	0.043*** (0.015)	0.001 (0.015)	-0.014 (0.014)	0.001 (0.014)
Severe winter conditions count	0.081* (0.047)	0.036 (0.047)	-0.074* (0.042)	-0.111*** (0.042)
Other count	0.046 (0.060)	-0.068 (0.054)	-0.036 (0.050)	0.042 (0.053)
Employment growth lag1	0.052*** (0.004)	0.051*** (0.004)	0.055*** (0.004)	0.057*** (0.004)
Observations	4313	4313	4086	3859
Log likelihood	-13665.78	-13672.57	-12424.11	-11551.72
Region FE	Yes	Yes	Yes	Yes
Region FE * time trend	Yes	Yes	Yes	Yes

Note: Spatial error model results using maximum likelihood estimations.

The dependent variable is the net migration rate of region i in year t .

The sample period is 2000 to 2019. λ indicates the spatial error dependence

parameter. In columns (2), (3) and (4), disaster counts are lagged by one,

two and three years, respectively. Standard errors in parentheses. * $p < 0.1$;

** $p < 0.05$; *** $p < 0.01$.

Table A2: Robustness checks: spatial error model results using inverse distance weights cut off at 1000 km

	<i>Dependent variable:</i>			
	Net migration rate			
	(1)	(2)	(3)	(4)
		Lag1	Lag2	Lag3
ρ	0.643*** (0.030)	0.650*** (0.030)	0.611*** (0.032)	0.619*** (0.032)
Severe disaster = 1	-0.064*** (0.021)	0.005 (0.020)	0.057*** (0.019)	0.004 (0.019)
SL Severe disaster = 1	-0.196** (0.082)	-0.163** (0.081)	-0.057 (0.075)	0.026 (0.076)
Storm count	-0.027* (0.016)	-0.021 (0.016)	-0.030** (0.015)	-0.009 (0.015)
SL Storm count	0.124** (0.051)	0.094 (0.050)	0.024 (0.045)	0.052 (0.046)
Cold wave count	0.027 (0.023)	0.026 (0.023)	0.010 (0.021)	0.089*** (0.021)
SL Cold wave count	0.064 (0.055)	0.077 (0.055)	0.036 (0.051)	-0.084* (0.050)
Heat wave count	0.032 (0.032)	-0.002 (0.032)	-0.004 (0.029)	0.013 (0.029)
SL Heat wave count	0.208** (0.082)	0.138* (0.080)	0.015 (0.074)	-0.083 (0.073)
Wildfire count	-0.031 (0.039)	0.089** (0.037)	0.028 (0.034)	0.008 (0.035)
SL Wildfire count	0.016 (0.169)	0.053 (0.161)	-0.062 (0.147)	0.219 (0.152)
Flood count	0.042*** (0.015)	-0.001 (0.015)	-0.013 (0.014)	0.000 (0.014)
SL Flood count	0.078 (0.060)	0.092 (0.057)	-0.034 (0.053)	0.011 (0.052)
Severe winter conditions count	0.064 (0.049)	0.032 (0.049)	-0.092** (0.045)	-0.116** (0.044)
SL Severe winter conditions count	0.173** (0.085)	0.061 (0.083)	0.091 (0.076)	-0.010 (0.076)
Other count	0.038 (0.063)	-0.111** (0.056)	-0.029 (0.052)	0.048 (0.054)
SL Other count	0.212 (0.146)	0.554*** (0.142)	-0.066 (0.131)	-0.254* (0.140)
Employment growth lag1	0.039*** (0.003)	0.039*** (0.004)	0.044*** (0.003)	0.047*** (0.003)
Observations	4313	4313	4086	3859
Log likelihood	-1740.806	-1746.856	-1241.154	-1097.642
Region FE	Yes	Yes	Yes	Yes
Region FE * time trend	Yes	Yes	Yes	Yes

Note: Spatial Durbin model results using maximum likelihood estimations. The dependent variable is the net migration rate of region i in year t . The sample period is 2000 to 2019. ρ indicates the spatial lag dependence parameter. SL indicates spatial lags. In columns (2), (3) and (4), disaster counts are lagged by one, two and three years, respectively. Standard errors in parentheses. *p<0.1; **p<0.05; ***p<0.01.

Table A3: Robustness checks: spatial Durbin model results using inverse distance weights cut off at 1000 km

	<i>Dependent variable:</i>			
	Net migration rate			
	(1)	(2)	(3)	(4)
		Lag1	Lag2	Lag3
λ	0.787*** (0.029)	0.790*** (0.029)	0.747*** (0.034)	0.768*** (0.033)
Severe disaster = 1	-0.074*** (0.020)	0.002 (0.020)	0.058*** (0.019)	0.001 (0.019)
Storm count	-0.027* (0.016)	-0.022 (0.016)	-0.027* (0.015)	-0.006 (0.015)
Cold wave count	0.018 (0.023)	0.016 (0.023)	0.012 (0.021)	0.094*** (0.021)
Heat wave count	0.040 (0.032)	0.012 (0.032)	0.004 (0.029)	0.016 (0.028)
Wildfire count	-0.024 (0.039)	0.091** (0.037)	0.032 (0.034)	0.005 (0.035)
Flood count	0.045*** (0.015)	0.001 (0.015)	-0.015 (0.014)	0.002 (0.014)
Severe winter conditions count	0.080* (0.048)	0.042 (0.048)	-0.082* (0.043)	-0.012*** (0.043)
Other count	0.057 (0.059)	-0.008 (0.053)	-0.044 (0.049)	0.025 (0.052)
Employment growth lag1	0.052*** (0.004)	0.051*** (0.004)	0.054*** (0.004)	0.057*** (0.004)
Observations	4313	4313	4086	3859
Log likelihood	-13680.45	-13689.76	-12443.18	-11571.26
Region FE	Yes	Yes	Yes	Yes
Region FE * time trend	Yes	Yes	Yes	Yes

Note: Spatial error model results using maximum likelihood estimations.

The dependent variable is the net migration rate of region i in year t .

The sample period is 2000 to 2019. λ indicates the spatial error dependence

parameter. In columns (2), (3) and (4), disaster counts are lagged by one,

two and three years, respectively. Standard errors in parentheses. * $p < 0.1$;

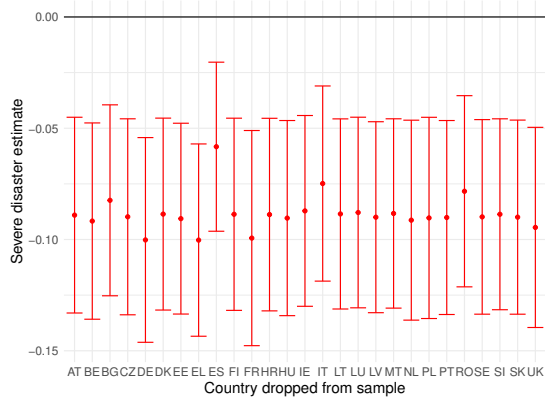
** $p < 0.05$; *** $p < 0.01$.

Table A4: Robustness checks: spatial error model results using inverse distance weights cut off at 1500 km

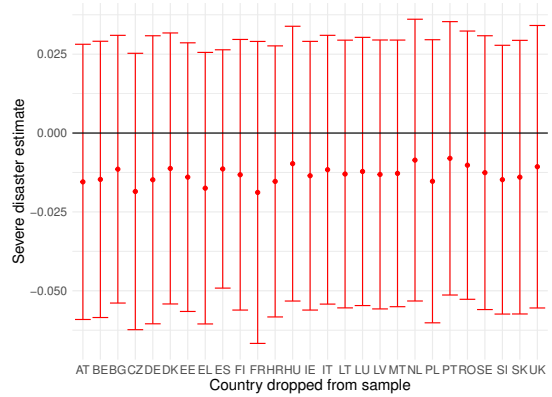
	<i>Dependent variable:</i>			
	Net migration rate			
	(1)	(2)	(3)	(4)
		Lag1	Lag2	Lag3
ρ	0.731*** (0.029)	0.752*** (0.028)	0.692*** (0.034)	0.699*** (0.033)
Severe disaster = 1	-0.065*** (0.021)	0.006 (0.021)	0.057*** (0.019)	0.001 (0.019)
SL Severe disaster = 1	-0.267** (0.108)	-0.028*** (0.011)	-0.051 (0.100)	0.074 (0.100)
Storm count	-0.034** (0.016)	-0.023 (0.016)	-0.026* (0.015)	-0.008 (0.015)
SL Storm count	0.191*** (0.062)	0.015** (0.060)	0.011 (0.055)	0.053 (0.055)
Cold wave count	0.019 (0.023)	0.013 (0.023)	0.012 (0.021)	0.098*** (0.021)
SL Cold wave count	0.128* (0.069)	0.017** (0.069)	0.037 (0.064)	-0.122* (0.063)
Heat wave count	0.032 (0.032)	0.002 (0.032)	0.004 (0.029)	0.017 (0.029)
SL Heat wave count	0.250*** (0.096)	0.019** (0.093)	-0.018 (0.086)	-0.137 (0.086)
Wildfire count	-0.027 (0.039)	0.095** (0.037)	0.035 (0.034)	0.006 (0.035)
SL Wildfire count	-0.076 (0.199)	-0.074 (0.188)	-0.200 (0.171)	0.312* (0.177)
Flood count	0.043*** (0.015)	-0.002 (0.015)	-0.013 (0.014)	0.003 (0.014)
SL Flood count	0.105 (0.080)	0.163** (0.077)	-0.073 (0.071)	-0.035 (0.071)
Severe winter conditions count	0.068 (0.049)	0.039 (0.049)	-0.089** (0.044)	-0.121*** (0.044)
SL Severe winter conditions count	0.201** (0.096)	0.106 (0.094)	0.072 (0.087)	-0.032 (0.087)
Other count	0.044 (0.062)	-0.048 (0.055)	-0.030 (0.051)	0.037 (0.054)
SL Other count	0.324 (0.203)	0.066*** (0.020)	-0.185 (0.180)	-0.410** (0.195)
Employment growth lag1	0.039*** (0.004)	0.040*** (0.004)	0.044*** (0.003)	0.048*** (0.004)
Observations	4313	4313	4086	3859
Log likelihood	-1757.918	-1765.788	-1260.178	-11571.26
Region FE	Yes	Yes	Yes	Yes
Region FE * time trend	Yes	Yes	Yes	Yes

Note: Spatial Durbin model results using maximum likelihood estimations. The dependent variable is the net migration rate of region i in year t . The sample period is 2000 to 2019. ρ indicates the spatial lag dependence parameter. SL indicates spatial lags. In columns (2), (3) and (4), disaster counts are lagged by one, two and three years, respectively. Standard errors in parentheses. *p<0.1; **p<0.05; ***p<0.01.

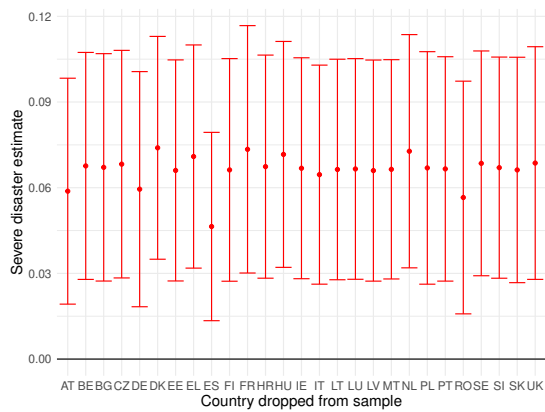
Table A5: Robustness checks: spatial Durbin model results using inverse distance weights cut off at 1500 km



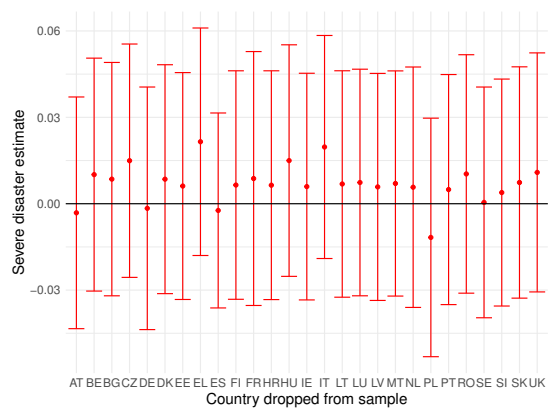
(a) Same period



(b) One-year lag



(c) Two-year lag



(d) Three-year lag

Figure A1: Leave-one-out estimates of severe disaster effect on net migration by country and time lag

Chapter 4

The Distributional Effects of CO₂ Pricing at Home and at the Border on German Income Groups

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The distributional effects of CO₂ pricing at home and at the border on German income groups

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ABSTRACT

While climate policy studies are widespread, fully fledged computable general equilibrium (CGE) model analyses of distributional policy effects are challenging because the required data and approaches are not directly available. To ease such distributional analyses, we provide a step-by-step “recipe” for disaggregating a country-specific representative consumer of a CGE model. Using this “recipe”, we implement German household survey data in a global CGE model by distinguishing three income groups of the German representative consumer. We find that the negative consumption effect of CO₂ pricing is highest for the low-income group, whereas the negative income effect is highest for the high-income group and exceeds the consumption effect. The low-income group benefits most from (per capita-based redistribution of) carbon pricing revenues and receives social transfers such that poor households can be better off with such climate policies than without them. CO₂ pricing of imports at the (EU) border slightly strengthens these distributional effects and is mainly beneficial for the low-income group. The geographic extension of emissions trading within a “climate club” leads to substantial efficiency gains that are beneficial for Germany and the EU.

1. Introduction

For public policy discussions, it has become increasingly important to extend the analysis of policy-induced welfare effects towards a deeper understanding of distributional (inequality) effects across households (consumers). Thus, recent economic studies have examined the distributional effects of climate policy on households with different income levels to obtain socially sensitive insights for policymakers with mixed results (see the review and the meta-analyses by [Wang et al., 2016](#) and [Ohlendorf et al., 2021](#)). The distributional effects of carbon border adjustments and of “climate clubs” on household income groups are novel aspects analyzed in this article.

In this article, we make three contributions. First, we contribute to the literature by applying an elaborated method to new data with a regional focus on Germany. Previous studies on distributional effects applied statistical methods to micro (household) data ([Wang et al., 2016](#); [Ohlendorf et al., 2021](#)), sometimes by combining macroeconomic data generated by numerical models with microeconomic (household) data (for an overview, see [Bourguignon and Bussolo, 2013](#)), e.g., via the integration of a microeconomic

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(household) approach in a macroeconomic model (e.g., Labandeira et al., 2009; Rausch et al., 2011; Dissou and Siddiqui, 2014; Goulder et al., 2019), particularly via so-called microsimulations (e.g., Landis et al., 2019; Buddelmeyer et al., 2012; Durand-Lasserre et al., 2015).

The disaggregation of representative consumers in computable general equilibrium (CGE) models is a challenging endeavor. Böhringer et al. (2021), for example, summarize the distributional effects of climate policy for meeting the goals of the Paris Agreement in Germany (UOL model), Norway (SNoW model), Spain (BC3 model), India (IEG model), and 11 or 21 European Union (EU) countries (JRC-GEM-E3-EUROMOD-ITT and CEPE model) (for results, see below). Cunha Montenegro et al. (2019) split consumers in EU countries into five income groups to study EU climate policies in a CGE model. In their CGE model, Kim and Kim (2003) distinguish among 14 Korean regions and ten income groups to study urban development strategies. In another CGE model, Jung et al. (2017) distinguish among 20 Korean income groups and show that skill- and capital-biased technical progress increases inequality. In a CGE model of China, Huang et al. (2019) combine income groups with a rural–urban distinction between households and find that the wise redistribution of climate policy revenues can reduce inequality.

Contributing to this literature, we derive consumer income groups from German household data and integrate them into a new straightforward CGE model calibrated to the GTAP 10¹ data (Aguilar et al., 2019) for the benchmark year 2014 (sector aggregation derived from Pothén and Hübler, 2018). As a result, complex general equilibrium (policy) effects are directly and explicitly included in the distributional analysis, and different from statistical micro data studies, consumption expenditure and income effects are calculated directly and simultaneously within the general equilibrium.

Second, as a methodological contribution that renders consumer disaggregation easily accessible, applicable and transparent, we introduce a model-independent step-by-step “recipe” for modelers who intend to implement different income groups of a representative consumer in an intuitive way.

Third, as a policy contribution, we not only investigate CO₂ pricing within Germany as a member of the European Union Emissions Trading Scheme (EU ETS) but also at the EU ETS border: the new Carbon Border Adjustment Mechanism (CBAM) planned for implementation in the EU in 2026 after a transition phase from 2023 to 2025.² Such a policy levies a CO₂ price on imports from countries without CO₂ pricing according to the imports’ total CO₂ contents from all production steps and intermediate goods inputs. As a result, imports are subject to the same CO₂ price as if they were produced domestically under the established emissions pricing scheme. As a consequence, the consumption of goods becomes more expensive. At the same time, the price decline of domestic production factors is mitigated because consumption shifts from imports to domestic production. By shedding light on these mechanisms, we contribute to the model-based literature on carbon border adjustment policies (see the model comparison study summarized by Böhringer et al., 2012), which has so far, to the best of our knowledge, not examined distributional effects across heterogeneous consumers within countries.

Additionally, we consider a so-called “climate club” that was announced by the German chancellor and launched at the COP³ 28 in Dubai. Such a climate club with a common climate policy approach (e.g., a minimum CO₂ price) implemented within its political scope was, for example, recommended by Nordhaus (2015). It can constitute a stable form of international cooperation if there is a penalty in the form of a tariff imposed on non-participants (Nordhaus, 2021). Weitzel et al. (2012), for example, find in a CGE model analysis that the strategic (terms-of-trade) gain from carbon border adjustment dominates their environmental benefit (CO₂ reduction) and that high tariff rates are required to incentivize the formation of stable climate policy coalitions. We contribute to the broad literature on international cooperation (e.g., IPCC, 2014; Finus et al., 2013) and climate policy coalitions (e.g., Ghosh et al., 2012; Paroussos et al., 2019; Shaw and Fu, 2020; Perdana and Vielle, 2023) by analyzing the distributional effects of climate clubs on household income groups. Related to our work, Chepeliev et al. (2021) assess the effects of Nationally Determined Contributions (NDCs) on the household income distribution within international climate policy coalitions (without carbon border adjustments). They combine a CGE model with microsimulations and find that global cooperation significantly reduces the burden on the poor.

Based on the input–output data and the actual CO₂ emissions reductions in 2014, we find the following results for three German consumer groups: low, middle and high income. (We compute descriptive statistics for five and ten income groups too. Our approach can be used to generate any reasonable number of consumers.)

First, whereas domestic CO₂ pricing is beneficial for low-income households (1.3% welfare surplus), it is disadvantageous for high-income households (1.2% welfare loss) and to a smaller extent for middle-income households (0.5% welfare loss). While this distributional pattern (with negative relative welfare effects increasing in income) is in line with that in other studies (e.g., Siriwardana et al., 2013; Sajeewani et al., 2015), it is interesting that the low-income group *gains* from climate policy. This occurs in our analysis because all income groups receive the same amount of revenue from CO₂ pricing on the basis of a fair per capita redistribution scheme (cf. Klenert et al., 2018 and the discussion/implementation of climate bonus payments in Germany and Austria), which dominates the expenditure and income effect (explained in the following section) in the low-income group. Additionally, low-income households receive substantial social redistribution transfers that dampen any climate policy-induced effects. A positive low-income effect also occurs in the CGE model analysis of the United States of America (USA) by Goulder et al. (2019). Likewise, Cunha Montenegro et al. (2019) find positive income growth effects for the low-income group of EU countries under specific EU climate policy scenarios. Labandeira et al. (2009) even find a positive effect of energy taxation for *all* income groups, with larger effects for poorer households in Spain.

¹ Global Trade Analysis Project, consistent global input–output database, version 10.

² https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661

³ Conference of the Parties.

Second, in accordance with the outcomes for the EU, Canada and the USA (Böhringer et al., 2021; Rausch and Mowers, 2014; Dissou and Siddiqui, 2014; Goulder et al., 2019), in our results, consumption expenditure effects are regressive. In particular, domestic climate policy causes a slightly stronger consumption price index increase for low-income German households than for middle-income German households, whose consumption price index increase is in turn slightly stronger than that for high-income households (across all groups, approximately 0.8%). Feindt et al. (2021), by contrast, find a neutral or progressive effect of carbon pricing within EU countries.

Third, (factor) income effects, on the contrary, are progressive, as shown for the EU, Canada and the USA (Böhringer et al., 2021; Dissou and Siddiqui, 2014; Goulder et al., 2019). This occurs because richer households own a larger portion of the production factors than poorer ones do, and factor prices are often dampened by climate policy. In our study, natural resource rents, including rents from fossil fuel ownership, drop sharply (by approximately 48.1%) due to CO₂ pricing. Labor income and, to a slightly larger extent, capital income decline moderately (by approximately 0.8% each). Land rents, on the other hand, increase significantly (by approximately 3.8%): intuitively, renewable energy expansion requires land and raises land rents.⁴ The land rent increase, however, is dominated by declining prices for the remaining factors. Hence, overall, German climate policy effects are progressive (cf. Beck et al., 2015).

Fourth, similar to domestic CO₂ pricing, additional CO₂ pricing of imports at the EU border (CBAM) (with equal per capita-based distribution of CBAM revenues across the income groups and without CO₂-content-related subsidies for exports) is more beneficial for the low-income group (approximately 0.1 percentage point gain) than for the middle-income group and the high-income group (very minor loss). The high-income group benefits most from mitigated price decreases of capital, labor and natural resources but it suffers about equally from increased consumption prices because it has not only the highest income but also the largest consumption of all income groups. Overall, CO₂ pricing of imports slightly strengthens the distributional effects of domestic CO₂ pricing and dampens the climate policy-induced welfare losses of Germany and the EU ETS countries.

Fifth, if policymakers were to redistribute the revenues from domestic CO₂ pricing between high-, middle- and low-income groups such that all groups become roughly equally compensated and the welfare loss is close to the economy-wide loss (0.6%) in all groups, then ceteris paribus, the low-income group will receive approximately 12% of the revenues, the middle-income group will receive 29% and the high-income group will receive 59%.

Sixth, when EU policymakers are able to encourage more economies in the world to join a climate club with a joint CO₂ price, the EU ETS countries will basically gain more when more countries join. For example, in a climate club of the EU (ETS) together with the remaining G7⁵ countries, China and India, the EU ETS countries can recuperate approximately half their climate policy costs. Via lower climate policy costs, the distributional effects on German income groups become less pronounced as well. The low-income group, however, suffers most from the resulting increase in consumption prices.

The article proceeds as follows. Section 2 explains our model-independent approach to disaggregating a typical representative consumer based on household data. We choose Germany, 18 goods and three income groups for an exemplary application. Section 3 describes a new corresponding CGE model with consumption, production, trade, complex intermediate goods linkages and CO₂ emissions. The consumer split derived in Section 2 enters this model here. Section 4 analyzes the distributional effects of CO₂ pricing in Germany and at the EU border based on this model. It discusses the robustness and the implications of the results. Section 5 concludes the article. Appendix A provides further details and statistics illustrating consumer disaggregation. Appendix B provides further details, numbers and figures characterizing the model.

2. Disaggregation

The following procedure can be applied to analyze the distributional effects of policies on income groups in a country or region of a (macroeconomic) model. We start with a formal definition of consumption and relevant sectors. Then, we explain the disaggregation of consumer income groups and present the disaggregation results for Germany as an illustrative example. For further details on the data sources, data aggregation, sector correspondences and descriptive results, please see Appendix A.

2.1. Foundation

This subsection describes a standard general description of consumption that can be part of any economic model. This will be the foundation of the consumer disaggregation procedure.

Following standard microeconomic theory and the model setup in Pothen and Hübler (2018), ch. 2.2, in each region s , a representative consumer chooses the optimal consumption bundle C_s of m goods and services (in the following, goods always include services) indexed as i and measured as output quantities $Y_{C,s,i}^{DM}$ to maximize utility derived from consumption C_s . P_s indicates a corresponding price index for the consumption bundle of goods. The bundle $Y_{C,s,i}^{DM}$ contains goods that are domestically produced in the same region/country s or imported from other countries/regions r . Domestically produced and imported goods are usually combined via a constant elasticity of substitution (CES) function. Hence, the consumer has implicit (nested) CES preferences over goods i . The exemplary CES functions used for the model application of this article are displayed in Appendix Figures B1 and B2.

⁴ Although renewable energies are not explicitly represented in the model, within the power sector, fossil fuels are substituted by land (and capital etc.).

⁵ Canada, France, Germany, Italy, Japan, the United Kingdom and the United States.

According to the Solow growth model philosophy, the representative consumer spends a fixed fraction ξ_s of her total income I_s on consumption, while the remaining fraction $(1 - \xi_s)$ is saved, i.e., savings expressed in pecuniary terms read $P_s S_s = (1 - \xi_s)I_s$. Thus, the value of total consumption is maximized, and the balanced budget condition *expenditures = income* always holds.

$$\begin{aligned} \max_{Y_{C,i,s}^{DM}, C_s} C_s, C_s &= CES_i(Y_{C,i,s}^{DM}) \\ \text{s. t. } P_s C_s &= \xi_s I_s \end{aligned} \quad (1)$$

The representative consumer of each region s is endowed with region-specific quantities of the production factors (inputs), for example, capital \bar{K}_s , labor \bar{L}_s , land \bar{N}_s and (natural) resources $\bar{R}_{s,i}$ (where resources are available only in relevant sectors i , such as the mining of fossil fuels). The consumer supplies them inelastically and receives (factor income) Θ_s depending on the corresponding endogenous factor prices P_s^K , P_s^L , P_s^N and $P_{s,i}^R$ (Pothen and Hübler, 2018):

$$\Theta_s = P_s^K \bar{K}_s + P_s^L \bar{L}_s + P_s^N \bar{N}_s + \sum_i P_{s,i}^R \bar{R}_{s,i} \quad (2)$$

The consumer also receives net transfers Ξ_s (from the government). The revenues for the transfers are increased by levying taxes or selling emissions allowances and decreased by granting subsidies. Furthermore, a given (current account) deficit Δ_s can be taken into account (Pothen and Hübler, 2018):

$$I_s = \Theta_s + \Xi_s + \Delta_s \quad (3)$$

Real consumption expenditures $C_s = \frac{\xi_s I_s}{P_s}$ reflect utility. Their relative change is used as a welfare measure of a policy or shock compared with the benchmark situation, where P_s can be interpreted as a true-cost-of-living index (Pothen and Hübler, 2018). Due to the division by P_s , consumer price changes are eliminated such that welfare changes are measured in terms of constant benchmark prices. In this way, we obtain a welfare measure following the concept of the Hicks equivalent variation. In a model with more than one consumer, particularly, with several income groups, P_s is defined individually for each consumer (income group) based on the individual consumption basket.

2.2. Approach

To disaggregate a representative consumer into n consumption groups, we need to split all relevant parameters of Eqs. (1) to (3) into n parts. For this purpose, let us define the set of n consecutive integer numbers $\Phi_s = \{1, \dots, n\}$ and the consumer group dimension ϕ .

By drawing on (household) data for all region-specific goods consumption expenditures $Y_{C,s,i}^{DM}$, we will need to find n share parameters $\lambda_{s,i,\phi}^C \forall \phi \in \Phi_s$ with $\sum_{\phi} \lambda_{s,i,\phi}^C = 1$ that allow us to split $Y_{C,s,i}^{DM}$ into n parts. Furthermore, we need to split savings $(1 - \xi_s)I_s$ with $\lambda_{s,\phi}^S \forall \phi \in \Phi_s$ such that $\sum_{\phi} \lambda_{s,\phi}^S = 1$. Similarly, on the income side, we need to find $\lambda_{s,\phi}^K$ with $\sum_{\phi} \lambda_{s,\phi}^K = 1$, which allows us to split \bar{K}_s into n parts. Likewise, we need to determine $\lambda_{s,\phi}^L$ with $\sum_{\phi} \lambda_{s,\phi}^L = 1$ for \bar{L}_s , $\lambda_{s,\phi}^N$ with $\sum_{\phi} \lambda_{s,\phi}^N = 1$ for \bar{N}_s , and $\lambda_{s,i,\phi}^R$ with $\sum_{\phi} \lambda_{s,i,\phi}^R = 1$ for $\bar{R}_{s,i}$. Finally, we need to identify $\lambda_{s,\phi}^{\Xi}$ with $\sum_{\phi} \lambda_{s,\phi}^{\Xi} = 1$ for net transfers Ξ_s and $\lambda_{s,\phi}^{\Delta}$ with $\sum_{\phi} \lambda_{s,\phi}^{\Delta} = 1$ for deficits Δ_s .

As a result, Eq. (1) to (3) can be rewritten n times for all $\phi \in \Phi_s$ in each region s subject to a consumer split. The aggregate expenditures and income replicate the original situation with just one consumer.

2.3. Sectors

For the following exemplary disaggregation procedure based on household data, we refer to the 18 sectors (goods and services) displayed in Table 1 as defined by Pothen and Hübler (2018). Each sector produces one good or service that the representative consumer purchases. The investment good (*INVS*) is produced in a separate sector by using inputs like any other good. Savings equal investments in each model region. Hence, the demand for the investment good is determined by the savings of the representative consumer of each model region. Consumers (households), however, do not directly spend money on investments. Instead, they save part of their income, which is in reality converted into investments by financial intermediaries, such as banks. Consequently, savings appear in the household data where the investment sector does not appear.

2.4. Data

We use the 2013 household income and expenditure survey for Germany (“Einkommens- und Verbrauchsstichprobe”, EVS) from the Research Data Centre (RDC) of the Federal Statistical Office and Statistical Offices of the Federal States (FDZ, 2021), as it includes very detailed information on income and its use in various expenditure categories. This survey covers 52,421 German households, which are extrapolated to 38,559,825 households with the provided extrapolation factors so that the survey is representative of Germany. The data are defined according to the SEA (German: “Systematik der Einnahmen und Ausgaben der privaten Haushalte”) classification (FDZ, 2019) following the Classification of Individual Consumption by Purpose (COICOP) of the United Nations and the more deeply differentiated European version (Statistisches Bundesamt, 2013).

For the global input–output structures with (intermediate and final goods) trade flows, international transport margins, CO₂ emissions, subsidies, taxes, tariffs, and so forth, we use version 10 of the Global Trade Analysis Project (GTAP) data (Aguiar et al.,

Table 1
Sectors covered by the analysis.

Sector	Description
<i>AGRI</i>	Agriculture
<i>COAL</i>	Coal
<i>CRUD</i>	Crude oil
<i>NGAS</i>	Natural gas
<i>PETR</i>	Refined petroleum
<i>FOOD</i>	Food production
<i>MINE</i>	Mining
<i>PAPR</i>	Paper and pulp
<i>CHEM</i>	Chemicals, rubber and plastic
<i>NMMS</i>	Mineral products nec.
<i>IRST</i>	Iron and steel
<i>NFMS</i>	Non-ferrous metals
<i>MANU</i>	Manufacturing
<i>ELEC</i>	Electricity
<i>TRNS</i>	Transport
<i>CONS</i>	Construction
<i>SERV</i>	Services
<i>INVS</i>	Investment)

Sectors (goods and services) i (or, alternatively, j) defined by [Pothen and Hübler \(2018\)](#), Table A2. The detailed model-to-GTAP sector mapping can be found in Appendix Table A1.

2019) for the year 2014 covering most countries in the world.⁶ The aggregation of the GTAP 10 sectors to our model sectors is detailed in Appendix Table A1.

2.5. Procedure

This subsection provides a “recipe” for modelers who aim to disaggregate a representative consumer to conduct a distributional policy analysis. The consumption data of each household are transferred from the utilized classification based on the purposes of product (goods) categories to the classification based on production sectors, which are then aggregated to the production sectors in the model. To obtain data on income and consumption for different income groups, a consumption and expenditure survey (such as the EVS) is required. Drawing on such a survey, the following procedure can be applied to any country or region. For a (macroeconomic) model implementation, a consistent (macroeconomic) database (such as GTAP) is required. Another prerequisite is a country- or region-specific consumption interdependence table or a consistent method for mapping the consumption pattern to the available production sectors.

For example, [Rausch et al. \(2011\)](#) use a consumption interdependence table of the USA (called bridge matrix) that links consumption of the US consumer expenditure survey (CEX) to the North American Industry Classification System (NAICS).⁷ [Luu et al. \(2020\)](#) show how EU household data classified according to COICOP can be mapped to GTAP sectors using concordance tables between different classifications.⁸ Therefore, the procedure explained in the following can be used for other European countries, the USA and other countries that use COICOP statistics or for which a consistent mapping can be created. The following steps 1. and 2. can slightly differ while the step-wise procedure of creating a mapping table that converts consumption expenditures into (aggregate) GTAP sectors remains valid.

To disaggregate the representative consumer, we proceed in eight steps:

1. First, we need to transfer the data on consumption by purpose into product (goods) categories by sector. To this end, we apply the consumption interdependence table of the German Federal Statistical Office ([Statistisches Bundesamt, 2020](#)) to transfer the product categories from the SEA classification (used in the EVS) to the Statistical Classification of Products by Activity (CPA) based on economy-wide input–output data.⁹ As the consumption interdependence table includes only 42 consumption categories (SEA classification), the consumption data are first aggregated to these categories and then transformed into the 85 production categories (CPA classification) resulting from the consumption interdependence table.

For each region s with a representative consumer that we would like to split, following [Kronenberg \(2010\)](#), we define $Y_{C,s,j}^G$ as the total consumption by purpose j (SEA) and $Y_{C,s,i}^H$ as the total consumption of goods category i (CPA). The given consumption interdependence table consists of the matrix \mathbf{A} , where the respective element $a_{s,i,j}$ contains the absolute amount of $Y_{C,s,j}^G$, which is mapped onto $Y_{C,s,i}^H$. We assume that the consumption of each household by purpose is distributed across goods categories with the

⁶ More information can be found at <https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx>.

⁷ The resulting NAICS sectors can then be linked to (aggregate) GTAP sectors in a second step.

⁸ Particularly, the Central Product Classification (CPC) and International Standard Classification of All Economic Activities (ISIC). A similar procedure can be used to link the US CEX to GTAP with concordance tables linking NAICS to CPC/ISIC.

⁹ See [Kronenberg \(2010\)](#), who also uses the consumption interdependence table to transform the consumption data into sectoral data for Germany.

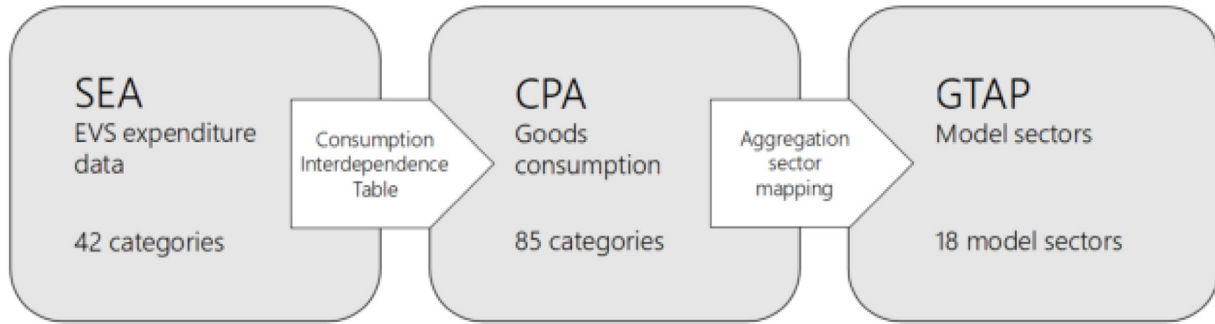


Fig. 1. Conversion and aggregation of sectors (goods).

Conversion and aggregation steps from the consumption (goods) expenditures data of the household survey to the required model sectors. EVS denotes “Einkommens- und Verbrauchsstichprobe”, SEA denotes “Systematik der Einnahmen und Ausgaben der privaten Haushalte”, CPA denotes “Statistical Classification of Products by Activity”, and GTAP denotes “Global Trade Analysis Project”.

same conversion coefficients.¹⁰ To calculate the goods consumption $Y_{C,s,i,\psi}^H$ of each household ψ , we proceed in two steps. First, we determine the conversion coefficients $\bar{a}_{s,i,j}$, i.e., the shares of consumption by purpose j that can be mapped onto goods category i :

$$\bar{a}_{s,i,j} = \frac{a_{s,i,j}}{\sum_j a_{s,i,j}} \quad (4)$$

Second, we apply these conversion coefficients to the consumption by purpose j . This yields the consumption of household ψ in each goods category i :

$$Y_{C,s,i,\psi}^H = \sum_j \bar{a}_{s,i,j} Y_{C,s,j,\psi}^G \quad (5)$$

In step 7, we will aggregate households into income groups.

2. In the next intermediate step, we aggregate the obtained values for the goods categories into the corresponding model sectors; see Section 2.3 and Appendix Table A2 for the sector mapping. In this procedure, we follow Rueda-Cantuche et al. (2020), who discuss how to transfer the input–output tables of the EU classification to GTAP and the concordance tables provided by GTAP.¹¹ Fig. 1 illustrates steps 1 and 2.

3. Now, we calculate the available income categories in the EVS: labor income, capital income and net transfers (transfers with deducted taxes). All data items used to calculate the disposable income¹² are distributed to these three categories following the suggestions by the UNECE (2011). The household data (EVS) usually contain various income sources that can be attributed to factor income from providing labor or capital. We follow UNECE (2011) by attributing income from self-employment to labor income. Net transfers include tax revenues generated by the government minus subsidy payments redistributed to the households.¹³ Appendix Table A3 displays the assignment of the EVS data to income categories.

4. Next, we calculate the savings of each household based on the respective EVS data. For details, see Appendix Table A4.

5. To render the data household size-independent, we follow Statistisches Bundesamt (2018) and draw on the Organization for Economic Co-operation and Development (OECD) equivalence scale (OECD, 2013) to obtain per capita values; see Appendix Section A.4. With the help of this equivalence scale, we calculate household-specific weighting factors that will be used in the next step.

6. Next, we create the desired number of n income groups.¹⁴ For the creation of income groups, the households are sorted from low to high by their equivalent income, i.e., the households’ disposable income divided by the weighting factors obtained in the previous step. Then, we create n groups with equal size (sum of the OECD weighting factors multiplied with the extrapolation coefficients) such that each group represents the same equivalent number of people. In our exemplary application, we distinguish between three German income groups representing low-, middle- and high-income.

7. Building on the previous steps, we are now able to aggregate the total consumption and income values and shares for each income group. In this aggregation procedure, we determine the sum of the source-specific income types $X_{s,f,\phi}$ from the available

¹⁰ We assume that these structural differences in the consumption linkage (not in the consumption structure itself) between households average out, as they are aggregated to relatively large groups.

¹¹ The concordance tables can be accessed here: <https://www.gtap.agecon.purdue.edu/databases/contribute/concordinfo.asp>. In our case, the CPA goods categories can in general be distributed to one model sector and do not need to be divided into more sectors. Crude petroleum and natural gas (no. 06), as an exception, is distributed to the model sectors of crude oil (CRUD) and natural gas (NGAS). The required consumption data are usually available in the household data (here, available in the EVS). For more details, see Appendices A.2 and A.3. Furthermore, as no consumption is assigned to the non-ferrous metals (NFMS) sector, 50% of the resulting iron and steel (IRST) sector data are assigned to the NFMS sector, assuming that the NFMS consumption is distributed in the same way as the IRST consumption.

¹² Available income after deducting taxes.

¹³ The EVS data also contain specific minor income types that can be assigned neither to capital nor to labor income. These income types are assigned to net transfers.

¹⁴ In general, any number of income groups can be created.

income sources indexed f , consumption expenditures $Y_{C,s,i,\phi}^{DM}$ on goods indexed i and savings $S_{s,\phi}$ over income groups indexed ϕ in country (region) s . We add up the indexed households ψ weighted with their extrapolation factors μ_ψ within each income group:¹⁵

$$X_{s,f,\phi} = \sum_{\psi \in \phi} X_{s,f,\psi} \mu_\psi, \quad Y_{C,s,i,\phi}^{DM} = \sum_{\psi \in \phi} Y_{C,s,i,\psi}^{DM} \mu_\psi, \quad S_{s,\phi} = \sum_{\psi \in \phi} S_{s,\psi} \mu_\psi \quad (6)$$

This sum can, in general, differ from the total values of the database (GTAP) underlying the model under scrutiny. This is not a problem, because we calculate the share parameters $\lambda_{s,f,\phi}^X$ and $\lambda_{s,i,\phi}^C$ for each of the n income groups for each of the k income sources f and each of the m goods (sectors) i as defined in Section 2.2. Based on the absolute savings values $S_{s,\phi}$, the calculation of the savings shares $\lambda_{s,\phi}^S$ across income groups ϕ is straightforward. This yields the *vertical distribution* of income, consumption expenditures and savings:

$$\lambda_{s,f,\phi}^X = \frac{X_{s,f,\phi}}{\sum_{\phi=1}^n X_{s,f,\phi}}, \quad \lambda_{s,i,\phi}^C = \frac{Y_{C,s,i,\phi}^{DM}}{\sum_{\phi=1}^n Y_{C,s,i,\phi}^{DM}}, \quad \lambda_{s,\phi}^S = \frac{S_{s,\phi}}{\sum_{\phi=1}^n S_{s,\phi}} \quad (7)$$

The household data (EVS), however, usually do not provide information on income from the production factors of land or natural resources. Likewise, we lack macroeconomic information on the distribution of these production factors across public and private consumers and across income groups. Therefore, by default we distribute them in the same way we distribute total consumption expenditures (referring to Section 2.2, $\sum_i \lambda_{s,i,\phi}^C = \lambda_{s,\phi}^N = \sum_i \lambda_{s,i,\phi}^R$). Then, we vary the distribution of land and resources income shares across the income groups in a sensitivity analysis (see Section 4.4).

8. Finally, we apply these share parameters to the model summarized in Section 3. Each corresponding absolute value of income, savings or expenditure in the model data is split into n values for n income groups. As a result, the disaggregated model data will exactly add up to the original absolute values, and the underlying (general) model equilibrium is restored, including the new income groups.

Referring to the nomenclature of Section 2.1, we apply the share parameters $\lambda_{s,f,\phi}^X$ and $\lambda_{s,\phi}^S$ obtained from the household data (EVS) to each income type, i.e., income from capital and labor (K, L) as well as net received transfers (Ξ) in the region (s) under scrutiny, and to savings $((1-\xi_s)I_s)$, which are all given by the model data (GTAP).¹⁶ Likewise, we apply the share parameters $\lambda_{s,i,\phi}^C$ to the expenditures $Y_{C,s,i}^{DM}$ on each good (sector) i given by the model data. The remaining components required for a (macroeconomic) model implementation, such as current account deficits (Δ_S), need to be taken from a separate (macroeconomic) database (GTAP).¹⁷

In a similar vein, we calculate the share parameters $i_{s,f,\phi}^X$ and $i_{s,i,\phi}^C$ referring to Eqs. (1), (2) and (3) that represent the distribution of expenditures across various goods i and of income across several income sources (horizontal distribution). In our application, these share parameters do not enter the model but are displayed for illustrated purposes in the next subsection. In other applications, they may enter the model calibration. Furthermore, drawing on the household data on total income, total expenditures and total savings, we can calculate the fixed fraction of total income that the representative consumer spends on consumption $\xi_{s,\phi}$, while the remaining fraction $(1 - \xi_{s,\phi})$ is saved. This yields the *horizontal distribution* of income and of consumption expenditures and the consumption fraction:

$$i_{s,f,\phi}^X = \frac{X_{s,f,\phi}}{\sum_{f=1}^k X_{s,f,\phi}}, \quad i_{s,i,\phi}^C = \frac{Y_{C,s,i,\phi}^{DM}}{\sum_{i=1}^m Y_{C,s,i,\phi}^{DM}}, \quad \xi_{s,\phi} = \frac{P_s C_{s,\phi}}{I_{s,\phi}} \quad (8)$$

2.6. Results

For the interpretation of (macroeconomic) policy results, it is helpful to understand the underlying (microeconomic) household characteristics first. For this purpose, in the following illustrations, we present the distribution of (private) disposable income $I_{s,\phi}$ across income groups ϕ , the vertical and horizontal distribution of income sources $X_{s,f,\phi}$ that are available in the EVS, i.e., capital income, labor income and net received transfers ($f \in \{K, L, \Xi\}$ in the examined region s , here Germany, DEU), and the distribution of income across total consumption $C_{s,\phi}$ and savings $S_{s,\phi}$. Then, we present the vertical and horizontal distribution of consumption expenditures $Y_{C,s,i,\phi}^{DM}$ across the 17 consumption goods (sectors i without investment, $INVS$) defined in Section 2.3.

In the following application, we distinguish three income groups ($n = 3$), for which Appendix A.7 provides further descriptive results. We calculate the distribution of income and private consumption across goods (sectors i) also for five and ten income groups ($n = 5, n = 10$); see Appendix A.8 regarding the resulting descriptive numbers and illustrations. According to the descriptive results, the distribution pattern is qualitatively similar when there are more than three income groups and is therefore omitted in the following model application and policy analysis for the sake of simplicity.

Fig. 2 displays the mean equivalent disposable income of each income group. Notably, the increase in disposable income from the middle- to the high-income group is larger than that from the low- to the middle-income group. Fig. 3 shows the horizontal

¹⁵ We do not need to apply the OECD weighting factors here as all groups have the same size. Therefore, multiplying each data position by the corresponding OECD weighting factor results in the same shares as dividing the absolute numbers by the equivalent size (which is the sum of the weighting factors). Furthermore, because households are assigned to only one income group, the (equivalent) sizes of the groups differ slightly. Therefore, we correct the values by multiplying them with the number of people that should be in each group and divide by the number of people that are actually in each group.

¹⁶ In our model application, net received transfers are implemented in absolute terms and adjusted to add up to zero across income groups ϕ in region s . As a result, the transfers are neutral with regard to the benchmark model equilibrium.

¹⁷ In our model application, the data on current account deficits (surpluses) are taken from GTAP and held constant throughout the analysis.

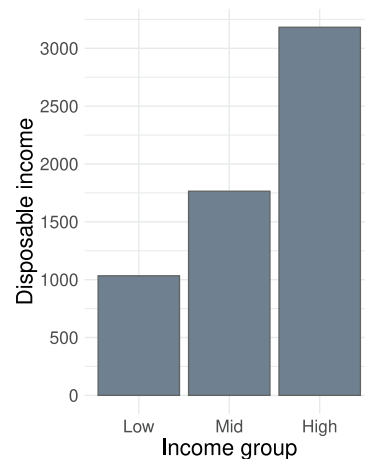


Fig. 2. Total German income by income group.

Distribution of the mean equivalent disposable income (total disposable income divided by the number of equivalent people based on the OECD scale) per month of the 52,421 German households in the survey across income groups in euros.

Data source: Authors' own calculation drawing on data from the Research Data Centre (RDC) of the German Federal Statistical Office and Statistical Offices of the Federal States, "Einkommens- und Verbrauchsstichprobe" 2013, base file 5 (FDZ, 2021).

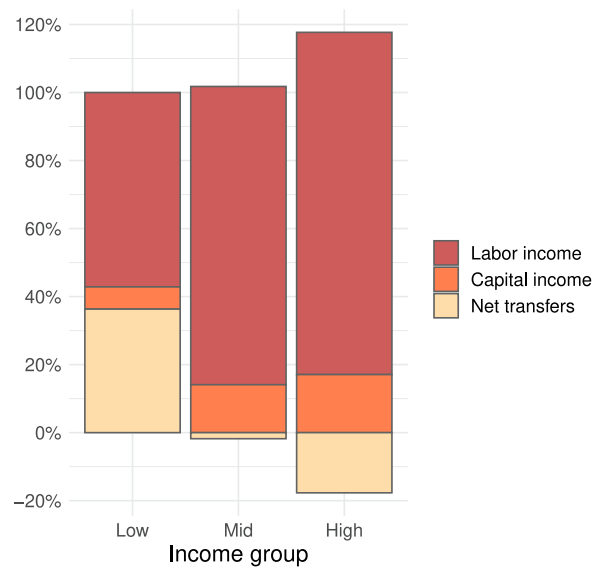


Fig. 3. German income sources by income group.

Horizontal distribution of income sources within each income group in Germany in percent (see Appendix Table A5 regarding the corresponding numbers).

Data source: Authors' own calculation; FDZ (2021).

distribution of income sources (Appendix Table A5 provides the corresponding numbers). The low-income group receives 36% of its income via net transfers from the government. A small share (7%) is obtained from capital, while the largest share (57%) is earned from labor. By contrast, the value of the taxes the middle-income group pays is slightly higher than the value of the governmental support it receives (net transfers share of -2%). The group's share of capital income (14%) is more than twice as large as that of the low-income group, while the former's labor income contributes by far the largest share to overall income (88%). The capital income share of the high-income group (17%) is slightly higher than that of the middle-income group. In absolute values, however, it is substantially larger because the former's disposable income is nearly twice as high as that of the latter (see Table A5). As expected, the high-income group is a significant net transfer payer (-18%).¹⁸

Fig. 4 illustrates the corresponding use of income for savings versus consumption in each income group (see Appendix Table A5).¹⁹ The low-income group's consumption share (103%) exceeds its income. Hence, the remaining part is financed via a debt

¹⁸ Because the paid transfers slightly exceed capital income, the high-income labor share slightly exceeds 100%.

¹⁹ In the EVS data, a statistical difference remains regarding the equation income = consumption + savings, which is disregarded here to create the consumption and savings shares.

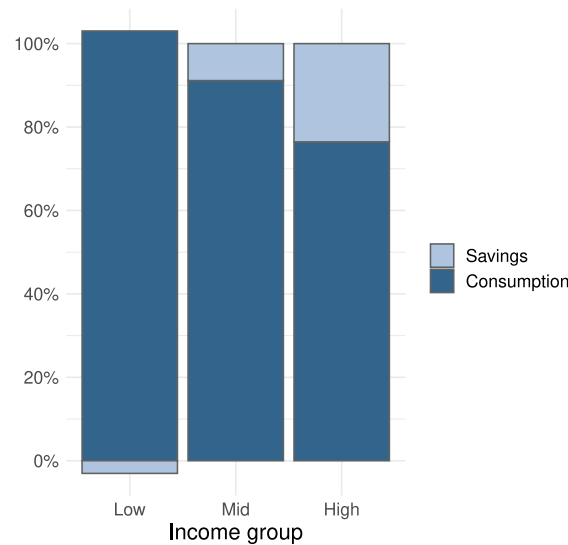


Fig. 4. German savings and consumption by income group. Horizontal distribution of the use of income in savings versus consumption expenditures within each income group in Germany in percent (see Appendix Table A5 regarding the corresponding numbers).
 Data source: Authors' own calculation; FDZ (2021).

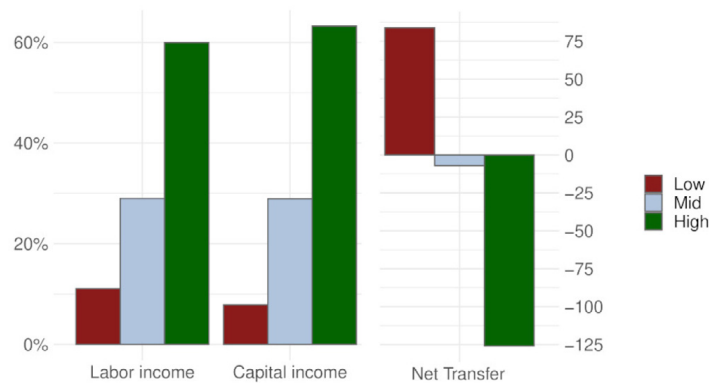


Fig. 5. German income by income source. Vertical distribution of income sources across income groups (low, middle, high) in Germany; net transfers in billions of euros, other sources in percent (see Appendix Table A6 regarding the corresponding numbers).
 Data source: Authors' own calculation; FDZ (2021).

reflected by a negative savings share. The middle-income group exhibits a positive savings share (9%). The savings share in the high-income group is more than twice that in the middle-income group (24%).

Fig. 5 depicts the vertical distribution of each income source across income groups (Appendix Table A6 provides the corresponding numbers). The vertical shares of labor and capital income also enter the calibration of the model described in the next subsection. Accordingly, the labor and capital income shares rise from low- to middle-income groups and from middle- to high-income groups, mimicking the distribution of disposable income, as displayed in Fig. 2. Whereas the relative capital and labor income shares are similar in the middle- and high-income groups (Fig. 3), capital and labor income in absolute values is more than twice as high in the high-income than in the middle-income group reflected in the vertical shares in Fig. 5. Note that income from self-employment, management or other well-paid jobs contributes to labor income. Nonetheless, the capital (labor) income share of the high-income group can be an underestimation (overestimation), because households with a monthly net income exceeding € 18,000 are not represented in the survey. To address this data limitation, we carry out a robustness check that varies the high-income group's capital share as summarized in Section 4.4. Net transfers are shown in absolute numbers as they enter the model calibration.²⁰

²⁰ The net transfers of the high-income group are adjusted such that the sum of net transfers over income groups adds up to zero and the original general equilibrium is restored.

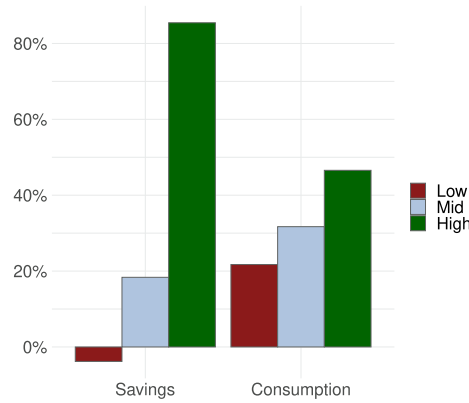


Fig. 6. German income by savings and consumption. Vertical distribution of income in savings versus consumption expenditures across income groups (low, middle, high) in Germany in percent (see Appendix Table A6 regarding the corresponding numbers). Data source: Authors' own calculation; FDZ (2021).

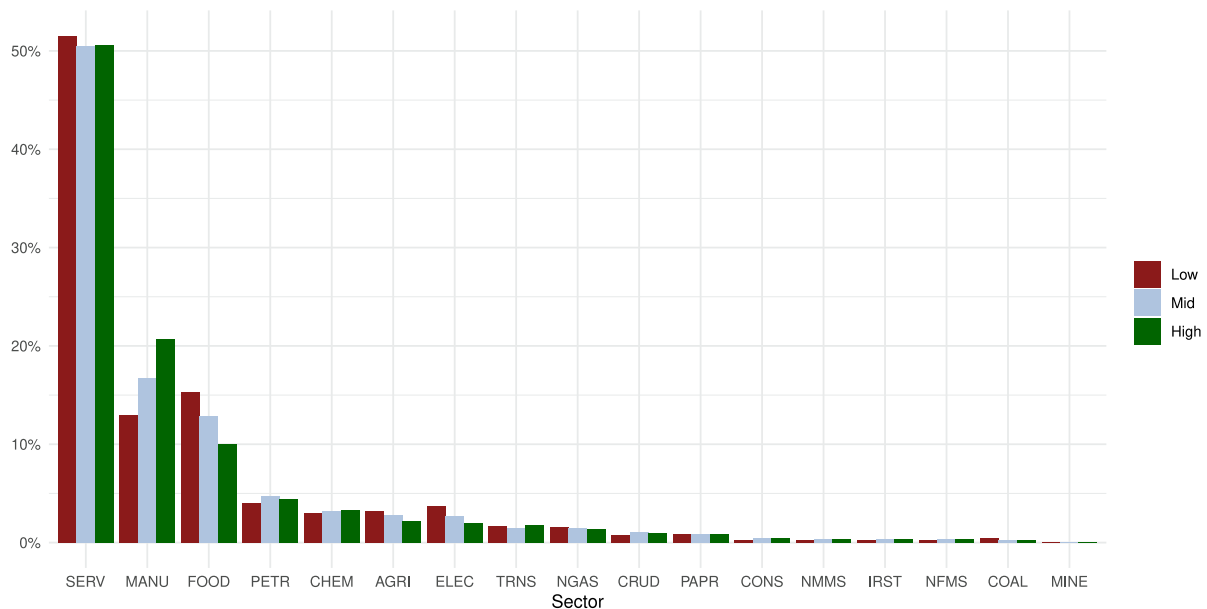


Fig. 7. Horizontal distribution of German consumption expenditures by goods. Horizontal distribution of each income group's consumption expenditures across types of goods (sectors) in Germany (see Appendix Table A7 regarding the corresponding numbers). Data source: Authors' own calculation; FDZ (2021).

Fig. 6 sketches the corresponding income use across income groups (see Appendix Table A6). As expected, the shares of savings and consumption increase from low- to middle-income groups and middle- to high-income groups.

Fig. 7 illustrates the horizontal distribution of each income group's consumption expenditures across the various types of goods (i.e., the sums across the goods equal 100%; see Appendix Table A7). Interestingly, the consumption pattern varies across income groups. With a share of approximately 50%, the services sector (*SERV*) sees the highest expenditures. Here, the low-income group contributes the largest expenditure share of all income groups, while the middle-income group spends the smallest share, which is very close to the high-income group's share. In the sectors food production (*FOOD*), agriculture (*AGRI*) and electricity (*ELEC*), the low-income group exhibits the largest expenditure shares as well, while the high-income group exhibits the smallest shares. This pattern differs, for example, in the manufacturing sector (*MANU*), where the high-income group has the largest expenditure share and the low-income group the smallest. In the refined petroleum (*PETR*) sector, the middle-income group exhibits the largest expenditure share and the low-income group the smallest.

Fig. 8 visualizes the corresponding vertical distribution of (private) consumption expenditures on each type of goods (sector) across income groups (i.e., the sums across the three income groups equal 100%; see Appendix Table A7.) These vertical shares also enter the model calibration. Obviously, the distribution is more uneven for some sectors, such as construction (*CONS*) or

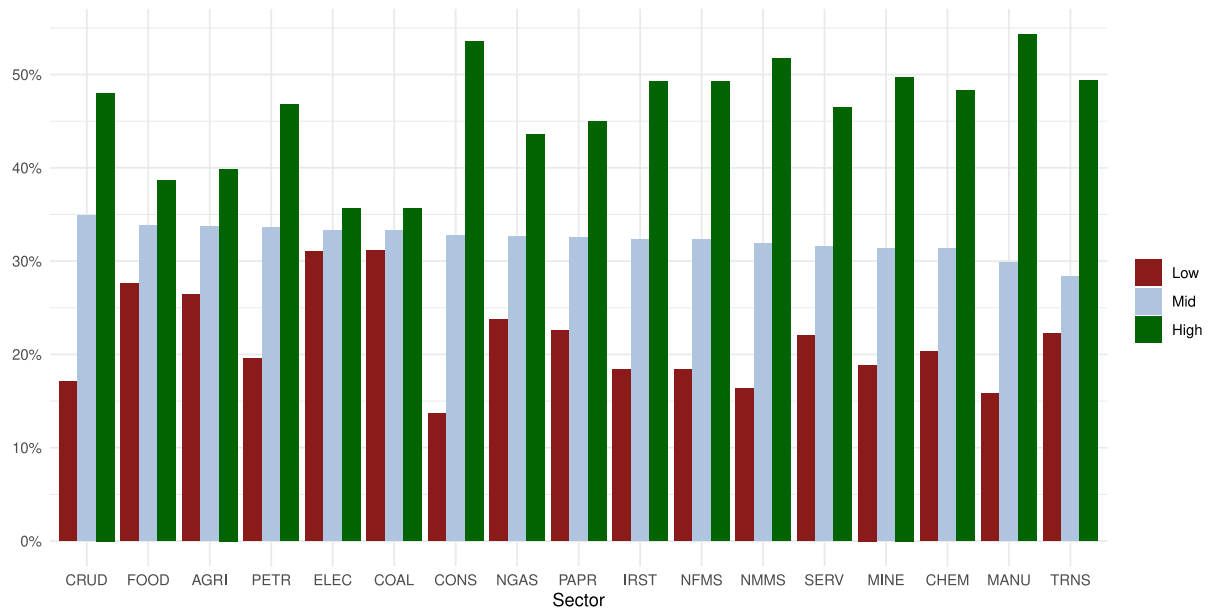


Fig. 8. Vertical distribution of German consumption expenditures by goods.

Vertical distribution of consumption expenditures on each type of good (sector) across income groups (low, middle, high) in Germany (see Appendix Table A7 regarding the corresponding numbers).

Data source: Authors' own calculation; FDZ (2021).

manufacturing (*MANU*), than for others, such as food production (*FOOD*) or electricity (*ELEC*), where the expenditure shares are similar across income groups. Nonetheless, the high-income group pays the largest share on all goods, and the low-income group the smallest share on all goods.

3. Model

To illustrate the application of our consumer split approach, we use a typical basic computable general equilibrium (CGE) model. It is designed to be as compact as possible to make it transparent and straightforward and to avoid any unnecessary uncertainty in model functions and parameters. The basic model builds on Thomas Rutherford's approach,²¹ and has been extended according to the requirements of this study. The model represents the world economy in the benchmark year 2014 according to the GTAP 10 data. This section provides a nontechnical model summary. Appendix B contains further model details.

Each of the 18 model regions (s or alternatively r) (see Table 2) includes one representative consumer that is split into three groups (low-, middle- and high-income) in Germany (*DEU*). Each representative consumer has Cobb–Douglas preferences over a range of 17 consumption goods bundles (see Appendix Figure B2). Each bundle encompasses domestically produced and imported varieties of the same good (see Appendix Figure B1). Each consumer owns the production factor endowments of the corresponding region and receives factor income by supplying them to the producers. Additionally, a consumer may receive income from (social/public or other kinds of) transfers or a regional (current account) deficit. Each regional deficit (or surplus) stays constant throughout the analysis. It is valued at the numeraire price defined by the price of the consumption bundle (consumer price index) in the *USA*. Each consumer spends a major fraction of her income on consumption, while the remaining fraction is saved, such that disposable income always equals expenditures plus savings.

International trade flows from region r to region s . Trade is modeled following the standard approach introduced by Armington (1969) (Figure B1). This approach implies that varieties of the same good originating from different regions are imperfect substitutes. Parameter values governing the substitutability of these varieties are transferred from Pothen and Hübler (2018) according to the trade model unification theory of Arkolakis et al. (2012). Tariffs (and subsidies) can be imposed on imports (and exports).

Each region contains 18 production sectors (i or j) (see Table 1). Overall, each sector produces one corresponding good (or service), 17 consumption/intermediate goods and one investment good. Investments match savings. Each sector uses intermediate goods and production factors (capital, labor, land and natural resources including endowments with fossil fuel resources) as inputs (see Appendix Figure B3). Capital and labor are mobile across sectors within each region but immobile across regions, i.e., foreign direct investments, international portfolio investments and international migration are not represented explicitly. There is perfect competition ruling out positive profits in all sectors.

²¹ Our model is programmed with the General Algebraic Modeling System (GAMS) and the interface Mathematical Programming System for General Equilibrium (MPSGE), https://www.gams.com/latest/docs/UG_MPSGE.html, <https://www.gams.com/latest/docs/mpsge.pdf>. A similar model can be found at GTAPinGAMS, https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=409.

Table 2
Countries and world regions distinguished by the global model.

Region	Description	Split	ETS	Region	Description	Split	ETS
<i>DEU</i>	Germany	Yes	Yes	<i>BRA</i>	Brazil	No	No
<i>FRA</i>	France	No	Yes	<i>CAN</i>	Canada	No	No
<i>GBR</i>	United Kingdom	No	Yes	<i>CHN</i>	China	No	No
<i>ITA</i>	Italy	No	Yes	<i>IND</i>	India	No	No
<i>EUR</i>	Rest of EU-27	No	Yes	<i>JPN</i>	Japan	No	No
<i>ROE</i>	Rest of ETS (non-EU)	No	Yes	<i>KOR</i>	South Korea	No	No
<i>FSU</i>	Former Soviet Union	No	No	<i>MEX</i>	Mexico	No	No
<i>ROA</i>	Rest of Asia	No	No	<i>OCE</i>	Austral. & Ocean.	No	No
<i>ROW</i>	Rest of the World	No	No	<i>USA</i>	United States	No	No

Model regions s (or, alternatively, r) defined by [Pothen and Hübler \(2018\)](#). “Split” indicates whether the representative consumer is split in a region. “ETS” indicates whether a region is part of the European Emissions Trading System (EU ETS). Other regions are assumed not to impose a price on CO₂. The detailed model-to-GTAP region mapping can be found in Appendix Table B1.

Each region has a government that purchases goods like a private consumer. Governments’ total expenditures (and surpluses or deficits) are taken from GTAP and then held constant, while governments’ demand for different domestically produced and imported goods adjusts endogenously in counterfactual scenarios. Endogenous tax revenues and subsidy payments are attributed to the representative consumer as a net transfer. Each production input or output (producer side) and any consumption good (consumer side) can be subject to taxation or subsidization. The benchmark year values of taxes (tariffs) and subsidies are also taken from GTAP.

The benchmark data on savings and investments are taken from GTAP as well. For Germany, the saved part of income of each income group is derived from the household data.

Consumers and producers emit CO₂ directly when they burn fossil fuels. To reflect these emissions, the consumption of each fossil fuel, coal (*COAL*), crude oil (*CRUD*), natural gas (*NGAS*) and refined petroleum (*PETR*), is associated with fuel-specific CO₂ emissions (Figure B1). When climate policy imposes a price on CO₂ emissions (via emissions trading or a tax), these emissions reflect a corresponding cost of buying emissions permits or paying a tax bill.

Consumers and producers in all sectors cause CO₂ emissions indirectly when they consume electricity or other goods (with embodied CO₂ footprints). Electricity consumption, for example, is associated with CO₂ emissions released during power generation in the power sector (*ELEC*). These emissions are taxed in the power sector within the European Emissions Trading Scheme (EU ETS) in the countries that are EU ETS members (see [Table 2](#)). If goods are imported into the EU, neither fossil fuels nor fossil fuel inputs in any sector are taxed. Therefore, CO₂ pricing at the EU border can put a price on these emissions (both direct emissions and indirect emissions according to the goods’ CO₂ footprints, see [Section 4](#)).

4. Policy

This section describes the policy scenarios, presents the results and discusses the method used herein.

4.1. Scenarios

To keep the application simple and straightforward and to avoid uncertainty in the choice of future developments and model parameters governing model dynamics, we refer to the situation in the *Benchmark* year 2014 with regard to consumption, production, CO₂ emissions and production factors. Based on that, we carry out a comparative static policy analysis, in which we compare each policy scenario with this *Benchmark* scenario without the policy. Market failures are not explicitly modeled. Given that climate change impacts are not included either, we carry out a cost-effectiveness analysis, i.e., the optimal implementation of a specific reduction in CO₂ emissions. Because the benchmark data incorporate taxes and subsidies that were in place in 2014, we are in a second-best world, which can result in more complicated outcomes than a first-best world.

We consider the following three policy scenarios:

1. *Domestic CO₂ price (Dom)*: CO₂ pricing encompasses the EU ETS member countries, whereas CO₂ pricing in other model (sub-) regions (such as California) is ruled out. To exploit the full potential of consumption-side disaggregation and to emulate emissions reduction policies in all parts of the EU ETS economies, we explicitly include all sectors and private consumption in CO₂ pricing without explicitly distinguishing between ETS and non-ETS sectors. This situation mimics the German CO₂ taxation in non-ETS sectors (transport and housing) and an EU ETS 2 with assumed equalized CO₂ prices across the pricing systems. Compared with a situation with heterogeneous CO₂ prices, substantial efficiency gains from having a common CO₂ price can be expected ([Pothen and Hübler, 2021](#)). Therefore, the implemented policy addresses all CO₂ emissions from burning fossil fuels in production and consumption, whereas other greenhouse gases are not included. Referring to the CO₂ emissions and their reductions around 2014, we assume a 10% CO₂ reduction in Germany and each EU ETS member country/region to obtain the initial allocation of CO₂ allowances and an EU ETS-wide 10% CO₂ reduction in all policy scenarios.²² Emissions allowances can be traded across countries/regions

²² In Germany (*DEU*), which is in the focus of our analysis, greenhouse gas emissions increased by 1.9% between 2012 and 2013, decreased by 4.2% between 2013 and 2014 and increased slightly by 0.4% between 2014 and 2015. Between 2005 and 2014, greenhouse gas emissions decreased by 9.3%; between 2014

and sectors within the EU ETS. The revenues of CO₂ pricing are redistributed across income groups in a fair per capita-wise way (cf. Klenert et al., 2018). This assumption is in line with climate bonus discussions and implementations in Germany, Austria and other countries. Given that all income groups contain the same number of households, each group receives the same share and amount of the CO₂ pricing revenues. To check the robustness of the results, we vary the distribution of the CO₂ pricing revenues across the income groups in a sensitivity analysis (see Section 4.4).

2. *Border CO₂ price (Bor)*: includes *Domestic CO₂ price*. Additionally, CO₂ pricing occurs at the border of the EU ETS member countries and is imposed on all imports, ruling out any regional or subregional CO₂ pricing elsewhere in the world (such as in California) for simplicity. CO₂ pricing covers all direct and indirect emissions that occur during all stages of producing a good (or service) and its intermediate inputs. (We do not grant CO₂-content-related subsidies for exports.) This policy follows the EU Carbon Border Adjustment Mechanism (CBAM), currently planned to be implemented in the EU beginning in 2026 after a transition phase from 2023 to 2025.²³ We calculate the required total CO₂ contents of goods following the standard Leontief inverse method (see, e.g., Peters and Hertwich, 2008; Hübler, 2012). The CO₂ contents of each good are differentiated by the country/region of origin.²⁴ The resulting CO₂ price is the same as if the goods were produced domestically within the EU ETS. Such a policy has two aims: first, to encourage emissions reductions abroad, and second, to level off the carbon playing field among competitors within and outside the EU ETS. This means, the policy intends to reduce the negative effects of CO₂ pricing on EU producers and reduce carbon leakage from the EU to the rest of the world. As before, the revenues of CO₂ pricing are redistributed per capita by default and varied in a sensitivity analysis (see Section 4.4).

3. *Climate club (Clu)*: includes *Domestic CO₂ price* or *Border CO₂ price* and extends the geographic scope of these policies successively beyond the borders of the original EU ETS and CBAM.²⁵ In the first strand of coalition scenarios, we add the major greenhouse gas emitters of the world, the United States (*USA*), China (*CHN*) (Chepeliev et al., 2021; Tagliapietra and Wolff, 2021; Perdana and Vielle, 2023) and India (*IND*) successively to the EU ETS to obtain “the big four” (Convery and Sterner, 2021).²⁶

In the second strand of coalition scenarios, we follow the announcement at the COP 28 that the G7 countries and the EU form a climate club and further countries will join (Climate Club, 2023). We denote the combination of the G7 countries with the EU ETS countries (that partly overlap) by *G7EU*.²⁷ As before, we successively add the major emitters China and India. The hypothetical global coalition *WORLD* includes all countries/regions and renders border carbon adjustments obsolete. It defines a global first-best reference point.

As in the scenarios *Domestic* and *Border CO₂ price*, each climate policy coalition implements an international emissions trading system with a common CO₂ price and a 10% CO₂ reduction in each member country/region that determines the initial allocation of CO₂ allowances and a 10% reduction target of the entire emissions trading system.

To express policy effects, such as welfare effects measured as Hicks equivalent variations, we compare either the first or the second policy scenario with the *Benchmark* scenario in 2014 and compute relative (percentage) changes, such as changes in real consumption (the consumption value divided by the consumer price index; see the end of Section 2.1), for each income group and the sum of these changes across all income groups.

4.2. Results

This subsection presents the results of the policy scenario simulations with regard to the EU policy effects on the model countries/regions as well as the distributional effects on the three German consumer income groups. Table 3 reports the regional results of the EU policy scenarios. Figs. 9 and 10 summarize and illustrate the policy effects on Germany. Table 4 presents selected regional results of the climate club scenarios, Appendix Table B3 provides the results of all climate club scenarios.

According to Table 3, the first policy scenario *Domestic CO₂ price* entails a CO₂ price of €45.72 in the EU ETS and has the following welfare effects on the countries and world regions in the model. It reduces the welfare of the EU ETS member countries implementing the policy with the strongest decline in the non-EU countries that are part of the EU ETS (*ROE*, -0.97%) followed by Italy (*ITA*, -0.67%) and Germany (*DEU*, -0.60%).²⁸ Interestingly, the climate policy effect is similar across the remaining EU-27 countries participating in the EU ETS, reaching approximately -0.5% (*EUR*, -0.49%; *GBR*, -0.46%; *FRA*, -0.51%). The negative welfare effect on the Former Soviet Union (*FSU*) countries is slightly smaller (-0.45%). Surprisingly, Australia and Oceania (*OCE*) lose more than other countries or regions (-0.69%). Due to their sheer size, the United States of America (*USA*) and the Rest of Asia

and 2020, they decreased by 18.5% (Umweltbundesamt, UBA, accessed 01-2022, <https://www.umweltbundesamt.de/en/data/environmental-indicators/indicator-greenhouse-gas-emissions>). Against this background, a 10% CO₂ reduction in 2014 is feasible and realistic. Drastic CO₂ reductions, however, would overcharge the model for three reasons: 1. the model is calibrated to the sectoral and technological situation in 2014 with corresponding consumer preferences, 2. we abstain from modeling uncertain future development scenarios, including a transition of the energy (electricity) system and energy efficiency gains, and 3. the energy input system is relatively inflexible in terms of substitution possibilities, and the electricity sector captures fossil, renewable, nuclear and other power generation technologies only implicitly.

²³ https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3661

²⁴ The set of countries/regions in the Leontief inverse matrix and in the model calibration is the same and is applied to the same GTAP 10 dataset.

²⁵ The EU ETS with CBAM already represents a climate club (Szulecki et al., 2022).

²⁶ China, the USA and the EU together emitted more than 50% of global CO₂ emissions, together with India approximately 60% in 2022 and in the benchmark year 2014 (based on Global Carbon Budget 2023 data, Friedlingstein et al., 2023).

²⁷ The G7 and EU countries jointly emitted approximately 25% of global emissions in 2022 and 30% in the benchmark year 2014 (Global Carbon Budget 2023, Friedlingstein et al., 2023).

²⁸ The German total welfare effect is computed in a model run without the consumer split, not by aggregating the welfare effects of the consumer groups.

Table 3
EU climate policy effects on countries and world regions.

Region	<i>Dom</i>	<i>Bor</i>	Region	<i>Dom</i>	<i>Bor</i>
<i>DEU</i> tot.	-0.60	-0.58			
Low	1.33	1.41	<i>BRA</i>	-0.03	-0.04
Mid	-0.50	-0.48	<i>CAN</i>	-0.08	-0.10
High	-1.21	-1.22	<i>CHN</i>	0.25	0.22
<i>FRA</i>	-0.51	-0.50	<i>IND</i>	0.14	0.12
<i>GBR</i>	-0.46	-0.46	<i>JPN</i>	0.08	0.09
<i>ITA</i>	-0.67	-0.66	<i>KOR</i>	0.10	0.12
<i>EUR</i>	-0.49	-0.45	<i>MEX</i>	-0.11	-0.12
<i>ROE</i>	-0.97	-0.90	<i>OCE</i>	-0.69	-0.74
<i>FSU</i>	-0.45	-0.56	<i>USA</i>	-0.01	-0.01
<i>ROA</i>	-0.01	-0.02	<i>ROW</i>	-0.27	-0.31

Regional welfare effects, measured as percentage changes in consumption divided by the true-cost-of-living index driven by the two EU policies under scrutiny relative to the *Benchmark* scenario, where *Dom* indicates policy scenario *Domestic CO₂ price* (CO₂ price = €45.72) and *Bor* policy scenario *Border CO₂ price* (CO₂ price = €46.14). The welfare gains of the German low-income group depend on the (per-capita-based) distribution of the revenues from CO₂ pricing. In a new hypothetical scenario in which the low-income group receives only 12% of the revenues, the middle-income group receives 29% and the high-income group receives 59%, the welfare effect on the three groups will be similar and located close to the welfare effect on the total German economy (-0.60%/-0.58% with *Dom/Bor*).

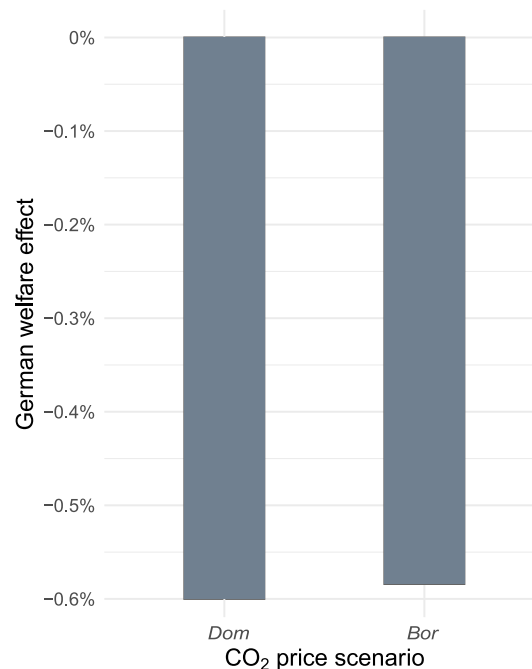


Fig. 9. EU policy effects on Germany.

German welfare effects measured as percentage changes in consumption divided by the true-cost-of-living index of the two EU policies, *Dom* = *Domestic CO₂ price* and *Bor* = *Border CO₂ price*, relative to the *Benchmark* scenario.

(*ROA*) are hardly affected (-0.01%). The welfare loss of the Rest of the World (*ROW*), comprising small and low-income economies, is more significant (-0.27%), while the losses for Canada (*CAN*, -0.08%) and Mexico (*MEX*, -0.11%) are moderate. Notably, the South and East Asian economies, particularly China (*CHN*, 0.25%), followed by India (*IND*, 0.14%), South Korea (*KOR*, 0.10%), and Japan (*JPN*, 0.08%), benefit from EU climate policy, presumably from trade redirection from EU exports to South and East Asian exports.

As shown in [Table 3](#), the second policy scenario (*Border CO₂ price*) generates the same pattern as the first one (*Domestic CO₂ price*) regarding the directions and magnitudes of welfare effects. The CO₂ price of €46.14 in the EU ETS is slightly higher than in the *Domestic CO₂ price* scenario. Overall, due to strategic gains on international goods markets, the EU ETS member countries gain slightly from introducing the *Border CO₂ price* compared with the *Domestic CO₂ price* (e.g., Germany, *DEU*, by 0.02 percentage points). In some cases, the gains are minor (the gain of the United Kingdom, *GBR*, is not visible in the table). Although the policy effects on the other countries and regions are small, most of them become worse off compared with *Domestic CO₂ price* (*FSU*, *ROA*, *ROW*, *BRA*, *CAN*, *CHN*, *IND*, *MEX*, *OCE* and effect not visible in the table: *USA*) due to the implicitly increased barrier to trade. As an exception, Japan (*JPN*) and Korea (*KOR*) make slight gains, presumably due to trade redirection from other countries'

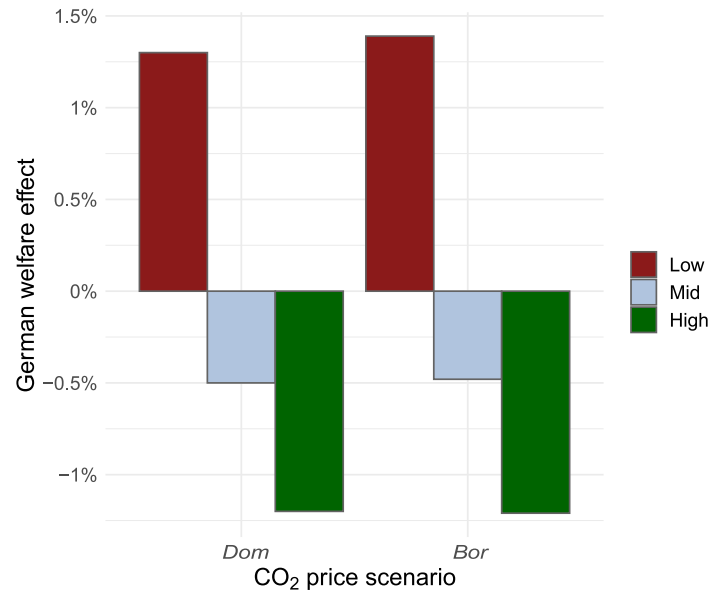


Fig. 10. EU policy effects on German income groups.

German welfare effects measured as percentage changes in consumption divided by the true-cost-of-living index of the two EU policies, *Dom* = Domestic CO₂ price and *Bor* = Border CO₂ price, relative to the *Benchmark* scenario.

Table 4
International climate policy coalition effects on countries and world regions.

Coalition	G7EU CHN/IND		WORLD	Region	G7EU CHN/IND		WORLD
	Dom	Bor	Dom/Bor		Dom	Bor	Dom/Bor
<i>DEU</i> tot.	-0.28	-0.27	-0.11	<i>BRA</i>	-0.03	-0.04	-0.41
Low	0.62	0.65	0.90	<i>CAN</i>	-0.05	-0.04	-0.23
Mid	-0.24	-0.23	-0.10	<i>CHN</i>	-0.46	-0.44	-0.23
High	-0.58	-0.57	-0.43	<i>IND</i>	-0.26	-0.24	0.19
<i>FRA</i>	-0.16	-0.15	0.03	<i>JPN</i>	-0.20	-0.18	0.12
<i>GBR</i>	-0.22	-0.22	-0.20	<i>KOR</i>	0.22	0.23	0.72
<i>ITA</i>	-0.28	-0.27	-0.08	<i>MEX</i>	-0.31	-0.34	-1.04
<i>EUR</i>	-0.22	-0.20	0.00	<i>OCE</i>	-0.70	-0.74	-1.81
<i>ROE</i>	-0.61	-0.59	-0.87	<i>USA</i>	-0.17	-0.17	-0.15
<i>FSU</i>	-0.33	-0.40	-0.53	<i>ROW</i>	-0.54	-0.57	-1.52
<i>ROA</i>	-0.05	-0.08	-0.10				

Regional welfare effects, measured as percentage changes in consumption divided by the true-cost-of-living index driven by the international *Climate club* (*Clu*) under scrutiny relative to the *Benchmark* scenario. EU refers to the entire EU ETS, which is enlarged to an international climate policy club including the remaining G7 countries (Canada, Japan and the United States) indicated by *G7EU* plus the major emitters China and India. They share a common CO₂ price under the policy scenario *Dom* (CO₂ price = €23.15) and add border carbon adjustments towards countries/regions outside the coalition under the policy scenario *Bor* (CO₂ price = €23.19). The hypothetical global coalition *WORLD* (CO₂ price = €26.90) includes all countries and renders border carbon adjustments obsolete.

exports to the EU towards exports to these countries. Compared with domestic CO₂ pricing, CO₂ pricing at the border is harmful for emerging (*CHN* and *IND*) and developing countries (included in the regions *ROA* and *ROW*).

Table B3 in Appendix B.7 provides all international *Climate Club* scenario results. As displayed in Table 4, the third *Climate Club* scenario with the members EU ETS/G7, China and India halves the joint CO₂ price of the scenarios *Domestic CO₂ price* and *Border CO₂ price* to approximately €23.20 due to efficient global emissions reduction options (low marginal abatement costs), especially in developing and emerging economies. Similarly, it approximately halves the relative welfare losses of Germany (*DEU*, -0.28% in *Dom*, -0.27% in *Bor*) and the other EU ETS members (*FRA*, -0.16%; *GBR*, -0.22%; *ITA*, -0.28%; *EUR*, -0.22%) compared with *Domestic CO₂ price* and *Border CO₂ price* in Table 3. The welfare loss of *ROE* declines by approximately one third to a relatively high loss of -0.61%. As expected, *Border CO₂ price* creates positive effects on climate policy coalition members and negative effects on outsiders. However, as in the EU policy simulations, the effects of *Border CO₂ price* compared with *Domestic CO₂ price* are overall small (similar to Weitzel et al., 2012; in their study, oil exporters and Russia experience stronger welfare losses). The effects on China (*CHN*) as a coalition outsider are mixed and small: China becomes worse (better) off when the United States (the G7) join the coalition but better (worse) off when they join with carbon border adjustments compared with the *Benchmark*. Canada (*CAN*) gains significantly when the United States (*USA*) join the EU ETS. As expected, countries/regions basically become worse off when they join a climate policy coalition with the strongest welfare losses in Australia & Oceania (*OCE*, -1.81%), the Rest of the World (*ROW*,

Table 5
EU climate policy effects on German goods and factor prices.

Price	Description	Dom	Bor
P_{DEU}	German consum. price	0.78	0.86
	Low	0.87	0.96
	Mid	0.82	0.90
	High	0.71	0.79
P_{DEU}^K	Capital price (rent)	-0.87	-0.81
P_{DEU}^L	Labor price (wage)	-0.80	-0.75
P_{DEU}^N	Land price (rent)	3.89	4.00
P_{DEU}^R	Natural resource price (rent)	-48.83	-48.62

German consumption price (true-cost-of-living index, P_{DEU}) and factor price effects (capital, K , labor, L , land, N and natural resources, R) in the two EU policies, Dom = Domestic CO_2 price and Bor = Border CO_2 price, relative to the *Benchmark* scenario. Each German income group has an own consumption price index, because it has distinct preferences and a distinct consumption structure. Factor prices are defined economy-wide (for all of Germany). The natural resource price P_{DEU}^R is an aggregate price that covers the fossil fuels and other natural resources.

-1.52%) and Mexico (MEX , -1.04%) in the *WORLD* coalition. As a notable exception, Korea (KOR) gains from all climate policy coalitions (0.08%–0.23%) where it is an outsider, and it gains even more in the *WORLD* coalition (0.72%) where it is an insider. India (IND) also gains (approximately 0.15%) when it is an outsider and in the *WORLD* coalition compared with the *Benchmark* scenario except in the “big four” coalition ($EUETS/USA/CHN/IND$, -0.29%) and the extended G7 ($EUG7/CHN/IND$, -0.26%). Interestingly, the remaining EU-27 countries (EUR) end up with a climate policy effect of nearly zero in the *WORLD* coalition. These results indicate that worldwide significant options to reduce CO_2 emissions efficiently (at lower marginal abatement costs than in the EU ETS) exist which are beneficial for the EU ETS members.

The scenario *Domestic CO_2 price* has the following distributional welfare effects on the three German income groups. The low-income group makes considerable gains (1.33%) compared with the *Benchmark* case, whereas the high-income group has losses of a similar magnitude (-1.21%). The middle-income group is located between these groups. Its loss (-0.50%) is close to the total welfare loss in Germany (almost -0.60%), indicating that the middle-income group roughly represents the average German consumer. Compared with *Domestic CO_2 price*, the *Border CO_2 price* policy is beneficial for the lower German income groups, with the largest gain (0.08 percentage points) in the low-income group, a smaller gain in the middle-income group (0.02 percentage points) and a minor loss (less than 0.01 percentage points) in the high-income group. *Climate club (Clu)* basically has the following distributional effects in Germany. When more countries join the climate club, the negative welfare effects on the middle- and high-income groups are reduced; however, the positive welfare effects on the low-income group are reduced as well.

4.3. Interpretation

Referring to the results presented in the last subsection, this subsection explains and interprets the distributional effects of CO_2 pricing on German income groups. To this end, [Table 5](#) reports price changes induced by the EU ETS scenarios and [Table 6](#) the corresponding changes induced by the international climate club scenarios. Conceptually, our interpretation follows [Goulder et al. \(2019\)](#). Different from our study, they apply their theory and model to climate policy (carbon taxes) in the USA. Likewise, [Dissou and Siddiqui \(2014\)](#) apply their distributional policy modeling approach to Canada.

In summary, our policy scenario analysis yields eight key results:

1. The distributional pattern of the effects of *Domestic CO_2 price* and *Border CO_2 price* (see [Table 3](#)) reveals that the negative effect of climate policy increases in households' income, which is in line with the literature (summarized by [Wang et al., 2016](#) and [Ohlendorf et al., 2021](#)). Notably, the low-income group *gains* from climate policy. This outcome is in accordance with [Goulder et al. \(2019\)](#) and [Böhringer et al. \(2021\)](#). [Labandeira et al. \(2009\)](#) even find a positive effect for *all* income groups in Spain. In our study, this gain occurs because all income groups receive the same per capita-based revenue from CO_2 pricing, which exceeds the negative expenditure and income effects (explained in the following) on the low-income group. Additionally, the low-income group significantly benefits from social redistribution transfers that are unaffected by climate policy and dampen any climate policy-induced effects.

2. As illustrated for EU countries by [Böhringer et al. \(2021\)](#), for the USA by [Goulder et al. \(2019\)](#) and for Canada by [Dissou and Siddiqui \(2014\)](#), consumption expenditure effects are regressive. [Table 5](#) shows that the climate policy-induced consumption price index increase from *Domestic CO_2 price* and *Border CO_2 price* for poor households is slightly stronger (0.87%) than that for middle-class households (0.82%), which is in turn larger than that for rich households (0.71%). This outcome, however, contradicts [Feindt et al. \(2021\)](#).

3. As demonstrated by [Böhringer et al. \(2021\)](#), [Goulder et al. \(2019\)](#) and [Dissou and Siddiqui \(2014\)](#), (factor) income effects are, on the contrary, progressive. In our study, *Domestic CO_2 price* and *Border CO_2 price* sharply reduce natural resource rents, including rents from fossil fuel ownership (by 48.83%). Labor income (0.80%) and, to a slightly larger extent, capital income (0.87%) decline moderately. Land rents, on the other hand, increase significantly (by 3.89%): One can imagine that renewable energy expansion, such as the installation of wind parks or solar fields, requires land and hence raises land rents, although this is not directly observed

Table 6
International climate policy coalition effects on German goods and factor prices.

Coalition	Price	Description	G7EU		WORLD
			Dom	CHN/IND	Dom/Bor
	P_{DEU}	German consum. price	1.24		1.41
		Low	1.28	1.25	1.46
		Mid	1.26	1.28	1.42
		High	1.21	1.26	1.37
	P_{DEU}^K	Capital price (rent)	0.48	0.48	0.70
	P_{DEU}^L	Labor price (wage)	0.51	0.51	0.71
	P_{DEU}^N	Land price (rent)	2.42	2.36	1.89
	P_{DEU}^R	Nat. resource price (rent)	-31.59	-31.38	-38.15

German consumption price (true-cost-of-living index, P_{DEU}) and factor price effects (capital, K , labor, L , land, N and natural resources, R) driven by the international *Climate club* (*Clu*) under scrutiny relative to the *Benchmark* scenario. For further explanations, see [Table 5](#).

in the model. Given that richer households own a larger part of the production factors than poorer ones, the former are more affected by factor price changes, particularly the dominating decline in resource rents, than the latter are.

4. To investigate the relative importance of the expenditure and income effect for the group-wise welfare effect, we run the model step by step: first, using the expenditure split only; second, including the income split; and third, with different redistributions of the revenues from CO₂ pricing among income groups (e.g., without any revenues transferred to the low-income group as a hypothetical scenario) and with different distributions of resource and land rents. It turns out that the income split is more important for the magnitudes of the welfare effects than the expenditure split, which is in agreement with [Goulder et al. \(2019\)](#). Furthermore, it turns out that in our study, the redistribution of revenues from CO₂ pricing (by default per capita) is more important than the distribution of resource rents.

Thus, in summary, richer households suffer higher losses from climate policy than poorer households, which can gain from climate policy, for the following reasons: first, the income effect dominates the expenditure effect, which affects especially high-income households; second, richer households do not receive net social transfers that dampen climate policy effects; third, richer households own more of the production factors that are affected by climate policy than poorer households do; and fourth, the land rent increase is dominated by the declining prices for the remaining factors, which again affects mostly rich households that own most of the land and the remaining factors.

5. The distributional patterns of *Border CO₂ price* with per capita-based distributions of revenues are similar to those of *Domestic CO₂ price* (see [Tables 3](#) and [5](#)). As expected, raising barriers to international trade via *Border CO₂ price* reduces imports to the EU countries and hence increases the scarcity of goods and raises their prices, as visible in [Table 5](#). Such goods price increases are disadvantageous for consumers (and similarly for producers with respect to intermediate goods prices). However, the reduced imports are replaced by domestically produced goods that require more production inputs. As a result, factor prices increase (or decrease to a smaller extent, respectively) with *Border CO₂ price* compared with *Domestic CO₂ price*, as visible in [Table 5](#). This generates a positive income effect for all income groups. Nonetheless, [Table 3](#) shows that the resulting welfare gain is most dominant in the low-income group (a 0.08 percentage point gain with *Border CO₂ price* relative to *Domestic CO₂ price*). This distributional pattern concurs with CGE model-based findings for trade liberalization in Chile ([O’Ryan et al., 2011](#)). The downside of this pattern is that negative effects from erecting trade barriers also tend to hit poor people harder than richer people ([Diao and Kennedy, 2016](#)). The middle-income group can also benefit from taxing imports (a 0.02 percentage point gain with *Border CO₂ price* relative to *Domestic CO₂ price*). In contrast, in the high-income group with the highest income and expenditures among the three groups, the losses from increased consumer prices and the gains from increased factor prices roughly counterbalance each other resulting in a minor loss (of less than 0.01 percentage points with *Border CO₂ price* relative to *Domestic CO₂ price*).

6. The estimated economy-wide welfare effect of *Domestic CO₂ price* on Germany amounts to -0.60% (see [Table 3](#)). Let us assume that German policymakers want to achieve an equal distribution of this effect across all income groups. Model runs with different distributions of revenues from CO₂ pricing reveal that a redistribution of approximately 12% for the low-income group, 29% for the middle-income group and 59% for the high-income group roughly achieves this egalitarian welfare distribution via climate policy without additional transfers from rich to poor groups.

7. Germany and the EU ETS countries gain when more countries in the world join a climate coalition with a joint CO₂ price, presumably, due to relatively low marginal abatement costs abroad. This reduces the climate policy-induced welfare losses of the German middle- (0.24% in *EUG7/CHN/IND, Dom*) and high-income groups (0.58% in *EUG7/CHN/IND, Dom*) compared with the analyzed EU policy (*Domestic CO₂ price*). Given the relatively low CO₂ prices in the scenario simulations, carbon border adjustments (*Bor*) are, however, blunt instruments for incentivizing countries to join a climate club.

8. Opposite effects are observed regarding the German low-income group. Because this group gains from CO₂ pricing, its welfare gain shrinks when more countries enter the climate policy coalition. This effect turns, however, when China and India join the G7 (*EUG7/CHN/IND, Dom*, 0.62%) and in the global coalition (*WORLD*, 0.90%). [Table 6](#) provides interesting insights into the underlying mechanisms: When more countries in the world introduce CO₂ pricing, consumption prices will increase, especially the consumption price index of the low-income group which is hit hard by this price increase given its relatively low income. When the climate coalition is extended, however, factor prices change as well. The wage rate and the capital rent increase relative to the

Benchmark (instead of a decline in the EU ETS scenarios). Likewise, the drastic devaluation of natural resources (including fossil fuels) in Germany is significantly dampened (−31.59% resource price change in *EUG7/CHN/IND*, *Dom* compared with −48.83% under EU policy in Table 5) because the CO₂ price in the EU ETS declines when more countries join the climate policy coalition and consequently the demand for fossil fuels increases in Germany. This effect is reversed under the assumption of a worldwide climate policy coalition (−38.15% resource price change in *WORLD*) because it exhibits a higher CO₂ price (€26.90) than, for example, the *EUG7/CHN/IND* club (€23.19 with *Bor*). Moreover, the increase in the land rent induced by the EU ETS policies is mitigated when the coalition expands, because the lower CO₂ price puts less pressure on the economy, especially the energy sector, to decarbonize by using more land (which is in reality particularly used for renewable energy installations that are not explicitly represented in the model).

4.4. Robustness

To evaluate the influence of uncertainty in crucial parameter values on the distributional policy results, we conduct a detailed sensitivity analysis following [Pothen and Hübler \(2018\)](#). To this end, we vary relevant (sets of) parameter values within our CGE model around the default values used in the analysis so far in three alternative ways: First, we assume upper and lower bounds of relevant parameter values. Second, we vary selected parameter values within an interval. Third, we carry out a computationally complex *Monte Carlo* analysis by repeatedly drawing random combinations of crucial parameter values. The results are presented in Sections B.6 to B.13 of the Appendix. The baseline (reference) values can be found in Table 3, particularly, the results for Germany (*DEU*).²⁹

Our sensitivity analysis is structured in eight steps:

1. In the robustness check reported in Table B4 of Appendix B.8, we uniformly vary the sector-specific *Armington* elasticities σ_i^M between *imported* goods by $\pm 10\%$ in all sectors i . In both policy scenarios, we find that deviations from the welfare effects in the baseline (see Table 3) are largest for the low-income group: Relative to the baseline, welfare gains increase (decrease) by 2.7% (2.5%) at the lower (upper) bound in the *Domestic CO₂ price* scenario. Similarly, we observe an increase (decrease) of 2.6% (2.4%) at the lower (upper) bound in the *Border CO₂ price* scenario. Compared with the low-income group, changes in welfare effects for the middle-income group are somewhat smaller in magnitude and less symmetric. We observe a decrease (increase) in the welfare loss of 1.7% (1.3%) at the lower (upper) bound in the *Domestic CO₂ price* scenario and a decrease (increase) in the welfare loss of 2.0% (1.6%) in the *Border CO₂ price* scenario. In contrast, only small changes are observed in the high-income group.

In the corresponding Monte Carlo analysis, we generate 1000 random draws from a $\pm 10\%$ interval around each of the sector-specific *Armington* elasticities σ_i^M (column 1 of Appendix Table B2) resulting in 1000 sets of sectoral parameter values.³⁰ We then recalibrate and solve the model for each set of parameter values and evaluate the welfare effects for the two policy scenarios. Appendix Figures B4 and B5 plot the resulting distributions of welfare effects for *Domestic CO₂ price* and *Border CO₂ price*, respectively, for each of the three income groups. Kernel density estimations are indicated by solid blue lines, and dashed vertical black lines represent 95% confidence intervals obtained via percentile bootstrapping ([Wilcox, 2012](#)) with 1000 drawings, i.e., using the 2.5th and 97.5th percentiles of the respective bootstrap distribution as the confidence interval.

We find that the welfare effects approximately follow normal distributions with narrow 95% confidence intervals. Interestingly, the distributions are slightly left-skewed for the middle-income group in both policy scenarios, which is in line with the slightly asymmetric changes in welfare effects observed in Table B4. For the *Domestic CO₂ price* scenario, the low-income group's welfare gain varies between 1.2973% and 1.2984% with 95% confidence, while the corresponding intervals for the middle- and high-income groups are (−0.4945%, −0.4940%) and (−1.2065%, −1.2057%), respectively. The welfare effects under *Border CO₂ price* exhibit similarly small 95% confidence intervals with (1.3892%, 1.3904%), (−0.4698%, −0.4693%) and (−1.2084%, −1.2076%) for low-, middle- and high-income groups, respectively.

2. The sensitivity analyses of the sector-specific elasticities between *domestically produced versus imported* goods σ_i^{DM} and the input elasticities between production factors σ_i^Z (Appendix Table B2) are conducted in an analogous fashion. The results are presented in Tables B5 and B6 and Figures B6 to B9 of Appendix B.9 and B.10. In accordance with the sensitivity analysis of the *Armington* elasticities, uniformly lowering σ_i^{DM} in all sectors leads to increases in welfare gains for the low-income group (vice versa for uniform increases of σ_i^{DM}). Likewise, lower values of σ_i^{DM} are associated with a small decrease in the welfare losses for the middle-income group. Overall, the results appear to be relatively robust to variations in σ_i^{DM} with changes in welfare effects ranging between −1.2% and 1.3% relative to the baseline across both policy scenarios. Regarding the distributional sensitivity analysis, Figures B6 and B7 indicate light-tailed distributions of welfare effects for the high-income group. This is confirmed by kurtosis values around 2.1, suggesting that extreme welfare effects occur less frequently than predicted based on a normal distribution.

3. Next, we vary the elasticity between different production factor inputs σ_i^Z . As shown in Table B6 of Appendix B.10, the welfare effects are hardly sensitive to variations in σ_i^Z by $\pm 10\%$: The choice of low values of σ_i^Z changes welfare effects of *Domestic CO₂ price* and *Border CO₂ price* by between −0.9% and 0.6% for all three income groups; likewise, welfare effects change by between −0.5% and 0.8% for high values of σ_i^Z . This insensitivity is also reflected in the narrow distributions shown in Figures B8 and B9.

²⁹ The differences between the welfare effects in the scenarios with alternative parameter choices and the baseline (reported in Table 3) are computed based on exact values (with more decimal places than those reported in the Tables) and then rounded to two decimal places.

³⁰ This means, the elasticity values of the model sectors i are varied simultaneously and independently so that each sectoral parameter value in-/decreases randomly within the $\pm 10\%$ interval.

4. We vary the elasticity of substitution σ^C in the consumption function of the consumer (in each region, in Germany also of each income group, see Appendix Figure B2) within a $\pm 50\%$ interval around the default value $\sigma^C = 1$ (Cobb–Douglas preferences for different goods) and solve the model under each policy scenario. As displayed in Table B7 of Appendix B.11, reducing σ^C by 50% results in an increase in the low-income group's welfare gain (by 35.2% or 34.6% depending on the scenario) and a decrease in the middle-income group's welfare loss (by 22.8% or 24.9%), while the high-income group experiences a small increase in its welfare loss (of more than 4.7% in both scenarios). Conversely, due to a 50% increase in σ^C , the low- and middle-income groups become worse off (at least 24.0% and 17.0%) while the high-income group's welfare loss decreases only slightly (2.8%) in both scenarios. These findings are also reflected in Figures B10 and B11 plotting the welfare effects of each policy scenario as a function of σ^C . The graphs show that the welfare gain of the low-income group decreases and the welfare loss of the middle-income group increases in higher values of σ^C , while the welfare loss of the high-income group decreases.

5. Data on factor income from land, natural resource and capital ownership and the distribution of revenues from CO₂ pricing are insufficiently available. Especially, natural resource ownership is crucial for climate policy effects, because the natural resources include fossil fuels. Therefore, we evaluate the distributional welfare effects given several alternative sets of the corresponding German income/revenue shares $\lambda_{DEU,f,\phi}^X$. By default, we distribute German income from land and natural resource ownership in the same way we distribute total consumption expenditures. Table B8 in Appendix B.12 reports the corresponding welfare effects assuming alternative distributions of the land and natural resources income shares across the income groups in the two policy scenarios. In column 1, we assume income shares of both land and natural resources to be 0%, 50% and 50% across the low-, middle- and high-income groups, respectively. We find that the welfare gain of the low-income group decreases (by 76% or 80% depending on the scenario), the respective welfare loss of the middle-income group decreases (by 84% or 88%) and the loss of the high-income group decreases (by approximately 4% in both scenarios). Analogously, column 2 assumes income shares of 50%, 0% and 50%, and column 3 assumes income shares of 50%, 50% and 0%. In both cases, the welfare loss of the respective income group with a share of 0% increases considerably. Column 4 sets the income shares of land and natural resources to the capital income shares of the three income groups (7.8%, 28.9% and 63.2% for the low-, middle- and high-income groups, respectively). In this case, the high-income group experiences a reduction of its welfare loss in both scenarios, whereas the middle-income group's welfare loss increases and the low-income group's welfare gain decreases significantly (51.5% and 48.5%). Column 5 sets the income shares to 1/3 for all three income groups, which leads to a considerable rise in the welfare gains of the low-income group (43.0% and 40.6%) and a small decrease in the losses of the middle-income group, while the welfare losses of the high-income group increase (ca. 16.0% in each case).

6. This robustness check addresses the lack of data from households with a monthly net income exceeding €18,000 by assuming alternative capital income shares $\lambda_{DEU,K,\phi}^X$ of the German income groups ϕ . To define a lower bound, we assume that the capital share of the German high-income group is as high as the average macro-economic German capital share, i.e., $\lambda_{DEU,K,high}^X = 16.46\%$, according to the German national accounts (disposable income in “Volkswirtschaftliche Gesamtrechnung”, VGR in 2013; [Statistisches Bundesamt, 2023](#)). To obtain an upper bound, we assume that only the high-income group receives more capital than recorded by the EVS data, such that the weighted average capital share across all German income groups matches the average share of 16.46%. In either case, the capital shares of the low- and middle-income groups are recalculated by keeping their absolute capital income values constant. Table B9 in Appendix B.12 displays the results. The middle-income group is affected most (between –16.53% and –31.60%) whereas the high-income group is affected least (between 1.39% and 2.38%). While the low- and middle-income groups become better off, the high-income group becomes worse off, because the decline in the capital price hits the high-income group harder when assuming a larger high-income capital share.

7. Table B10 in Appendix B.12 presents the welfare effects assuming alternative CO₂ pricing revenue shares across the income groups compared to the default per-capita distribution. Columns 1 to 3 assume the same distribution of income shares as the corresponding columns in Table B8. In column 1, setting the revenue share of the low-income group to 0% leads to a very considerable welfare loss for this group (switching from +1.3% to –1.8%, i.e., a 233.4% reduction), while the middle-income group experiences a substantial welfare gain (switching from –0.5% to +0.2%, i.e., a 144.6% improvement) and the high-income group a moderate decrease in its welfare loss (38.0%). Accordingly, for the groups that do not receive revenues, column 2 exhibits a high increase in the welfare loss of the middle-income group (289.5%) and column 3 a moderate increase in the welfare loss of the high-income group (76.2%). The other two groups receiving 50% of the revenues experience a significant increase in their welfare gain (116.7% in the low-income group) or a substantial reduction in their welfare loss (145.0% in the middle-income group). Column 4 reports the results of an alternative scenario assuming that the CO₂ pricing revenue shares are equal to the expenditure shares of the three income groups in total consumption. In this case, the high-income group experiences a moderate reduction in its welfare loss compared to the default per-capita distribution (30.7%), while the middle-income group slightly loses (16.4%) and the low-income group becomes considerably worse off (81.0%).

8. The default emissions target in the scenarios *Domestic CO₂ price* and *Border CO₂ price* is a 10% CO₂ reduction. This target is derived from the actual emissions reduction in the EU ETS in the benchmark year 2014. In the sensitivity analysis, we vary the emissions target in the range of 99% to 87% around the default target and repeatedly solve the model.³¹ The results of the policies *Domestic CO₂ price* and *Border CO₂ price* are presented in Figures B12 and B13 of Appendix B.13. In both policy scenarios, the welfare effects are qualitatively the same as under the default emissions target and quantitatively similar. While the welfare gains

³¹ More ambitious emissions reductions do not lead to feasible model solutions, because the model does not feature renewable energies, energy efficiency improvements or other decarbonization options explicitly; particularly, it does not feature a dynamic transition of the energy system.

of the low-income group increase in the emissions reductions, the middle- and high-income groups experience greater welfare losses due to more ambitious emissions reductions. These results suggest that the distributional patterns of the policies under scrutiny are qualitatively robust to moderate variations in the emissions target, and more ambitious emissions reductions cause stronger distributional effects across household income groups.

5. Conclusion

Computable general equilibrium (CGE) models have become standard tools for exploring new policies, such as climate policies. For policymakers and public debates, distributional effects have become increasingly important, especially against the background of increasing inequality. The explicit representation of consumers at different income levels *within* CGE models, however, is challenging. Therefore, it is important to analyze expenditure, income and tax revenue effects simultaneously in an interacting way based on a general equilibrium framework instead of computing those effects separately with statistical methods or in a cascade of modeling and econometric methods. Thus, we hope to provide some guidance for modelers who would like to implement a split of regionally representative consumers into n income groups independent of the particular model based on a standard consumption function.

Having implemented such a consumer split in our application in Germany, we find that the magnitudes and the *direction* of the investigated policy effects can be diverse across income groups and considerably different from the effects on a single representative consumer. In our case, notably, low-income households *benefit* from climate policy with a magnitude of the relative welfare change that significantly exceeds the economy-wide negative welfare effect. Because this benefit depends on the use of revenues of taxation (in our case, CO₂ pricing), our approach also allows the identification of the distribution of revenues that would make all income groups equally well off and thus replicates the economy-wide welfare effect throughout all income groups. A strict focus on economy-wide welfare effects can be misleading for a socially sensitive policy investigation. CO₂ pricing at the border, such as the EU CBAM, alters the distributional effects of domestic CO₂ only slightly. Hence, such a policy does not seem to introduce new distributional patterns but strengthens existing climate policy effects. Given the relatively low CO₂ prices and hence low CO₂-based tariff rates in the policy simulations, carbon border adjustments, are, however, blunt instruments for incentivizing countries to join a climate club. Notwithstanding, the EU ETS countries can substantially gain when they are able to encourage more countries in the world to join a climate club with a joint CO₂ price. The resulting increase in consumption prices is, however, especially harmful for low-income households, which can be compensated through a social transfer.

Our exemplary model is designed to be straightforward, compact and transparent. Therefore, it does not include a complex energy input and power generation system or complex future development scenarios with economic growth and an explicit energy transition. In future research, the model can be extended to a dynamic model that represents the transition of the energy system and enables the analysis of ambitious climate policy targets, possibly with forward-looking (strategic) behavior.

A future holistic distributional analysis (of climate policy) could also examine sector-specific differences of policy effects (as studied by Hübler and Lösche, 2013) as well as technology-specific effects (across renewable, fossil and nuclear energy technologies in the power sector, as studied by Fischer et al., 2021). In addition to different income groups, different social groups can be defined, e.g., based on professions, as far as the required data are available (see Siriwardana et al., 2013). In reality, however, not all households or social groups are affected by sector-specific shocks in the same way. Households often receive most of their income from one or a few sectors, which makes them vulnerable to shocks affecting these sectors. This mechanism is currently not represented in the model. The implementation of this mechanism requires household data that include the sectoral source of labor, capital and other types of income. Furthermore, data containing different income groups' expenditures on different *imported* goods would enable a more precise analysis of the *distributional* effects of import tariffs. New data could also provide better information on expenditures on durable goods across income groups. In studies like ours, insufficient expenditure information on durable goods can create a bias if these expenditures differ across income groups (in relative terms).

Further extensions of (publicly) available data sources may encompass private and public land and resource ownership, particularly the ownership of fossil fuels, because changes in the related revenues are significant drivers of distributional effects according to our policy analysis. Notwithstanding, our detailed distributional sensitivity analysis including upper and lower bound parameter values, alternative distributions of income/revenue shares across income groups and a complex *Monte Carlo* analysis confirms the (qualitative) validity of the policy results. To address the limitations of income and expenditure surveys, one can also link them to complementary surveys. In Germany (EVS data), the Socio-Economic Panel ("Sozio-oekonomisches Panel", SOEP), the wage and income tax statistics ("Faktisch anonymisierte Lohn- und Einkommenssteuerstatistik", FAST) and the Linked-Employer–Employee Dataset (LIAB) provide useful data sources (see, e.g., Bach et al., 2009, 2017; Buhlmann et al., 2022).

CRedit authorship contribution statement

Michael Hübler: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Malin Wiese:** Data curation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Marius Braun:** Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Johannes Damster:** Data curation, Software, Visualization.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.reseneeco.2024.101435>.

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Supplementary online appendix for

The distributional effects of CO₂ pricing at home and at the border on German income groups

Michael Hübler, Malin Wiese, Marius Braun, Johannes Damster

A Consumer disaggregation procedure

A.1 Data source

To disaggregate the representative consumer based on national accounts (Volkswirtschaftliche Gesamtrechnung, VGR), household expenditure data are required. Kronenberg (2010), for example, creates an input-output table with the household income and expenditure survey “Einkommens- und Verbrauchsstichprobe” (EVS) for the German federal state Mecklenburg-Vorpommern. Because the EVS is collected every five years only and was not collected in 2014, which is the base year of the Global Trade Analysis Project (GTAP) 10 data used in the model, we use the EVS of 2013 (FDZ, 2021), which is the closest year in which the survey was conducted. For this analysis, we only use the part of the survey that asks respondents explicitly about income and expenditures, the so-called “Haushaltsbuch” (HB) data file, a scientific use file with 98% coverage of all responses. More information on the data set (in German) can be found in FDZ (2019, 2020).

A.2 Conversion of consumption to goods categories

We use the consumption interdependence table provided by the German Federal Statistical Office (Statistisches Bundesamt, 2020) to transfer the consumption data from the EVS to the goods categories of the Classification of Products by Activity (CPA). The interdependence table is not available for the year of the EVS (2013) or the base year of the GTAP data; therefore, we use the available table from 2015, which is the year closest to the years of the EVS and GTAP 10 data (2013 and 2014, respectively). Because the consumption interdependence table is large, it is not displayed here but can be accessed online.³²

The following adjustments are required. We disaggregate the CPA category “Crude oil and natural gas” into the two model sectors *CRUD* and *NGAS*. Furthermore, we

³²https://www.statistischebibliothek.de/mir/receive/DEHeft_mods_00130396.

omit the CPA sector “Crude petroleum and natural gas” from the consumption interdependence table. We then calculate new conversion coefficients of the CPA sector that include “Electricity, gas, other fuels and district heating” such that the new coefficients add up to one. The newly created categories of “Crude oil” and “Natural gas” are not transferred into the CPA classification; they directly form the model categories *CRUD* and *NGAS*.

A.3 Aggregation of goods categories to model sectors

Table A1 displays how we aggregate the GTAP 10 sectors to our model sectors. Table A2 shows how the goods categories in the CPA classification are allocated to the GTAP 10 sectors or directly to the model sectors. The CPA sector “Crude petroleum and natural gas” (no. 06) is distributed across the two model sectors “Crude oil” (*CRUD*) and “Natural gas” (*NGAS*).

A.4 OECD equivalence scale

The EVS data are defined at the household level. When evaluating distributional effects, however, it is advisable to transfer income and consumption to the individual level because the available income per person in households with more members will be smaller than that in households with fewer members. In theory, however, we attempt to maximize consumption per capita. Notwithstanding, economies of scale emerge when households share goods or space such that the corresponding expenditures per person decline with a larger household size. Therefore, to obtain appropriate per capita-based data, we follow the German Federal Statistical Office (Statistisches Bundesamt, 2015) by applying the Organisation for Economic Co-operation and Development (OECD) equivalence scale (OECD, 2013). This scale attributes a weight of one to the household head (with the highest individual income), a weight of 0.5 to every other person in the household who is at least 14 years old, and a weight of 0.3 to every person who is less than 14.

Table A1
Aggregation of GTAP sectors to model sectors

Model		GTAP 10		
Sector	Description	No.	Code	Description
AGRI	Agriculture	1	pdr	Paddy rice
		2	wht	Wheat
		3	gro	Cereal grains nec.
		4	v_f	Vegetables, fruit, nuts
		5	osd	Oil seeds
		6	c_b	Sugar cane, sugar beet
		7	pfb	Plant-based fibres
		8	ocr	Crops nec.
		9	ctl	Bovine cattle, sheep and goats, horses
		10	oap	Animal products nec.
		11	rmk	Raw milk
		12	wol	Wool, silk-worm cocoons
		13	frs	Forestry
		14	fsh	Fishing
COAL	Coal	15	coa	Coal
CRUD	Crude oil	16	oil	Oil
NGAS	Natural gas	17	gas	Gas
		47	gdt	Gas manufacture, distribution
MINE	Mining	18	oxt	Other extraction
FOOD	Food production	19	cmt	Bovine meat products
		20	omt	Meat products nec.
		21	vol	Vegetable oils and fats
		22	mil	Dairy products
		23	pcr	Processed rice
		24	sgr	Sugar
		25	ofd	Food products nec.
		26	b_t	Beverages and tobacco products
MANU	Manufacturing	27	tex	Textiles
		28	wap	Wearing apparel
		29	lea	Leather products
		30	lum	Wood products
		39	fmp	Metal products
		40	ele	Computer, electronic and optical products
		41	eeq	Electrical equipment
		42	ome	Machinery and equipment nec.
		43	mvh	Motor vehicles and parts
		44	otn	Transport equipment nec.
45	omf	Manufactures nec.		
PAPR	Paper and pulp	31	ppp	Paper products, publishing
PETR	Refined petroleum	32	p_c	Petroleum, coal products
CHEM	Chemical, rubber, and plastic products	33	chm	Chemical products
		34	bph	Basic pharmaceutical products
		35	rpp	Rubber and plastic products
NMMS	Mineral products nec.	36	nmm	Mineral products nec.
IRST	Iron and steel	37	i_s	Ferrous metals
NFMS	Non-ferrous metals	38	nfm	Metals nec.
ELEC	Electricity	46	ely	Electricity
SERV	Services	48	wtr	Water
		50	trd	Trade (wholesale and retail)
		51	afs	Accommodation, food and service activities
		56	cmn	Communication
		57	ofi	Financial services nec.
		58	ins	Insurance
		59	rsa	Real estate activities
		60	obs	Business services nec.
		61	ros	Recreational and other services
		62	osg	Public administration and defense
		63	edu	Education
		64	hht	Human health and social work activities
		65	dwe	Dwellings
TRNS	Transport	52	otp	Transport nec.
		53	wtp	Water transport
		54	atp	Air transport
		55	whs	Warehousing and support activities
CONS	Construction	49	cns	Construction

Aggregation of the GTAP sectors to the model sectors i defined by Pothen and Hübler (2018) adapted to the GTAP 10 database (Aguilar et al., 2019). The original GTAP sectors can be found at https://www.gtap.agecon.purdue.edu/databases/v10/v10_sectors.aspx.

Table A2
Conversion from CPA to GTAP and model sectors

CPA Nr.	CPA Name	GTAP 10	Model
1	01	Products of agriculture, hunting and related services	AGRI
2	02	Products of forestry, logging and related services	AGRI
3	03	Fish and other fishing products; aquaculture products; support services for fishing	AGRI
4	5.1	Hard coal	COAL
5	5.2	Lignite	COAL
6	06	Crude petroleum and natural gas	CRUD
	06.1	Crude petroleum	NGAS
	06.2	Natural gas	MINE
7	07	Metal ores	MINE
8	08-09	Other mining and quarrying products and mining support services	FOOD
9	10	Food products	FOOD
10	11	Beverages	FOOD
11	12	Tobacco products	b-t
12	13	Textiles	b-t
13	14	Wearing apparel	FOOD
14	15	Leather and related products	MANU
15	16	Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials	MANU
16	17.1	Pulp, paper and paperboard	MANU
17	17.2	Articles of paper and paperboard	MANU
18	18	Printing and recording services	MANU
19	19.1	Coke oven products	MANU
20	19.2	Refined petroleum products	MANU
21	20	Chemicals and chemical products	MANU
22	21	Basic pharmaceutical products and pharmaceutical preparations	PAPR
23	22.1	Rubber products	PAPR
24	22.2	Plastic products	PAPR
25	23.1	Glass and glass products	PAPR
26	23.2-23.9	Refractory products, clay building materials, Other porcelain and ceramic products, Cement, lime and plaster, articles of concrete, cement and plaster, Cut, shaped and finished stone, Other non-metallic mineral products	PAPR
27	24.1-24.3	Basic iron and steel and ferroalloys, tubes, pipes, hollow profiles and related fittings, of steel, and other products of the first processing of steel	PAPR
28	24.4	Basic precious and other non-ferrous metals	PAPR
29	24.5	Casting services of metals	PAPR
30	25	Fabricated metal products, except machinery and equipment	PAPR
31	26	Computer, electronic and optical products	PAPR
32	27	Electrical equipment	PAPR
33	28	Machinery and equipment n.e.c.	PAPR
34	29	Motor vehicles, trailers and semi-trailers	PAPR
35	30	Other transport equipment	PAPR
36	31	Furniture	PAPR
37	32	Other manufactured goods	PAPR
38	33	Repair and installation services of machinery and equipment	PAPR
39	35.1, 35.3	Electricity, transmission and distribution services, Steam and air conditioning supply services	PAPR
40	35.2	Manufactured gas; distribution services of gaseous fuels through mains	PAPR
41	36	Natural water; water treatment and supply services	PAPR
42	37	Sewage services; sewage sludge	PAPR

CPA categories no. 1 and no. 9 are transferred to sectors *AGRI* and *FOOD*. The specially treated CPA category "Crude oil and natural gas" is disaggregated into the two categories "Crude petroleum" (assigned no. 06.1) and "Natural gas" (assigned no. 06.2), which are not original CPA categories resulting from the consumption interdependence table but are calculated directly from the corresponding data in the EVS.
Table continues on the next page.

CPA Nr.	CPA Name	GTAP 10	Model
43	Waste collection, treatment and disposal services; materials recovery services	wtr	SERV
44	Remediation services and other waste management services	wtr	SERV
45	Buildings and building construction works	cns	CONS
46	Constructions and construction work for civil engineering	cns	CONS
47	Specialized construction work	cns	CONS
48	Wholesale and retail trade and repair services of motor vehicles and motorcycles	trd	SERV
49	Wholesale trade services, except of motor vehicles and motorcycles	trd	SERV
50	Retail trade services, except of motor vehicles and motorcycles	trd	SERV
51	Land transport services and transport services via pipelines	otp	TRNS
52	Water transport services	wtp	TRNS
53	Air transport services	atp	TRNS
54	Warehousing and support services for transportation	whs	TRNS
55	Postal and courier services	cmn	SERV
56	Accommodation services and food and beverage serving services	afs	SERV
57	Publishing services	cmn	SERV
58	Motion picture, video and television program production services, sound recording and music publishing and programming and broadcasting services	cmn	SERV
59	Telecommunications services	cmn	SERV
60	Computer programming, consultancy and related services and information services	cmn	SERV
61	Financial services, except insurance and pension funding	ofi	SERV
62	Insurance, reinsurance and pension funding services, except compulsory social security	ins	SERV
63	Services auxiliary to financial services and insurance services	ins, ofi	SERV
64	Real estate services	rsa	SERV
65	Legal and accounting services and Services of head offices; management consulting services	obs	SERV
66	Architectural and engineering services; technical testing and analysis services	obs	SERV
67	Scientific research and development services	obs	SERV
68	Advertising and market research services	obs	SERV
69	Other professional, scientific and technical services	obs	SERV
70	Veterinary services	obs	SERV
71	Rental and leasing services	obs	SERV
72	Employment services	obs	SERV
73	Travel agency, tour operator and other reservation services and related services	obs	SERV
74	Security and investigation services, Services for buildings and landscape, Office administration, office support and other business support services	obs	SERV
75	Administration services of the state and the economic and social policy of the community and Provision of services to the community as a whole	osg	SERV
76	Compulsory social security services	osg	SERV
77	Education services	edu	SERV
78	Human health services	hht	SERV
79	Residential care services and social work services without accommodation	hht	SERV
80	Creative, arts and entertainment services and library, archive, museum and other cultural services and Gambling and betting services	ros	SERV
81	Sporting services and amusement and recreation services	ros	SERV
82	Services furnished by membership organizations	ros	SERV
83	Repair services of computers and personal and household goods	obs	SERV
84	Other personal services	ros	SERV
85	Services of households as employers of domestic personnel and undifferentiated goods and services produced by private households for own use	ros	SERV

Model sectors defined by Pothén and Hübler (2018) adapted to GTAP 10. The goods categories following the Classification of Products by Activity (CPA) are derived from the German consumption interdependence table, which can be accessed at https://www.statistischebibliothek.de/mir/receive/DEHeft_mods.00130396.

A.5 Income calculation

Table A3
EVS data items used to generate the required income types

Data item	Number in the EVS
Income from employment	EF109-EF119
+ Non-cash benefits belonging to the salary	EF120-EF133
+ Income from self-employment	EF134-EF136, EF176, EF137
= <i>Labor income</i>	
Income from assets	EF178-EF182
= <i>Capital income</i>	
Pensions from state pension insurance	EF138-EF140
+ Other pensions	EF142-EF144
+ Transfers from public health insurance funds	EF145, EF146
+ Transfers from programs for the promotion of employment	EF147-EF149, EF151-EF152
+ Transfers of regional authorities	EF153-EF161, EF183-EF184, EF162-EF168
+ Public pensions	EF169-EF170
+ Income from non-public transfer payments	EF171-EF173, EF185-EF192, EF174
+ Additional payments from the employer / pension insurance provider	EF116, EF117, EF141
+ Revenue from sale of goods and other revenue	EF68
+ Income from subletting	EF193
– Income and church taxes (including solidarity surcharge)	EF94
– Compulsory social insurance contributions, contributions to voluntary public and private health insurance	EF95
– Other taxes	EF96
– Insurance contributions	EF98
– Other transfers made	EF100
– Other expenses	EF103
– Contributions to supplementary public service pension scheme (e.g. VBL employee’s share)	EF230
– Voluntary contributions to public pension insurance	EF232
= <i>Net transfers</i>	

Data items from the “Einkommens- und Verbrauchsstichprobe” (EVS) 2013 (FDZ, 2021) used to generate the required income types of labor income, capital income and net transfers.

A.6 Savings calculation

Table A4
EVS data items used to generate savings

Data item	Number in the EVS
Expenditure on asset formation	EF101
+ Repayment of loans (principal and interest)	EF102
– Income from the liquidation of tangible assets	EF69
– Income from the liquidation of financial assets	EF70
– Income from loans	EF71
= <i>Savings</i>	

Data items of the “Einkommens- und Verbrauchsstichprobe” (EVS) 2013 (FDZ, 2021) used to generate the required savings data.

A.7 Resulting data on three income groups

The following tables contain the numbers presented in the figures in Section 2.6.

Table A5

Horizontal source distribution of German income and its use for consumpt. and savings

Income group	Labor income	Capital income	Net transfers	Disposable income	Consumption	Savings
Low	132.10	15.07	83.96	231.13	246.05	-7.25
	(57.15%)	(6.52%)	(36.33%)	(100%)	(103.04%)	(-3.04%)
Mid	346.13	55.59	-7.04	394.68	359.11	34.91
	(87.70%)	(14.09%)	(-1.78%)	(100%)	(91.14%)	(8.86%)
High	716.01	121.51	-125.89	711.63	527.29	162.49
	(100.62%)	(17.08%)	(-17.69%)	(100%)	(76.44%)	(23.56%)

Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of disposable income across income sources and consumption expenditures versus savings within each income group. Data source: authors' own calculation drawing on data from the Research Data Centre (RDC) of the German Federal Statistical Office and Statistical Offices of the Federal States, "Einkommens- und Verbrauchsstichprobe" 2013, base file 5 (FDZ, 2021).

Table A6

Vertical group distribution of German income and its use for consumption and savings

Income group	Labor income	Capital income	Net transfers	Disposable income	Consumption	Savings
Low	132.10	15.07	83.96	231.13	246.05	-7.25
	(11.06%)	(7.84%)	(-171.45%)	(17.28%)	(21.73%)	(-3.81%)
Mid	346.13	55.59	-7.04	394.68	359.11	34.91
	(28.98%)	(28.93%)	(14.37%)	(29.51%)	(31.71%)	(18.36%)
High	716.01	121.51	-125.89	711.63	527.29	162.49
	(59.96%)	(63.23%)	(257.08%)	(53.21%)	(46.56%)	(85.45%)
Total	1,194.24	192.18	-48.97	1,337.45	1,132.45	190.15
	(100%)	(100%)	(100%)	(100%)	(100%)	(100%)

Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of each income type, disposable income, consumption expenditures and savings across the income groups. Data source: authors' own calculation; FDZ (2021), see above.

Table A7

Distribution of German consumption across goods in billions of euros

Income group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
Low	7.80	7.38	1.01	0.61	1.89	9.03	37.57	0.65	0.65	31.84	0.01	3.85	0.62	2.25	9.85	126.82	4.22	246.05
Mid	9.98	11.38	1.07	1.46	3.86	9.66	46.07	1.14	1.14	60.04	0.02	5.28	1.20	3.24	16.92	181.26	5.38	359.11
High	11.80	17.54	1.15	2.38	5.31	10.36	52.64	1.73	1.73	109.28	0.04	7.06	1.95	4.49	23.59	266.90	9.34	527.29
Total	29.58	36.29	3.23	4.45	11.05	29.06	136.29	3.52	3.52	201.16	0.08	16.19	3.77	9.98	50.36	574.98	18.94	1132.45

Horizontal goods distribution of German consumption in percent

Income group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
Low	3.17	3.00	0.41	0.25	0.77	3.67	15.27	0.26	0.26	12.94	0.01	1.56	0.25	0.92	4.00	51.54	1.71	100
Mid	2.78	3.17	0.30	0.41	1.07	2.69	12.83	0.32	0.32	16.72	0.01	1.47	0.33	0.90	4.71	50.47	1.50	100
High	2.24	3.33	0.22	0.45	1.01	1.97	9.98	0.33	0.33	20.72	0.01	1.34	0.37	0.85	4.47	50.62	1.77	100

Vertical group distribution of German consumption in percent

Income group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
Low	26.38	20.33	31.14	13.66	17.07	31.08	27.57	18.41	18.41	15.83	18.87	23.77	16.36	22.56	19.56	22.06	22.28	21.73
Mid	33.75	31.35	33.25	32.76	34.92	33.26	33.80	32.35	32.35	29.85	31.39	32.63	31.92	32.49	33.60	31.52	28.39	31.71
High	39.87	48.32	35.60	53.57	48.02	35.66	38.63	49.24	49.24	54.32	49.74	43.60	51.72	44.95	46.83	46.42	49.33	46.56
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

The absolute values at the top refer to Germany in the year 2013 and are reported in billions of euros. The corresponding percentage shares in the middle display the distribution of consumption expenditures across goods (sectors) within each income group. The percentage shares at the bottom display the distribution of consumption expenditures for each good across income groups. Data source: authors' own calculation; FDZ (2021), see above.

A.8 Resulting data on more income groups

A.8.1 Five income groups

Figure A1
Distribution of total German income

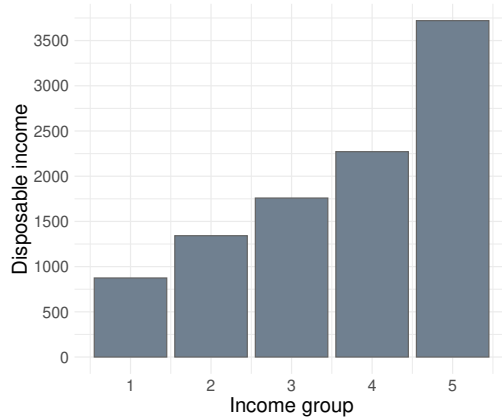


Figure A2
German income sources by income group

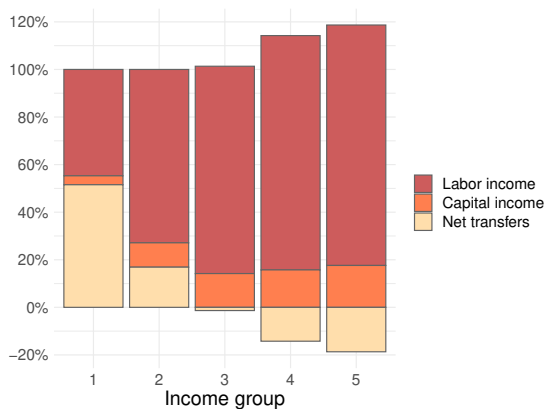


Figure A3
German savings/cons. by income group

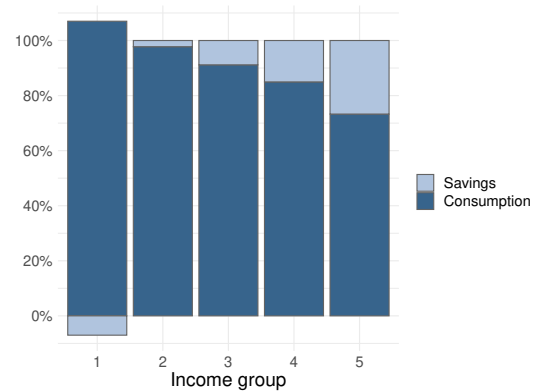


Figure A4
German income sources by source type

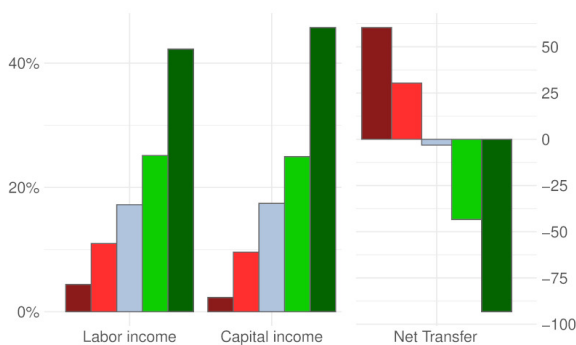
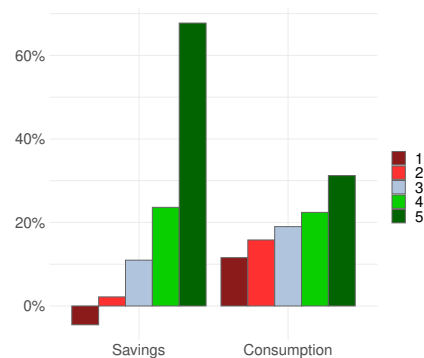


Figure A5
German savings vs. consumption



Income group 1 has the lowest income, and group 5 the highest income. Top row: distribution of the mean equivalent disposable income (total disposable income divided by the number of equivalent people based on the OECD scale) per month of the 52,421 German households in the survey across the income groups in euros. Middle row: Horizontal distribution of income sources (left) and their use for savings versus consumption expenditures (right) within each income group in percent. Bottom row: Vertical distribution of income sources (left) and their use for savings versus consumption expenditures (right) across income groups; net transfers are in billions of euros, and other sources are in percent. Data source: authors' own calculation drawing on data from the Research Data Centre (RDC) of the German Federal Statistical Office and Statistical Offices of the Federal States, "Einkommens- und Verbrauchsstichprobe" 2013, base file 5 (FDZ, 2021). See the following tables for the numbers.

Table A8

Horizontal source distribution of German income and its use for consumpt. and savings

Income group	Labor income	Capital income	Net transfers	Disposable income	Consumption	Savings
1	52.45 (44.71%)	4.42 (3.77%)	60.46 (51.53%)	117.33 (100%)	130.92 (107.01%)	-8.58 (-7.01%)
2	131.23 (72.88%)	18.43 (10.23%)	30.42 (16.89%)	180.08 (100%)	179.00 (97.75%)	4.12 (2.25%)
3	205.65 (87.15%)	33.50 (14.20%)	-3.19 (-1.35%)	235.97 (100%)	215.19 (91.16%)	20.86 (8.84%)
4	300.25 (98.51%)	47.94 (15.73%)	-43.39 (-14.24%)	304.80 (100%)	253.83 (84.97%)	44.91 (15.03%)
5	504.64 (101.08%)	87.88 (17.60%)	-93.26 (-18.68%)	499.25 (100%)	353.50 (73.29%)	128.83 (26.71%)

Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of the disposable income across income sources and expenditures within each income group (1 lowest, 5 highest). Data source: authors' own calculation; FDZ (2021), see above.

Table A9

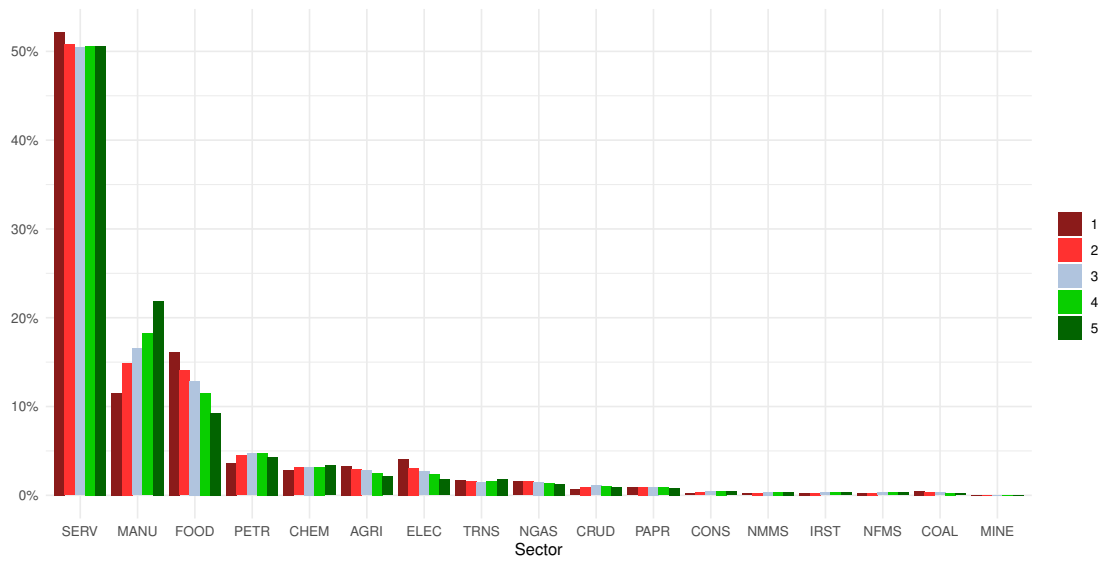
Vertical group distribution of German income and its use for consumption and savings

Income group	Labor income	Capital income	Net transfers	Disposable income	Consumption	Savings
1	52.45 (4.39%)	4.42 (2.30%)	60.46 (-123.48%)	117.33 (8.77%)	130.92 (11.56%)	-8.58 (-4.51%)
2	131.23 (10.99%)	18.43 (9.59%)	30.42 (-62.12%)	180.08 (13.46%)	179.00 (15.81%)	4.12 (2.17%)
3	205.65 (17.22%)	33.50 (17.43%)	-3.19 (6.52%)	235.97 (17.64%)	215.19 (19.00%)	20.86 (10.97%)
4	300.25 (25.14%)	47.94 (24.95%)	-43.39 (88.62%)	304.80 (22.79%)	253.83 (22.41%)	44.91 (23.62%)
5	504.64 (42.26%)	87.88 (45.73%)	-93.26 (190.47%)	499.25 (37.33%)	353.50 (31.22%)	128.83 (67.75%)
Total	1,194.22 (100%)	192.17 (100%)	-48.96 (100%)	1,337.43 (100%)	1,132.44 (100%)	190.15 (100%)

Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of each income type, disposable income, consumption expenditures and savings across the income groups (1 lowest, 5 highest). Data source: authors' own calculation; FDZ (2021), see above.

Figure A6

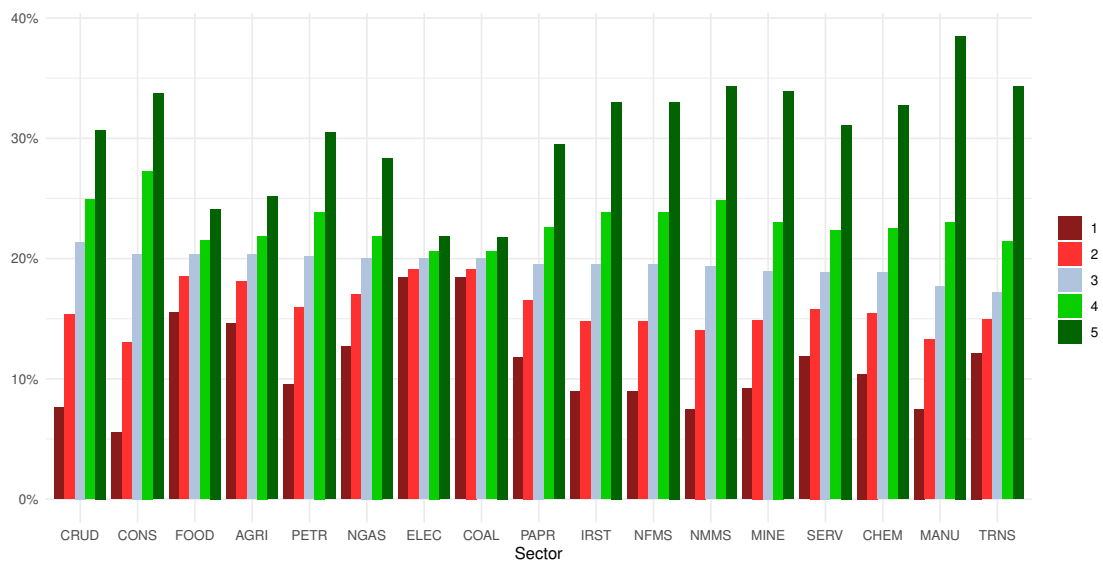
Horizontal distribution of German consumption expenditures of each group across goods



Horizontal distribution of each income group's (1 lowest, 5 highest) consumption expenditures across goods (sectors) in Germany. Data source: authors' own calculation; FDZ (2021), see above. See the following table for the numbers.

Figure A7

Vertical distribution of German consumption expenditures on each good across groups



Vertical distribution of consumption expenditures on each good (sector) across the income groups (1 lowest, 5 highest) in Germany. Data source: authors' own calculation; FDZ (2021), see above. See the following table for the numbers.

Table A10

Distribution of German consumption across goods in billions of euros

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	4.31	3.77	0.60	0.25	0.85	5.35	21.13	0.31	0.31	15.11	0.01	2.06	0.28	1.18	4.81	68.30	2.30	130.92
2	5.35	5.61	0.62	0.58	1.70	5.55	25.20	0.52	0.52	26.69	0.01	2.76	0.53	1.65	8.01	90.86	2.83	179.00
3	6.01	6.85	0.65	0.91	2.36	5.82	27.75	0.69	0.69	35.59	0.01	3.25	0.73	1.95	10.15	108.54	3.25	215.19
4	6.47	8.17	0.67	1.21	2.75	5.99	29.32	0.84	0.84	46.31	0.02	3.54	0.94	2.26	12.03	128.42	4.06	253.83
5	7.44	11.88	0.70	1.50	3.39	6.35	32.89	1.16	1.16	77.46	0.03	4.59	1.29	2.94	15.36	178.86	6.49	353.50
Total	29.58	36.29	3.23	4.45	11.05	29.06	136.29	3.52	3.52	201.16	0.08	16.19	3.77	9.98	50.36	574.97	18.94	1,132.44

Horizontal goods distribution of German consumption in percent

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	3.30	2.88	0.46	0.19	0.65	4.09	16.14	0.24	0.24	11.54	0.01	1.57	0.21	0.90	3.68	52.17	1.76	100
2	2.99	3.14	0.35	0.32	0.95	3.10	14.08	0.29	0.29	14.91	0.01	1.54	0.30	0.92	4.48	50.76	1.58	100
3	2.79	3.18	0.30	0.42	1.10	2.70	12.90	0.32	0.32	16.54	0.01	1.51	0.34	0.91	4.72	50.44	1.51	100
4	2.55	3.22	0.26	0.48	1.08	2.36	11.55	0.33	0.33	18.24	0.01	1.40	0.37	0.89	4.74	50.59	1.60	100
5	2.10	3.36	0.20	0.42	0.96	1.80	9.30	0.33	0.33	21.91	0.01	1.30	0.37	0.83	4.35	50.60	1.84	100

Vertical group distribution of German consumption in percent

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	14.58	10.40	18.45	5.54	7.65	18.40	15.51	8.93	8.93	7.51	9.21	12.71	7.43	11.79	9.55	11.88	12.15	11.56
2	18.08	15.47	19.12	13.05	15.37	19.11	18.49	14.75	14.75	13.27	14.88	17.04	14.08	16.57	15.91	15.80	14.92	15.81
3	20.33	18.87	20.01	20.40	21.37	20.01	20.36	19.49	19.49	17.69	18.96	20.04	19.33	19.55	20.15	18.88	17.19	19.00
4	21.87	22.52	20.61	27.29	24.92	20.63	21.51	23.83	23.83	23.02	23.04	21.89	24.82	22.60	23.88	22.33	21.44	22.41
5	25.14	32.74	21.81	33.73	30.70	21.85	24.13	33.01	33.01	38.51	33.90	28.33	34.33	29.49	30.50	31.11	34.30	31.22
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

The absolute values at the top refer to Germany in the year 2013 and are reported in billions of euros. The corresponding percentage shares in the middle display the distribution of consumption expenditures across goods (sectors) within each income group (1 lowest, 5 highest). The percentage shares at the bottom display the distribution of consumption expenditures for each sector good across the income groups. Data source: authors' own calculation; FDZ (2021), see above.

A.8.2 Ten income groups

Figure A8
Distribution of total German income

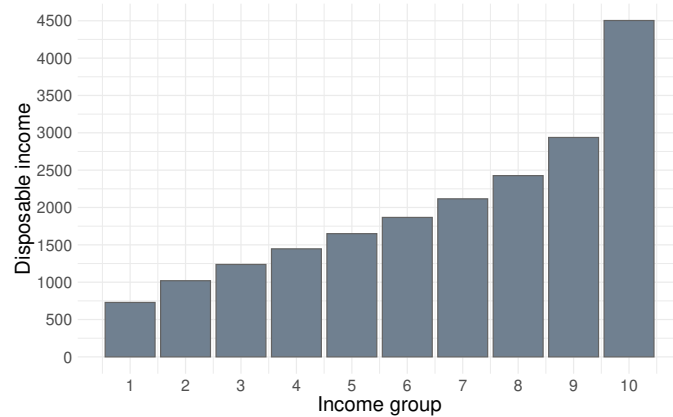


Figure A9
German income sources by income group

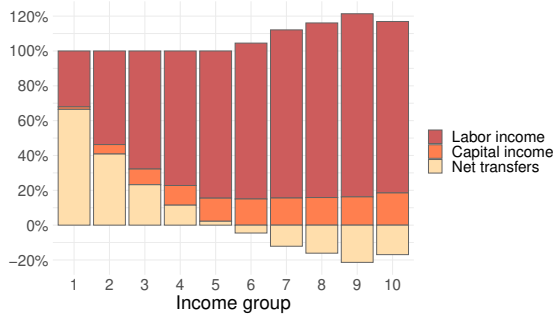


Figure A10
German savings/cons. by income group

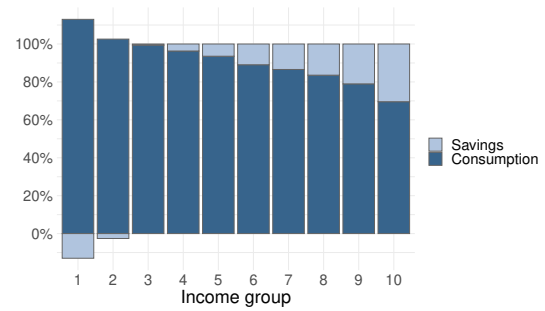


Figure A11
German income sources by source type

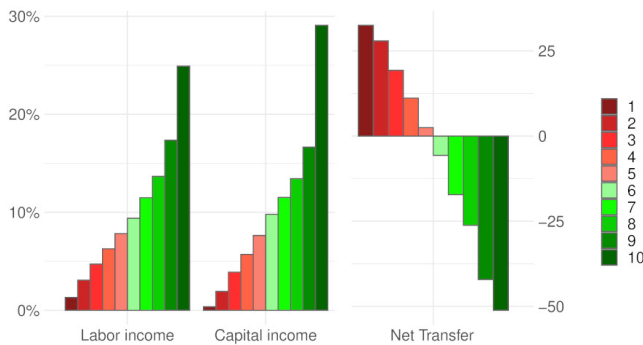
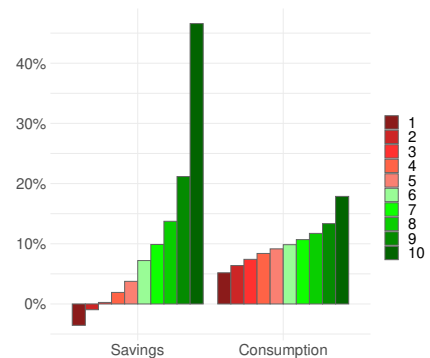


Figure A12
German savings vs. consumption



Income group 1 has the lowest income, and group 10 has the highest income. Top row: distribution of the mean equivalent disposable income (total disposable income divided by the number of equivalent people based on the OECD scale) per month of the 52,421 German households in the survey across the income groups in euros. Middle row: Horizontal distribution of income sources (left) and their use for savings versus consumption expenditures (right) within each income group in percent. Bottom row: Vertical distribution of income sources (left) and their use for savings versus consumption expenditures (right) across the income groups; net transfers in billions of euros, other sources in percent. Data source: authors' own calculation drawing on data from the Research Data Centre (RDC) of the German Federal Statistical Office and Statistical Offices of the Federal States, "Einkommens- und Verbrauchsstichprobe" 2013, base file 5 (FDZ, 2021). See the following tables for the numbers.

Table A11

Horizontal source distribution of German income and its use for consumpt. and savings

Income Group	Labor Income	Capital Income	Net Transfers	Disposable Income	Consumption	Savings
1	15.68 (32.07%)	0.71 (1.44%)	32.52 (66.49%)	48.91 (100%)	58.68 (113.01%)	-6.75 (-13.01%)
2	36.78 (53.74%)	3.71 (5.43%)	27.94 (40.83%)	68.43 (100%)	72.25 (102.59%)	-1.82 (-2.59%)
3	56.28 (67.79%)	7.47 (9.00%)	19.27 (23.21%)	83.03 (100%)	83.95 (99.43%)	0.48 (0.57%)
4	74.96 (77.23%)	10.96 (11.29%)	11.14 (11.48%)	97.06 (100%)	95.05 (96.31%)	3.65 (3.69%)
5	93.53 (84.50%)	14.68 (13.26%)	2.48 (2.24%)	110.69 (100%)	103.69 (93.55%)	7.14 (6.45%)
6	112.12 (89.50%)	18.82 (15.03%)	-5.67 (-4.53%)	125.28 (100%)	111.50 (89.05%)	13.71 (10.95%)
7	137.04 (96.52%)	22.13 (15.59%)	-17.19 (-12.11%)	141.98 (100%)	121.06 (86.56%)	18.80 (13.44%)
8	163.21 (100.24%)	25.82 (15.86%)	-26.20 (-16.09%)	162.82 (100%)	132.77 (83.56%)	26.12 (16.44%)
9	207.23 (105.14%)	32.00 (16.23%)	-42.12 (-21.37%)	197.10 (100%)	151.12 (78.97%)	40.25 (21.03%)
10	297.42 (98.43%)	55.89 (18.50%)	-51.14 (-16.92%)	302.17 (100%)	202.38 (69.55%)	88.58 (30.45%)

Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of the disposable income across income sources and consumption expenditures versus savings within each income group (1 lowest, 10 highest). Data source: authors' own calculation; FDZ (2021), see above.

Table A12

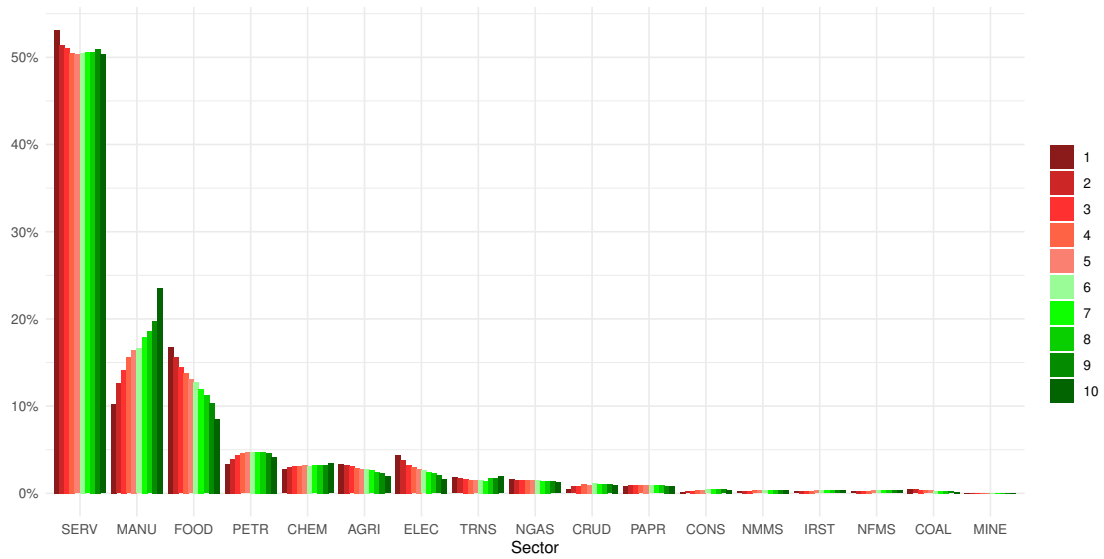
Vertical group distribution of German income and its use for consumption and savings

Income Group	Labor Income	Capital Income	Net Transfers	Disposable Income	Consumption	Savings
1	15.68 (1.31%)	0.71 (0.37%)	32.52 (-66.40%)	48.91 (3.66%)	58.68 (5.18%)	-6.75 (-3.55%)
2	36.78 (3.08%)	3.71 (1.93%)	27.94 (-57.06%)	68.43 (5.12%)	72.25 (6.38%)	-1.82 (-0.96%)
3	56.28 (4.71%)	7.47 (3.89%)	19.27 (-39.35%)	83.03 (6.21%)	83.95 (7.41%)	0.48 (0.25%)
4	74.96 (6.28%)	10.96 (5.70%)	11.14 (-22.75%)	97.06 (7.26%)	95.05 (8.39%)	3.65 (1.92%)
5	93.53 (7.83%)	14.68 (7.64%)	2.48 (-5.06%)	110.69 (8.28%)	103.69 (9.16%)	7.14 (3.76%)
6	112.12 (9.39%)	18.82 (9.79%)	-5.67 (11.58%)	125.28 (9.37%)	111.50 (9.85%)	13.71 (7.21%)
7	137.04 (11.48%)	22.13 (11.51%)	-17.19 (35.10%)	141.98 (10.62%)	121.06 (10.69%)	18.80 (9.88%)
8	163.21 (13.67%)	25.82 (13.43%)	-26.20 (53.50%)	162.82 (12.17%)	132.77 (11.72%)	26.12 (13.74%)
9	207.23 (17.35%)	32.00 (16.65%)	-42.12 (86.01%)	197.10 (14.74%)	151.12 (13.34%)	40.25 (21.17%)
10	297.42 (24.90%)	55.89 (29.08%)	-51.14 (104.43%)	302.17 (22.59%)	202.38 (17.87%)	88.58 (46.58%)
Total	1,194.25 (100%)	192.18 (100%)	-48.97 (100%)	1,337.46 (100%)	1,132.45 (100%)	190.16 (100%)

Absolute values refer to Germany in the year 2013 and are reported in billions of euros. The percentage shares displayed in parentheses show the distribution of each income type, disposable income, consumption expenditures and savings across the income groups (1 lowest, 10 highest). Data source: authors' own calculation; FDZ (2021), see above.

Figure A13

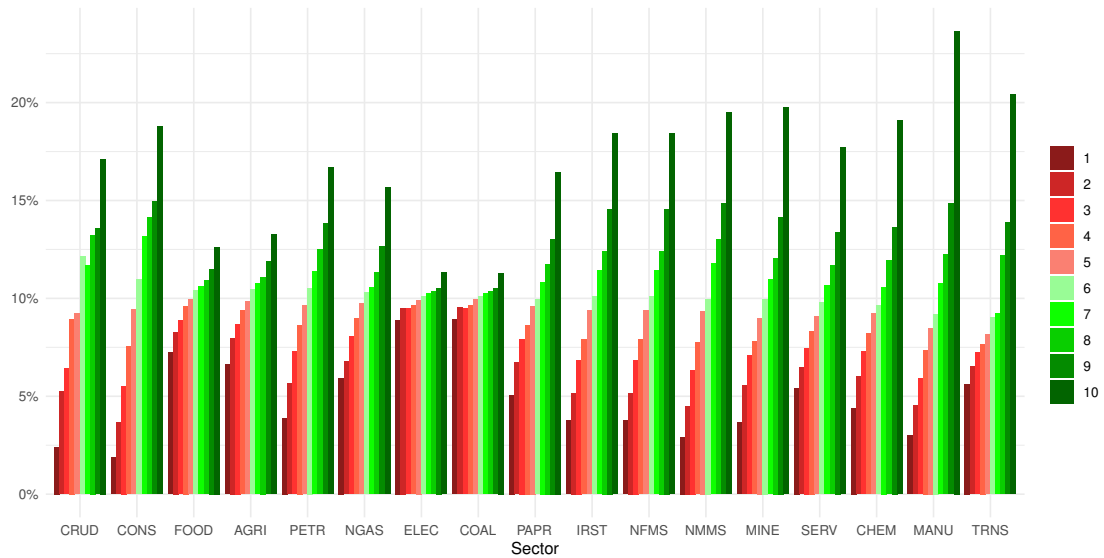
Horizontal distribution of German consumption expenditures of each group across goods



Horizontal distribution of each income group's (1 lowest, 10 highest) consumption expenditures across goods (sectors) in Germany. Data source: authors' own calculation; FDZ (2021), see above. See the following table for the numbers.

Figure A14

Vertical distribution of German consumption expenditures on each good across groups



Vertical distribution of consumption expenditures on each good (sector) across income groups (1 lowest, 10 highest) in Germany. Data source: authors' own calculation; FDZ (2021), see above. See the following table for the numbers.

Table A13
Distribution of German consumption across goods in billions of euros

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	1.96	1.60	0.29	0.08	0.27	2.58	9.84	0.13	0.13	6.02	0.00	0.96	0.11	0.51	1.96	31.17	1.06	58.68
2	2.36	2.18	0.31	0.16	0.58	2.76	11.29	0.18	0.18	9.09	0.00	1.10	0.17	0.67	2.85	37.13	1.24	72.25
3	2.57	2.64	0.31	0.25	0.71	2.76	12.10	0.24	0.24	11.88	0.01	1.31	0.24	0.79	3.66	42.89	1.37	83.95
4	2.78	2.97	0.31	0.34	0.99	2.80	13.10	0.28	0.28	14.82	0.01	1.45	0.29	0.86	4.35	47.98	1.45	95.05
5	2.92	3.35	0.32	0.42	1.02	2.88	13.55	0.33	0.33	17.07	0.01	1.58	0.35	0.96	4.85	52.20	1.54	103.69
6	3.10	3.50	0.33	0.49	1.34	2.93	14.20	0.36	0.36	18.52	0.01	1.67	0.38	0.99	5.30	56.34	1.71	111.50
7	3.19	3.84	0.33	0.59	1.29	2.98	14.45	0.40	0.40	21.68	0.01	1.71	0.44	1.08	5.73	61.20	1.75	121.06
8	3.28	4.33	0.33	0.63	1.46	3.01	14.87	0.44	0.44	24.63	0.01	1.84	0.49	1.17	6.30	67.22	2.31	132.77
9	3.51	4.95	0.34	0.67	1.50	3.06	15.68	0.51	0.51	29.87	0.01	2.05	0.56	1.30	6.95	77.01	2.63	151.12
10	3.93	6.93	0.36	0.84	1.89	3.29	17.21	0.65	0.65	47.59	0.01	2.54	0.73	1.64	8.41	101.85	3.87	202.38
Total	29.58	36.29	3.23	4.45	11.05	29.06	136.29	3.52	3.52	201.16	0.08	16.19	3.77	9.98	50.36	574.98	18.94	1132.45

Horizontal goods distribution of German consumption

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	3.34	2.72	0.49	0.14	0.46	4.40	16.78	0.22	0.22	10.26	0.00	1.64	0.19	0.86	3.34	53.11	1.81	100
2	3.26	3.01	0.43	0.23	0.80	3.83	15.62	0.25	0.25	12.58	0.01	1.52	0.23	0.93	3.95	51.39	1.71	100
3	3.07	3.14	0.37	0.29	0.85	3.28	14.41	0.29	0.29	14.15	0.01	1.56	0.28	0.94	4.36	51.08	1.64	100
4	2.92	3.13	0.33	0.35	1.04	2.94	13.78	0.29	0.29	15.59	0.01	1.53	0.31	0.91	4.58	50.47	1.53	100
5	2.81	3.23	0.31	0.41	0.99	2.78	13.07	0.32	0.32	16.47	0.01	1.52	0.34	0.92	4.67	50.34	1.49	100
6	2.78	3.14	0.29	0.44	1.20	2.63	12.73	0.32	0.32	16.61	0.01	1.50	0.34	0.89	4.75	50.53	1.53	100
7	2.63	3.17	0.27	0.48	1.07	2.46	11.93	0.33	0.33	17.90	0.01	1.41	0.37	0.89	4.73	50.55	1.44	100
8	2.47	3.26	0.25	0.47	1.10	2.27	11.20	0.33	0.33	18.55	0.01	1.38	0.37	0.88	4.74	50.63	1.74	100
9	2.32	3.28	0.22	0.44	0.99	2.03	10.37	0.34	0.34	19.77	0.01	1.36	0.37	0.86	4.60	50.96	1.74	100
10	1.94	3.42	0.18	0.41	0.94	1.63	8.50	0.32	0.32	23.51	0.01	1.25	0.36	0.81	4.15	50.33	1.91	100

Vertical group distribution of German consumption

Group	AGRI	CHEM	COAL	CONS	CRUD	ELEC	FOOD	IRST	NFMS	MANU	MINE	NGAS	NMMS	PAPR	PETR	SERV	TRNS	Total
1	6.62	4.40	8.92	1.87	2.42	8.89	7.22	3.75	3.75	2.99	3.66	5.94	2.93	5.06	3.89	5.42	5.62	5.18
2	7.97	6.00	9.53	3.67	5.23	9.51	8.28	5.18	5.18	4.52	5.55	6.77	4.50	6.72	5.67	6.46	6.53	6.38
3	8.70	7.27	9.50	5.52	6.43	9.48	8.88	6.86	6.86	5.90	7.09	8.07	6.35	7.93	7.28	7.46	7.25	7.41
4	9.38	8.20	9.63	7.53	8.95	9.62	9.61	7.89	7.89	7.37	7.79	8.97	7.73	8.64	8.64	8.34	7.67	8.39
5	9.86	9.24	9.93	9.44	9.24	9.93	9.94	9.38	9.38	8.49	8.99	9.74	9.36	9.60	9.62	9.08	8.16	9.16
6	10.47	9.63	10.08	10.96	12.12	10.09	10.42	10.11	10.11	9.20	9.97	10.30	9.98	9.95	10.53	9.80	9.03	9.85
7	10.77	10.58	10.26	13.15	11.68	10.26	10.60	11.42	11.42	10.78	10.98	10.55	11.80	10.83	11.38	10.64	9.24	10.69
8	11.10	11.94	10.35	14.13	13.24	10.36	10.91	12.41	12.41	12.24	12.07	11.33	13.02	11.76	12.50	11.69	12.20	11.72
9	11.87	13.64	10.52	14.96	13.57	10.53	11.50	14.57	14.57	14.85	14.15	12.66	14.85	13.04	13.81	13.39	13.88	13.34
10	13.27	19.10	11.29	18.78	17.13	11.32	12.63	18.43	18.43	23.66	19.75	15.66	19.49	16.45	16.69	17.71	20.41	17.87
Total	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

The absolute values at the top refer to Germany in the year 2013 and are reported in billions of euros. The corresponding percentage shares in the middle display the distribution of consumption expenditures across goods (sectors) within each income group (1 lowest, 10 highest). The percentage shares at the bottom display the distribution of consumption expenditures for each good across income groups. Data source: authors' own calculation; FDZ (2021), see above.

B Computable general equilibrium model

Appendix B describes the exemplary basic model with regard to the trade, consumption and production structure followed by the corresponding parameter values, i.e., elasticities of substitution. It begins by characterizing the model solution that represents a global general equilibrium of all goods and factor markets.

B.1 Model implementation and solution

The model solution defines a holistic global market solution derived from consumer and producer optimization, excluding any external effects, such as climate change impacts.

The model follows the standard approach to setting up a general equilibrium (CGE) model by defining a balanced (consumer) budget, zero (producer) profit and (goods and factor) market clearance conditions. Production factor endowments (with capital K , labor L , land N , and natural resources R including fossil fuels) are given in each model region (r or, equivalently, s) and attached to the representative consumer (or each income group). The regional representative consumers and the regional sectoral producers (of each good or service i or, equivalently, j) maximize their utility or profits, respectively, which leads to optimality conditions. They form a system of n equations with n unknowns, for which a unique solution representing a Walrasian (Arrow–Debreu) equilibrium of all markets exists.

The computable general equilibrium (CGE) model is programmed as a mixed complementarity problem (MCP) in general algebraic modeling system (GAMS; Bussieck and Meeraus (2004)).³³ It features the mathematical programming system for general equilibrium analysis (MPSGE) introduced by Thomas Rutherford.³⁴ It is solved by using the PATH algorithm (Dirkse and Ferris (1995)) with the MPSGE solver. The model is calibrated to the newest GTAP³⁵ 10 data for the benchmark year 2014 (cf. Pothen and Hübler (2018)). The *Monte Carlo* (sensitivity) analysis with 1000 random draws of parameter sets and corresponding model solutions in each experiment is carried out by using the Snakemake workflow management system.³⁶

For each model region r (equivalently s), the model solution contains the quantities of private consumption C (of each income group if available) and the corresponding utility based on consumption expenditures, public consumption G , sectoral production Y , sec-

³³<https://www.gams.com/>.

³⁴https://www.gams.com/latest/docs/UG_MPSGE.html, <https://www.gams.com/latest/docs/mpsge.pdf>.

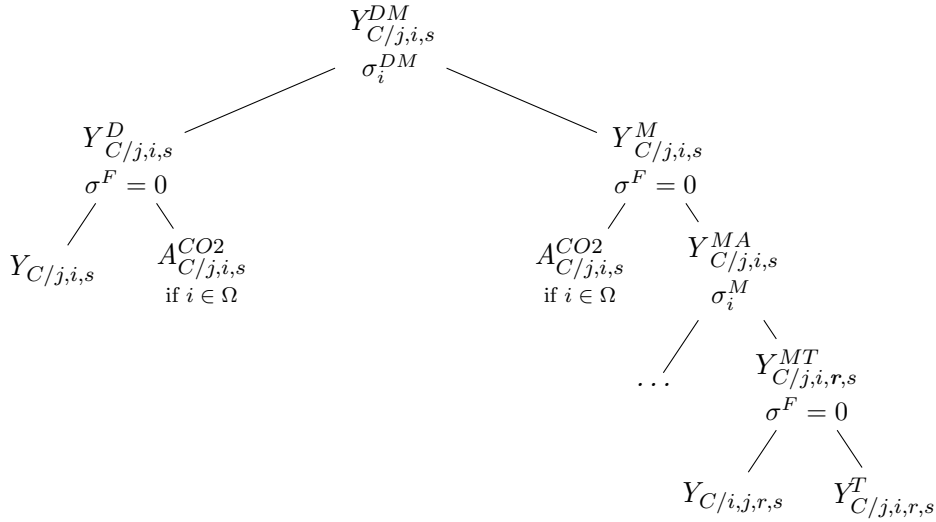
³⁵Global Trade Analysis Project, <https://www.gtap.agecon.purdue.edu/databases/v10/index.aspx>.

³⁶<https://snakemake.readthedocs.io/en/stable/>.

toral imports M , associated sectoral transportation services Y^T , and the corresponding market equilibrium prices p of goods and factors, including a CO₂ price p^E , while the total CO₂ emissions \bar{E}_r are given for each region as an emissions cap. Relative (percentage) changes in consumption (utility) between a policy and the reference scenario represent regional (or income-group-specific) welfare changes that are used as the main policy outcome.

B.2 Representation of international trade

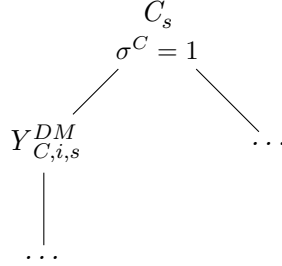
Figure B1
Nesting structure of international trade



This nesting structure represents a constant elasticity of substitution (CES) function describing international trade in goods (and services) i (or, equivalently, j). Goods i are produced in regions r , internationally traded and consumed in region s (see Figure B2) or used as intermediate inputs in production in s (see Figure B3) (where $s = r$ implies domestic consumption within a region). Therefore, this function is defined for consumption, C , and for each sector j in s , symbolized by C/j . Y denotes production. Similar to consumption, C , it is measured in pecuniary terms. D indicates domestically produced goods, and M indicates imported goods. Y^{MT} combines production Y with transport services Y^T . Each traded good can be subject to taxation (via tariffs on the import side) or subsidization (on the export side). Y^{MA} aggregates a good i over all available regions r of origin to an Armington aggregate. $\Omega = \{COAL, CRUD, NGAS, PETR\}$ is a subset of all sectors containing fossil fuels that release fossil fuel-specific amounts A of CO₂ when used in production. Therefore, a CO₂ price is attached to them, resulting in bundles Y^D and Y^M . For each i , Y^{DM} combines the domestically produced good Y^D with the aggregate of imports Y^M . σ denotes an elasticity of substitution between inputs. A higher σ value implies better substitutability. $\sigma^F = 0$ characterizes a Leontief relation without room for substitution. The sector-specific elasticity values σ_i^{DM} and σ_i^M are displayed in Table B2.

B.3 Consumption structure

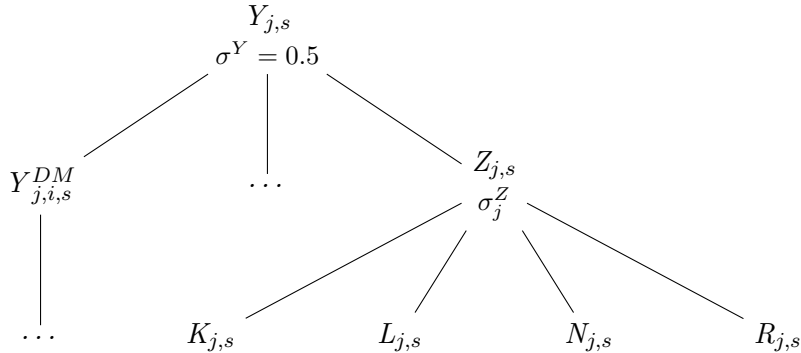
Figure B2
Nesting structure of consumption



This nesting structure represents a constant elasticity of substitution (CES) function describing private (utility) or public consumption. (Unlike private consumption, public consumption does not include CO₂ inputs.) The consumption bundle Y^{DM} of each good i used in consumption C in region s is detailed in Figure B1. Any consumption good (or service) can be subject to taxation or subsidization. $\sigma^C = 1$ implies a Cobb-Douglas aggregate over all available goods i (including fossil fuels).

B.4 Production structure

Figure B3
Nesting structure of sectoral production



For each good (sector) j in a region s , this nesting structure represents a constant elasticity of substitution (CES) production function. The intermediate goods bundle Y^{DM} of each good i used in production, Y , in region s is detailed in Figure B1. Y denotes production, Z the combined production factors (both are quantities measured in pecuniary terms): capital K , labor L , land N , and natural resources R including fossil fuels. Each input and output can be subject to taxation or subsidization. $\sigma^Y = 0.5$ implies an aggregate over all available intermediate goods inputs i (including fossil fuels) and the combined production factor inputs with a low substitutability.

B.5 Model regions

Table B1
Aggregation of GTAP regions to model regions

Model		GTAP 10
Region	Description	Description (code)
<i>DEU</i>	Germany	Germany (DEU)
<i>FRA</i>	France	France (FRA)
<i>GBR</i>	United Kingdom	United Kingdom (GBR)
<i>ITA</i>	Italy	Italy (ITA)
<i>EUR</i>	Rest of EU-27	Austria (AUT), Belgium (BEL), Bulgaria (BGR), Romania (ROU), Cyprus (CYP), Czech Republic (CZE), Denmark (DNK), Spain (ESP), Estonia (EST), Finland (FIN), Greece (GRC), Hungary (HUN), Ireland (IRL), Latvia (LVA), Lithuania (LTU), Luxembourg (LUX), Malta (MLT), Netherlands (NLD), Poland (POL), Portugal (PRT), Slovakia (SVK), Slovenia (SVN), Sweden (SWE)
<i>ROE</i>	Rest of ETS (non-EU)	Norway (NOR), Rest of European Free Trade Association (Iceland, Liechtenstein, XEF)
<i>FSU</i>	Former Soviet Union	Armenia (ARM), Azerbaijan (AZE), Belarus (BLR), GEO, Kazakhstan (KAZ), Kyrgyzstan (KGZ), Ukraine (UKR), Russian Federation (RUS), Rest of Eastern Europe (Moldova, XEE), Rest of Europe (XER), Rest of Former Soviet Union (Turkmenistan, Uzbekistan, XSU)
<i>ROA</i>	Rest of Asia	Mongolia (MNG), Taiwan (TWN), Rest of East Asia (DPR of Korea, Macao, XEA), Brunei Darussalam (BRN), Cambodia (KHM), Indonesia (IDN), Lao PDR (LAO), Malaysia (MYS), Philippines (PHL), Singapore (SGP), Thailand (THA), Viet Nam (VNM), Rest of Southeast Asia (Myanmar, Timor-Leste, XSE), Bangladesh (BGD), Nepal (NPL), Pakistan (PAK), Sri Lanka (LKA), Rest of South Asia (Afghanistan, Bhutan, Maldives, XSA)
<i>BRA</i>	Brazil	Brazil (BRA)
<i>CAN</i>	Canada	Canada (CAN)
<i>CHN</i>	China	China (CHN), Hong Kong (HKG)
<i>IND</i>	India	India (IND)
<i>JPN</i>	Japan	Japan (JPN)
<i>KOR</i>	South Korea	Republic of Korea (KOR)
<i>MEX</i>	Mexico	Mexico (MEX)
<i>OCE</i>	Australia & Oceania	Australia (and surrounding islands, AUS), New Zealand (NZL), Rest of Oceania (Pacific islands, XOC)
<i>USA</i>	United States	United States of America (USA)
<i>ROW</i>	Rest of the World	Albania (ALB), Croatia (HRV), Switzerland (CHE), Türkiye (TUR), all remaining countries in the Middle East, Africa, South America and elsewhere

Aggregation of the GTAP countries/regions to the model countries/regions s (or, alternatively, r) defined by Pothen and Hübler (2018) adapted to the GTAP 10 database (Aguiar et al., 2019). The original GTAP regions can be found at <https://www.gtap.agecon.purdue.edu/databases/regions.aspx?version=10.211>.

B.6 Elasticities of substitution

Table B2
Sector-specific elasticities of substitution in the CES functions of the model

Sector i	Description	Armgt. elast. btw. region-spec. imp. σ_i^M	Trade elast. btw. dom. & imp. σ_i^{DM}	Input elast. btw. prod. factors σ_i^Z
<i>AGRI</i>	Agriculture	2.69	2.35	0.25
<i>COAL</i>	Coal	10.02	3.05	0.20
<i>CRUD</i>	Crude oil	7.89	5.20	0.20
<i>NGAS</i>	Natural gas	7.94	12.96	0.49
<i>PETR</i>	Refined petroleum	9.67	2.10	1.26
<i>FOOD</i>	Food production	3.80	2.48	1.12
<i>MINE</i>	Mining	2.43	0.90	0.20
<i>PAPR</i>	Paper and pulp	5.18	2.95	1.26
<i>CHEM</i>	Chemicals, rubber and plastic	4.45	3.30	1.26
<i>NMMS</i>	Mineral products nec.	6.39	2.90	1.26
<i>IRST</i>	Iron and steel	4.21	2.95	1.26
<i>NFMS</i>	Non-ferrous metals	4.43	4.20	1.26
<i>MANU</i>	Manufacturing	5.05	3.83	1.26
<i>ELEC</i>	Electricity	18.66	2.80	1.26
<i>TRNS</i>	Transport	6.21	1.90	1.70
<i>CONS</i>	Construction	15.07	1.90	1.40
<i>SERV</i>	Services	6.43	1.92	1.36

Model sectors (goods and services as defined by Pothen and Hübler (2018)) and related elasticities of substitution (rounded to two digits). Armington elasticities are derived from the structural estimation of the Eaton and Kortum trade model by Pothen and Hübler (2018) according to the trade model unification theory of Arkolakis et al. (2012). The remaining trade and input elasticities are taken from the GTAP 10 database (Aguiar et al., 2019).

B.7 International climate policy clubs

Table B3
International climate policy coalition effects on countries and world regions

Coalition	<i>EU</i>		<i>EU/USA</i>		<i>EU/USA/CHN</i>		<i>EU/USA/CHN/IND</i>	
Region	<i>Dom</i>	<i>Bor</i>	<i>Dom</i>	<i>Bor</i>	<i>Dom</i>	<i>Bor</i>	<i>Dom</i>	<i>Bor</i>
<i>DEU</i> tot.	-0.60	-0.58	-0.40	-0.39	-0.30	-0.29	-0.29	-0.28
Low	1.33	1.41	0.69	0.73	0.54	0.56	0.57	0.59
Mid	-0.50	-0.48	-0.34	-0.34	-0.25	-0.24	-0.24	-0.24
High	-1.22	-1.22	-0.75	-0.76	-0.57	-0.56	-0.56	-0.56
<i>FRA</i>	-0.51	-0.50	-0.27	-0.26	-0.19	-0.18	-0.18	-0.17
<i>GBR</i>	-0.46	-0.46	-0.28	-0.27	-0.22	-0.22	-0.22	-0.22
<i>ITA</i>	-0.67	-0.66	-0.40	-0.39	-0.29	-0.28	-0.28	-0.27
<i>EUR</i>	-0.49	-0.45	-0.31	-0.29	-0.24	-0.22	-0.23	-0.22
<i>ROE</i>	-0.97	-0.90	-0.63	-0.61	-0.51	-0.50	-0.54	-0.52
<i>FSU</i>	-0.45	-0.56	-0.28	-0.35	-0.25	-0.30	-0.28	-0.34
<i>ROA</i>	-0.01	-0.03	0.00	-0.01	-0.02	-0.04	-0.03	-0.05
<i>BRA</i>	-0.03	-0.04	-0.01	-0.02	-0.03	-0.03	-0.03	-0.03
<i>CAN</i>	-0.08	-0.10	0.48	0.39	0.32	0.25	0.31	0.24
<i>CHN</i>	0.03	0.02	-0.01	0.00	-0.50	-0.49	-0.47	-0.46
<i>IND</i>	0.14	0.12	0.13	0.12	0.17	0.16	-0.29	-0.28
<i>JPN</i>	0.08	0.09	0.08	0.08	0.12	0.12	0.15	0.16
<i>KOR</i>	0.10	0.12	0.08	0.08	0.13	0.14	0.18	0.19
<i>MEX</i>	-0.11	-0.12	-0.22	-0.26	-0.22	-0.25	-0.25	-0.28
<i>OCE</i>	-0.69	-0.74	-0.48	-0.52	-0.50	-0.54	-0.55	-0.59
<i>USA</i>	-0.01	-0.01	-0.19	-0.18	-0.18	-0.17	-0.18	-0.17
<i>ROW</i>	-0.27	-0.31	-0.23	-0.26	-0.35	-0.38	-0.44	-0.47

Coalition	<i>G7EU</i>		<i>G7EU/CHN</i>		<i>G7EU/CHN/IND</i>		<i>WORLD</i>	
Region	<i>Dom</i>	<i>Bor</i>	<i>Dom</i>	<i>Bor</i>	<i>Dom</i>	<i>Bor</i>	<i>Dom/Bor</i>	
<i>DEU</i> tot.		-0.41	-0.40	-0.30	-0.29	-0.28	-0.27	-0.11
Low		0.79	0.83	0.60	0.63	0.62	0.65	0.90
Mid		-0.35	-0.34	-0.25	-0.24	-0.24	-0.23	-0.07
High		-0.80	-0.80	-0.59	-0.58	-0.58	-0.57	-0.43
<i>FRA</i>		-0.26	-0.25	-0.17	-0.16	-0.16	-0.15	0.03
<i>GBR</i>		-0.29	-0.28	-0.22	-0.22	-0.22	-0.22	-0.20
<i>ITA</i>		-0.41	-0.39	-0.29	-0.28	-0.28	-0.27	-0.08
<i>EUR</i>		-0.31	-0.28	-0.23	-0.21	-0.22	-0.20	0.00
<i>ROE</i>		-0.73	-0.71	-0.58	-0.56	-0.61	-0.59	-0.87
<i>FSU</i>		-0.34	-0.42	-0.29	-0.36	-0.33	-0.40	-0.53
<i>ROA</i>		-0.02	-0.04	-0.04	-0.06	-0.05	-0.08	-0.10
<i>BRA</i>		-0.01	-0.02	-0.03	-0.03	-0.03	-0.04	-0.41
<i>CAN</i>		0.07	0.09	-0.04	-0.02	-0.05	-0.04	-0.23
<i>CHN</i>		0.01	-0.01	-0.49	-0.48	-0.46	-0.44	-0.23
<i>IND</i>		0.20	0.19	0.22	0.21	-0.26	-0.24	0.19
<i>JPN</i>		-0.36	-0.35	-0.22	-0.21	-0.20	-0.18	0.12
<i>KOR</i>		0.12	0.12	0.16	0.17	0.22	0.23	0.72
<i>MEX</i>		-0.30	-0.34	-0.28	-0.31	-0.31	-0.34	-1.04
<i>OCE</i>		-0.67	-0.71	-0.64	-0.68	-0.70	-0.74	-1.81
<i>USA</i>		-0.18	-0.17	-0.17	-0.17	-0.17	-0.17	-0.15
<i>ROW</i>		-0.35	-0.38	-0.45	-0.48	-0.54	-0.57	-1.52

Regional welfare effects of CO₂ pricing in different international coalitions (*Climate Club*) compared with the *Benchmark* scenario measured as percentage changes divided by the true-cost-of-living index. EU refers to the entire EU ETS, which is successively enlarged to international climate policy coalitions that share a common CO₂ price under the policy scenario *Dom* and add border carbon adjustments towards countries/regions outside the coalition under the policy scenario *Bor*. G7 encompasses Canada, France, Germany, Italy, Japan, the United Kingdom, the United States and the European Union as a “non-enumerated member”; hence, the G7 countries partly overlap with the EU ETS countries, indicated by *G7EU*. The hypothetical global coalition *WORLD* includes all countries (regions) and renders border carbon adjustments obsolete.

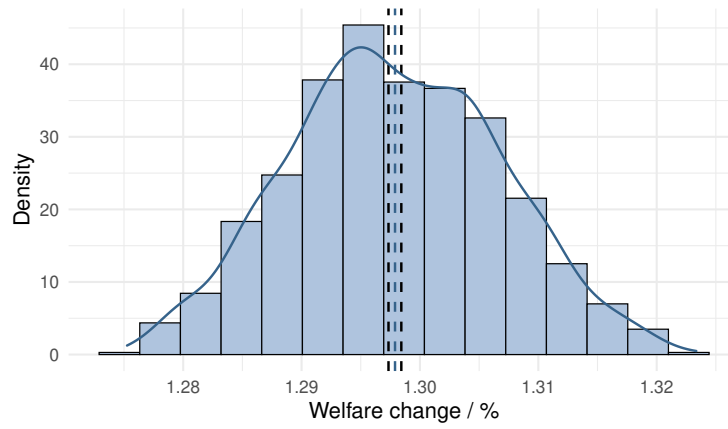
B.8 Sensitivity analysis: Armington elasticities

Table B4
Robustness check: alternative Armington elasticities σ_i^M

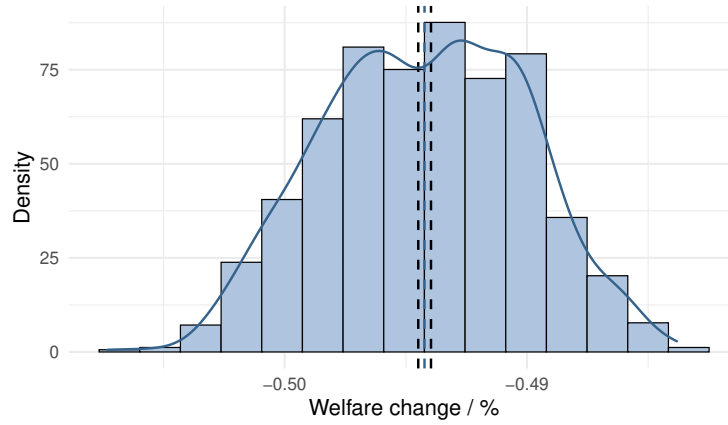
Income group	<i>Domestic CO₂ price</i>				<i>Border CO₂ price</i>			
	LO		UP		LO		UP	
Low	1.36	(2.73)	1.29	(-2.51)	1.44	(2.64)	1.37	(-2.43)
Mid	-0.49	(-1.65)	-0.50	(1.28)	-0.47	(-2.02)	-0.48	(1.60)
High	-1.22	(-0.01)	-1.22	(-0.14)	-1.22	(-0.16)	-1.22	(-0.01)

Welfare effects of *Domestic CO₂ price* and *Border CO₂ price* are reported as percentage changes for variation of Armington elasticities σ_i^M by $\pm 10\%$. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change - baseline change)/(baseline change). LO = lower bound with all $\sigma_i^M \cdot 0.9$; UP = upper bound with all $\sigma_i^M \cdot 1.1$.

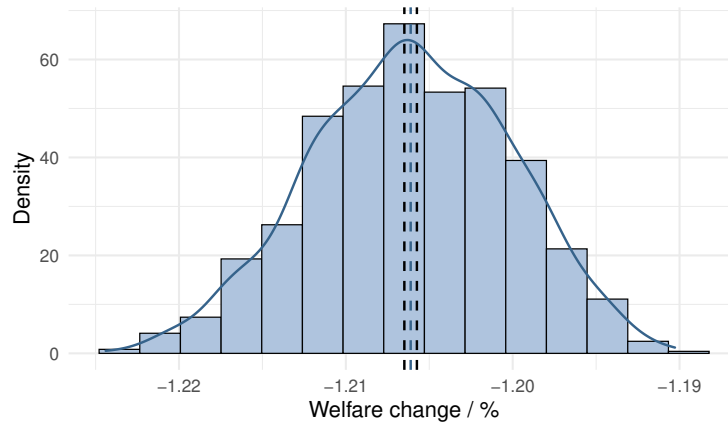
Figure B4
 Distributional sensitivity analysis of Armington elasticities σ_i^M :
Domestic CO₂ price



(a) Low-income group



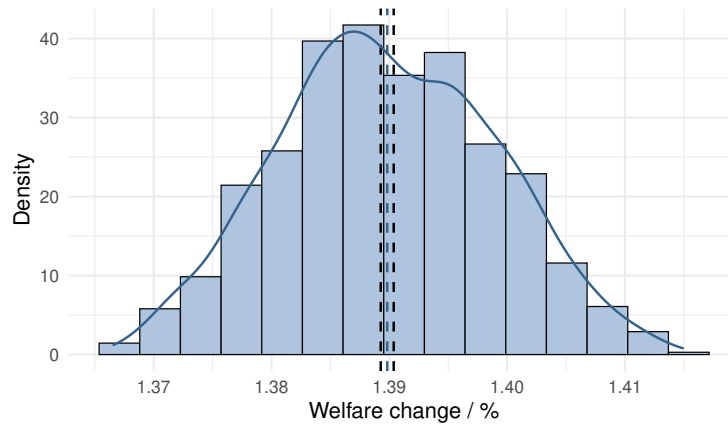
(b) Middle-income group



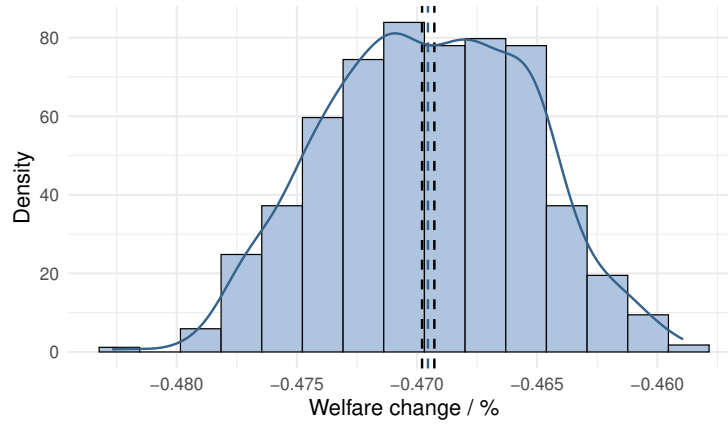
(c) High-income group

Distribution of welfare effects of *Domestic CO₂ price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a $\pm 10\%$ interval around each sector-specific Armington elasticity σ_i^M . Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

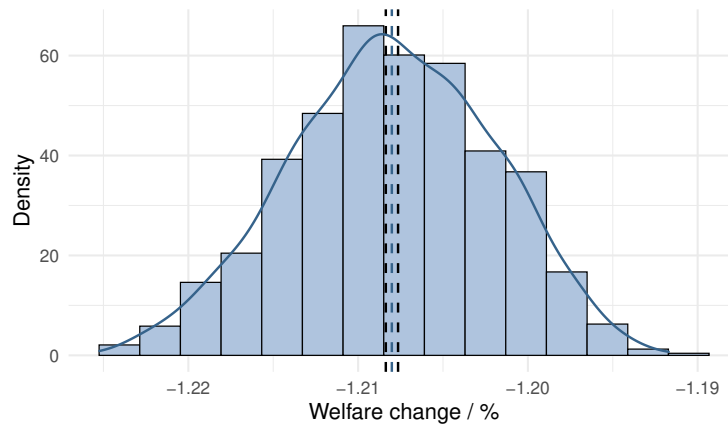
Figure B5
 Distributional sensitivity analysis of Armington elasticities σ_i^M :
Border CO₂ price



(a) Low-income group



(b) Middle-income group



(c) High-income group

Distribution of welfare effects of *Border CO₂ price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a $\pm 10\%$ interval around each sector-specific Armington elasticity σ_i^M . Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

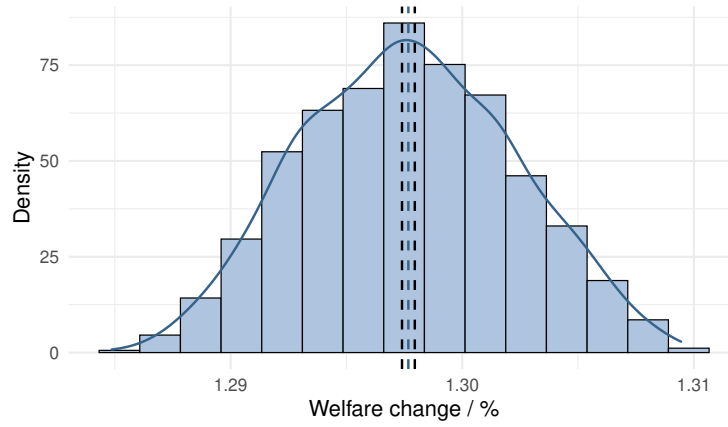
B.9 Sensitivity analysis: domestic import elasticities

Table B5
Robustness check: alternative domestic import elasticities σ_i^{DM}

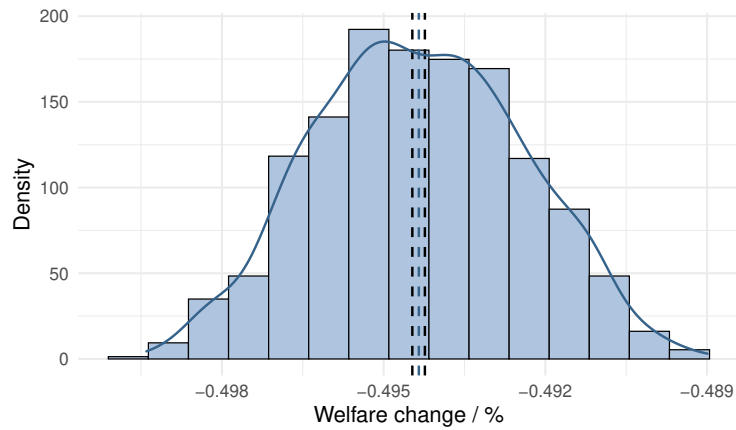
Income group	<i>Domestic CO₂ price</i>				<i>Border CO₂ price</i>			
	LO		UP		LO		UP	
Low	1.34	(1.25)	1.31	(-1.20)	1.42	(1.24)	1.39	(-1.20)
Mid	-0.50	(-0.18)	-0.50	(0.12)	-0.47	(-0.26)	-0.48	(0.20)
High	-1.22	(0.35)	-1.22	(-0.37)	-1.23	(0.34)	-1.22	(-0.36)

Welfare effects of *Domestic CO₂ price* and *Border CO₂ price* are reported as percentage changes for variation of domestic import elasticities σ_i^{DM} by $\pm 10\%$. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change - baseline change)/(baseline change). LO = lower bound with all $\sigma_i^{DM} \cdot 0.9$; UP = upper bound with all $\sigma_i^{DM} \cdot 1.1$.

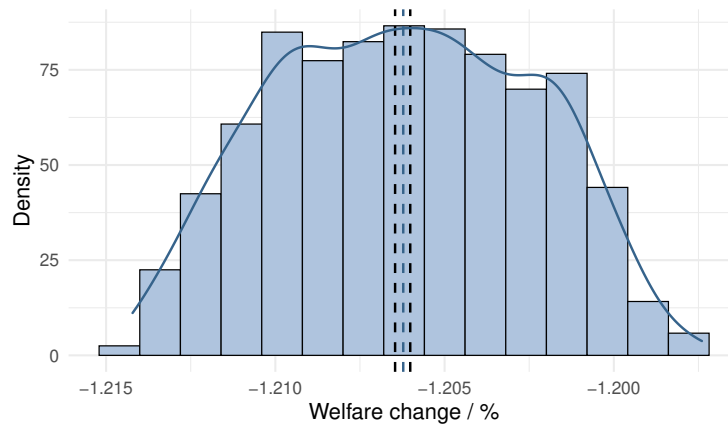
Figure B6
 Distributional sensitivity analysis of domestic import elasticities σ_i^{DM} :
Domestic CO₂ price



(a) Low-income group



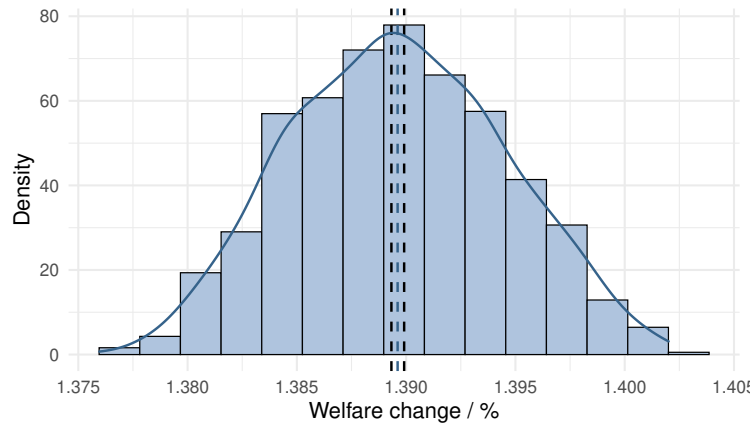
(b) Middle-income group



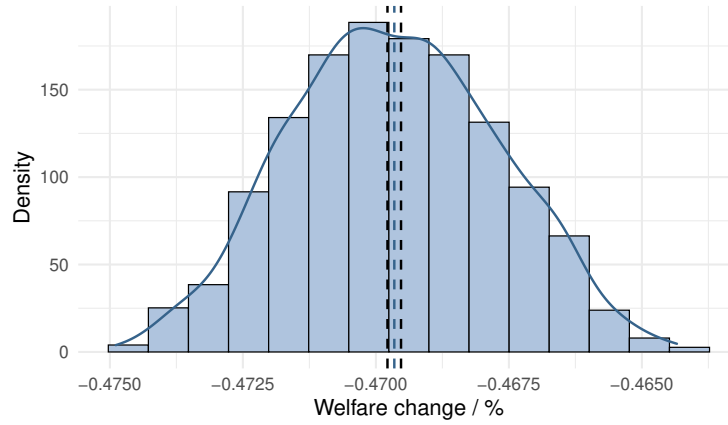
(c) High-income group

Distribution of welfare effects of *Domestic CO₂ price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a $\pm 10\%$ interval around each sector-specific domestic import elasticity σ_i^{DM} . Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

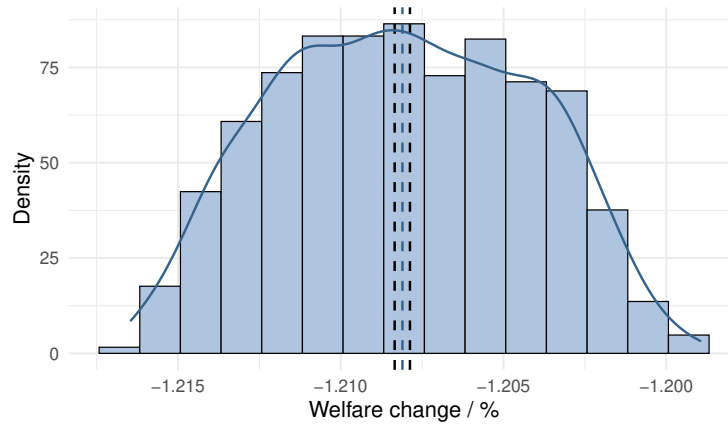
Figure B7
 Distributional sensitivity analysis of domestic import elasticities σ_i^{DM} :
Border CO₂ price



(a) Low-income group



(b) Middle-income group



(c) High-income group

Distribution of welfare effects of *Border CO₂ price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a $\pm 10\%$ interval around each sector-specific domestic import elasticity σ_i^{DM} . Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

B.10 Sensitivity analysis: input elasticities between production factors

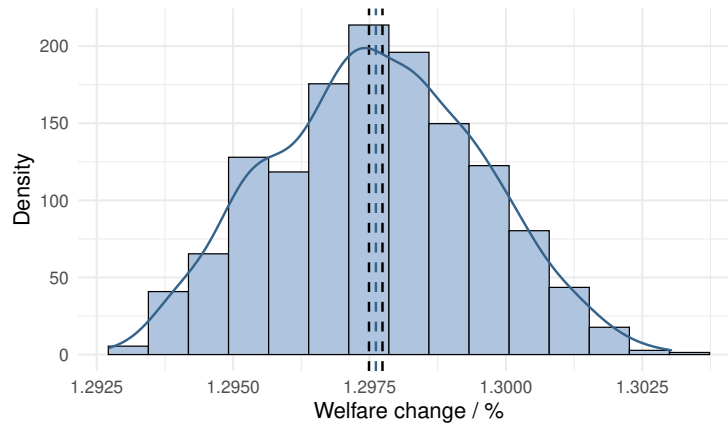
Table B6

Robustness check: alternative input elasticities between production factors σ_i^Z

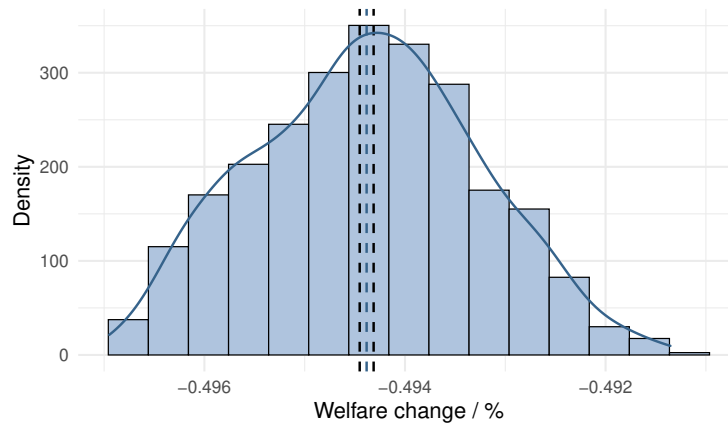
Income group	<i>Domestic CO₂ price</i>				<i>Border CO₂ price</i>			
	LO		UP		LO		UP	
Low	1.33	(0.58)	1.32	(-0.52)	1.41	(0.56)	1.40	(-0.50)
Mid	-0.49	(-0.84)	-0.50	(0.76)	-0.47	(-0.90)	-0.48	(0.82)
High	-1.22	(-0.28)	-1.22	(0.26)	-1.22	(-0.29)	-1.23	(0.26)

Welfare effects of *Domestic CO₂ price* and *Border CO₂ price* are reported as percentage changes for variation of input elasticities between production factors σ_i^Z by $\pm 10\%$. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change - baseline change)/(baseline change). LO = lower bound with all $\sigma_i^Z \cdot 0.9$; UP = upper bound with all $\sigma_i^Z \cdot 1.1$.

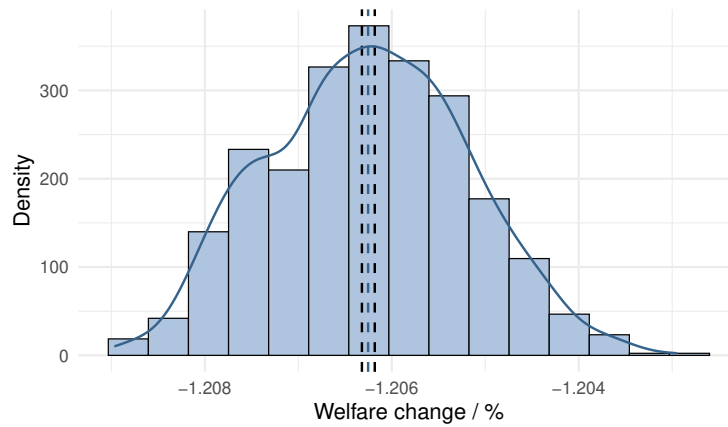
Figure B8
 Distributional sensitivity analysis of input elasticities between production factors σ_i^Z :
Domestic CO₂ price



(a) Low-income group



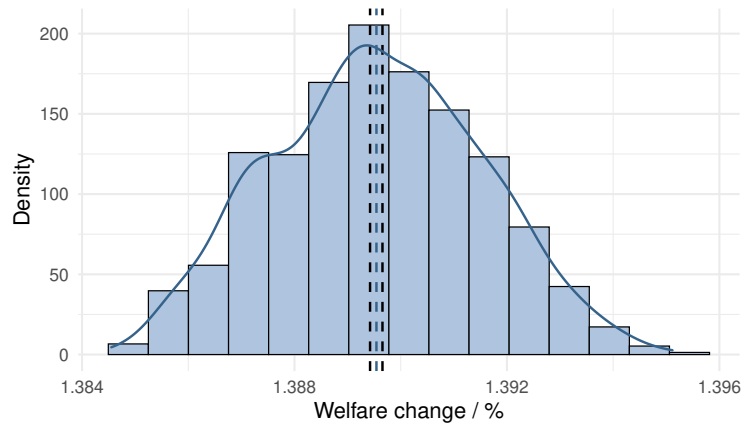
(b) Middle-income group



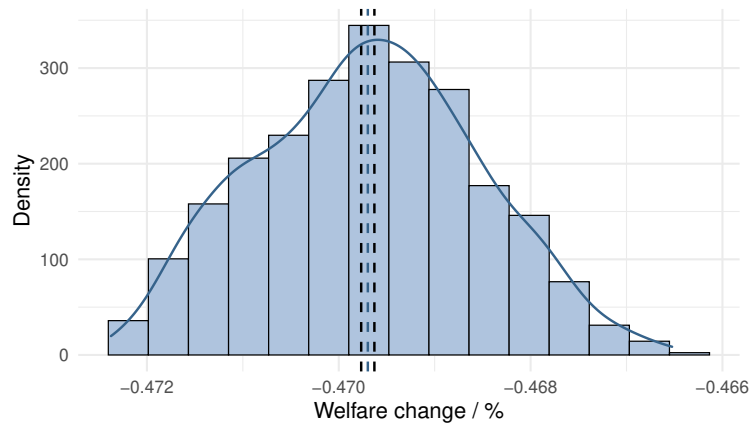
(c) High-income group

Distribution of welfare effects of *Domestic CO₂ price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a $\pm 10\%$ interval around each sector-specific input elasticity between production factors σ_i^Z . Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

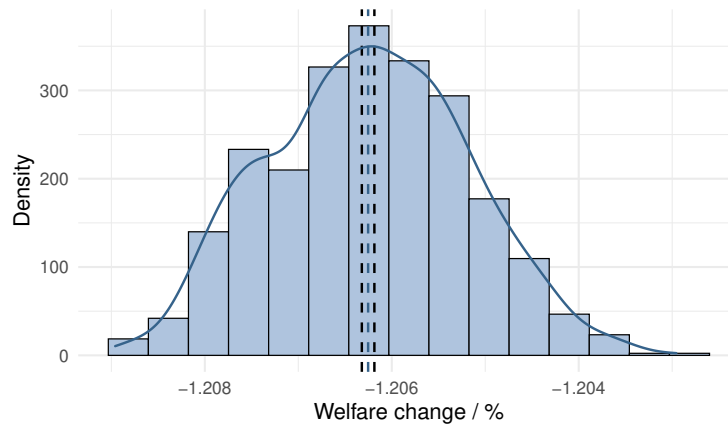
Figure B9
 Distributional sensitivity analysis of input elasticities between production factors σ_i^Z :
Border CO₂ price



(a) Low-income group



(b) Middle-income group



(c) High-income group

Distribution of welfare effects of *Border CO₂ price* for the low-, middle- and high-income groups. The distributions are generated from 1000 random draws from a $\pm 10\%$ interval around each sector-specific input elasticity between production factors σ_i^Z . Dashed vertical blue lines indicate mean welfare effects, while dashed vertical black lines indicate bootstrap 95% confidence intervals. Solid blue lines represent Kernel density estimations.

B.11 Sensitivity analysis: elasticity of substitution in consumption

Table B7

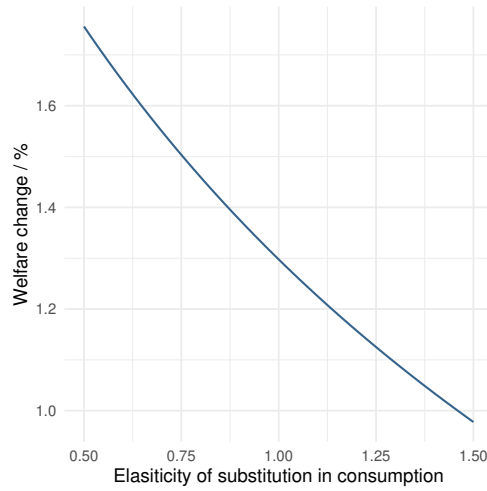
Robustness check: alternative elasticities of substitution in consumption σ^C

Income group	<i>Domestic CO₂ price</i>				<i>Border CO₂ price</i>			
	LO		UP		LO		UP	
Low	1.79	(35.21)	1.00	(-24.53)	1.89	(34.58)	1.07	(-24.02)
Mid	-0.38	(-22.81)	-0.58	(16.98)	-0.36	(-24.90)	-0.56	(18.45)
High	-1.28	(4.71)	-1.19	(-2.80)	-1.28	(4.79)	-1.19	(-2.84)

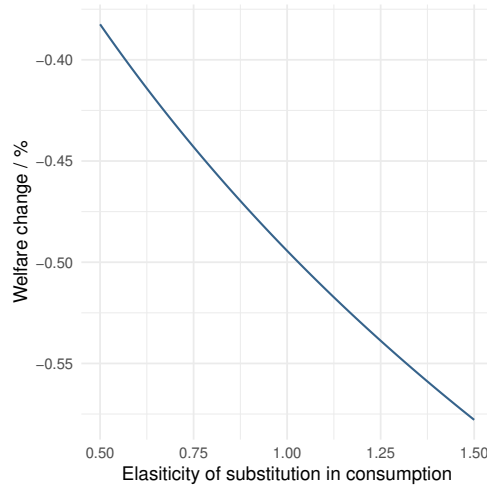
Welfare effects of *Domestic CO₂ price* and *Border CO₂ price* are reported as percentage changes for variation of elasticity of substitution in consumption σ^C by $\pm 50\%$. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change - baseline change)/(baseline change). LO = lower bound with $\sigma^C = 0.5$; UP = upper bound with $\sigma^C = 1.5$.

Figure B10

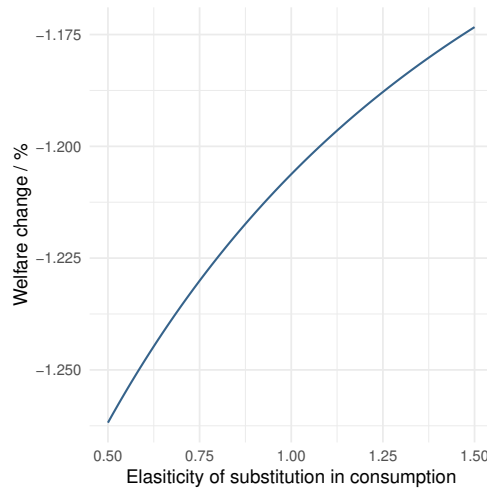
Sensitivity analysis of the elasticity of substitution in consumption: *Domestic CO₂ price*



(a) Low-income group



(b) Middle-income group

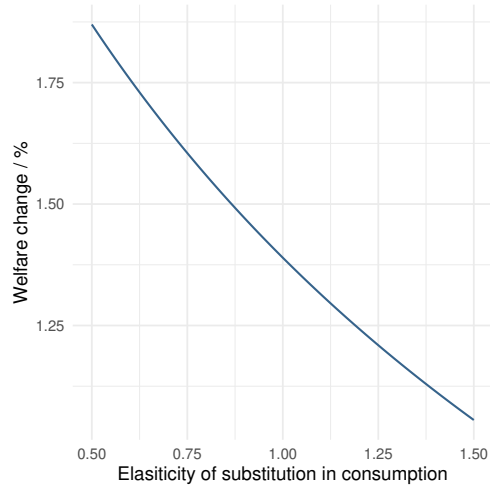


(c) High-income group

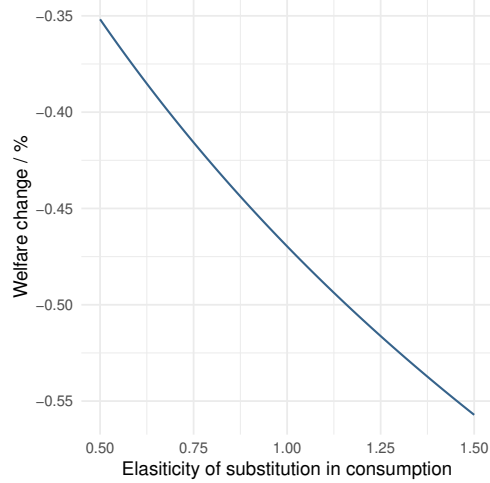
Welfare effects of *Domestic CO₂ price* as a function of the elasticity of substitution in consumption for the low-, middle- and high-income groups.

Figure B11

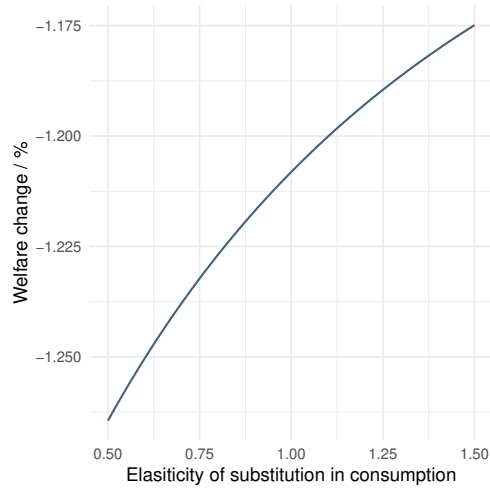
Sensitivity analysis of the elasticity of substitution in consumption: *Border CO₂ price*



(a) Low-income group



(b) Middle-income group



(c) High-income group

Welfare effects of *Border CO₂ price* as a function of the elasticity of substitution in consumption for the low-, middle- and high-income groups.

B.12 Sensitivity analysis: factor income and CO₂ pricing revenue shares

Table B8
Robustness check: alternative land and natural resources income shares

Income group	<i>Domestic CO₂ price</i>									
	(1)		(2)		(3)		(4)		(5)	
Low	0.26	(-80.49)	2.72	(104.79)	2.72	(104.91)	0.64	(-51.45)	1.90	(43.02)
Mid	-0.08	(-84.01)	-1.22	(145.78)	-0.08	(-84.30)	-0.56	(12.82)	-0.46	(-7.50)
High	-1.17	(-4.13)	-1.17	(-4.20)	-1.91	(56.38)	-0.97	(-20.14)	-1.41	(16.00)
Income group	<i>Border CO₂ price</i>									
	(1)		(2)		(3)		(4)		(5)	
Low	0.34	(-75.91)	2.80	(98.83)	2.80	(98.94)	0.72	(-48.52)	1.98	(40.57)
Mid	-0.06	(-87.78)	-1.20	(152.33)	-0.06	(-88.09)	-0.54	(13.39)	-0.44	(-7.84)
High	-1.17	(-4.12)	-1.17	(-4.20)	-1.91	(56.28)	-0.98	(-20.11)	-1.42	(15.97)

Welfare effects of *Domestic CO₂ price* and *Border CO₂ price* are reported as percentage changes for alternative values of land and natural resources income shares. In column 1, income shares of both land and natural resources are 0%, 50% and 50% for low-, middle- and high-income groups, respectively. Analogously, column 2 assumes income shares of 50%, 0% and 50%, and column 3 assumes income shares of 50%, 50% and 0%. In column 4, income shares are set to capital income shares of the three income groups. In column 5, income shares are set to 1/3 for all three income groups. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change - baseline change)/(baseline change).

Table B9
Robustness check: alternative capital income shares

Income group	<i>Domestic CO₂ price</i>				<i>Border CO₂ price</i>			
	LO		UP		LO		UP	
Low	1.45	(9.13)	1.54	(15.76)	1.53	(8.88)	1.62	(15.35)
Mid	-0.42	(-16.53)	-0.36	(-29.28)	-0.40	(-17.88)	-0.33	(-31.60)
High	-1.23	(1.40)	-1.24	(2.30)	-1.24	(1.39)	-1.25	(2.38)

Welfare effects of *Domestic CO₂ price* and *Border CO₂ price* are reported as percentage changes for variation of German capital income shares $\lambda_{DEU,K,\phi}^X$ derived from the national accounts ("Volkswirtschaftliche Gesamtrechnung, VGR"). Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change - baseline change)/(baseline change). LO = lower bound; UP = upper bound regarding the size of the high-income group's capital share.

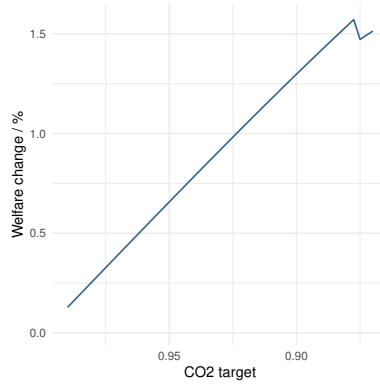
Table B10
Robustness check: alternative CO₂ pricing revenue shares

Income group	<i>Domestic CO₂ price</i>							
	(1)		(2)		(3)		(4)	
Low	-1.77	(-233.37)	2.87	(116.68)	2.87	(116.74)	0.25	(-81.05)
Mid	0.22	(-144.61)	-1.93	(289.53)	0.22	(-144.95)	-0.58	(16.38)
High	-0.76	(-38.01)	-0.75	(-38.15)	-2.15	(76.19)	-0.84	(-30.73)

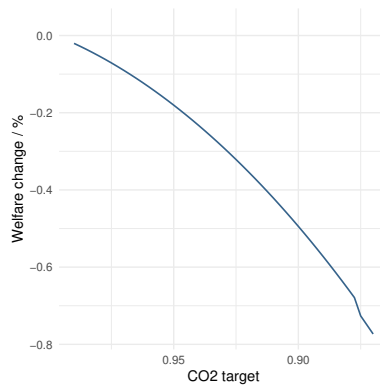
Welfare effects of *Domestic CO₂ price* are reported as percentage changes for alternative values of CO₂ pricing revenue shares. In column 1, CO₂ pricing revenue shares are 0%, 50% and 50% for low-, middle- and high-income groups, respectively. Analogously, column 2 assumes revenue shares of 50%, 0% and 50%, and column 3 assumes revenue shares of 50%, 50% and 0%. In column 4, revenue shares are set to the consumption shares of the three income groups. Additionally, deviations of these numbers relative to the standard results are reported in per cent in parentheses, i.e. (robustness check change - baseline change)/(baseline change).

B.13 Sensitivity analysis: CO₂ emissions target

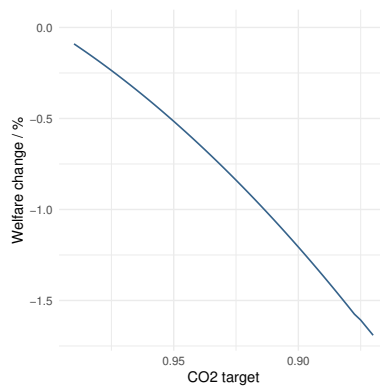
Figure B12
Sensitivity analysis of the CO₂ target: *Domestic CO₂ price*



(a) Low-income group



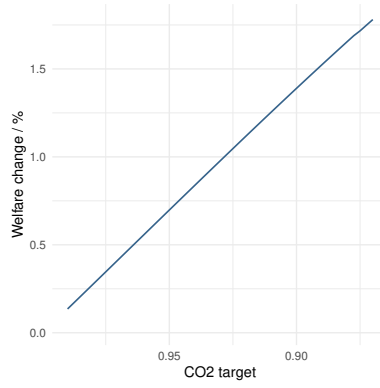
(b) Middle-income group



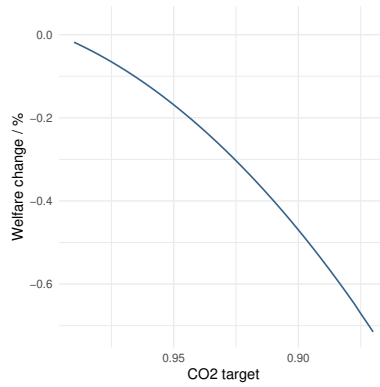
(c) High-income group

Welfare effects of *Domestic CO₂ price* as a function of the CO₂ target relative to 2014 emissions for the low-, middle- and high-income groups.

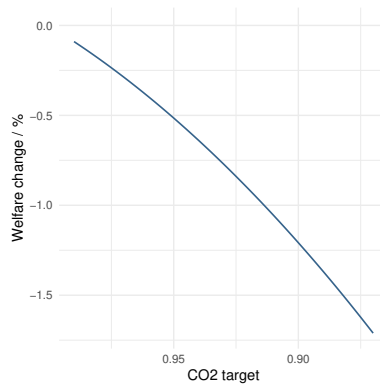
Figure B13
Sensitivity analysis of the CO₂ target: *Border CO₂ price*



(a) Low-income group



(b) Middle-income group



(c) High-income group

Welfare effects of *Border CO₂ price* as a function of the CO₂ target relative to 2014 emissions for the low-, middle- and high-income groups.

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Chapter 5

Regional Climate Policy Analysis in the EU Member Country Germany

Reference for this Paper:

Hübler, M., M. Braun and N. Keimes (2025), Regional Climate Policy Analysis in the EU Member Country Germany, *Working Paper*.

Regional climate policy analysis in the EU member country Germany

Michael Hübler* Marius Braun[†] Nils Keimes[‡]

April 2025

Abstract

This article studies regional policy effects within Germany and among other member countries of the European Union (EU). It uses an advanced trade model to examine the EU emissions trading system (EU ETS) with the carbon border adjustment mechanism (CBAM) and reveals significant differences in policy effects across EU countries and within Germany. Under a medium CO₂ target, CBAM has a negligible average welfare effect on the entire EU while it can eliminate the carbon leakage caused by the EU ETS. Assuming a less stringent CO₂ target, CBAM creates a welfare gain of the EU, whereas, assuming a more stringent target, it creates a welfare loss compared with the EU ETS alone. More stringent CO₂ targets in the EU ETS increase the effectiveness of CBAM in reducing carbon leakage and hence global emissions. The implemented Eaton and Kortum trade module appears to contribute little to the scrutinized policy effects compared to Armington models. Because official and constructed regional data sets are often incomplete, outdated or not publicly available and their compilation and resolution are not standardized, the official public provision of a comprehensive, harmonized, up-to-date regional data set, at least with federal state level resolution, is advisable.

JEL classifications: C68; F18; Q52; Q54; R50

Keywords: regional data; advanced trade model; climate policy; carbon border adjustments; EU ETS; CBAM; Germany

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1 Introduction

Input-output tables are an important basis for model-based assessments of climate, trade or other economic policies and economic shocks, such as energy or food price changes. Although national input-output tables are widely available, within-country data (regional input-output tables, RIOTs, and multi-regional input-output, MRIO, tables) are scarce, especially for relatively small countries, in particular, Germany. Within-country disaggregation of data and models is more elaborated for large countries, structured in federal states or provinces, i.e., the United States, China and India (see, for example, Caliendo et al. 2018; Zhang et al. 2020; Leimbach et al. 2024). In Europe, within-country data are available for Germany, the United Kingdom, Belgium and Spain and have been applied to assess regional carbon footprints (Lenzen et al. 2010; Towa et al. 2022) and the impact of trade relationships on water resources (Cazcarro et al. 2013). Therefore, in this article, we provide guidance for researchers (modellers) who want to carry out a regional policy analysis of Germany (or other countries) based on the literature and our own policy analysis of the current European climate and trade policy. From our analysis, we derive policy recommendations considering regional specificity.

Within-country data are necessary to assess the regional effects of policies or shocks within countries in a precise way. This relevance especially stems from the differential economic impacts of policies or shocks across regions due to differences in the economic importance of active sectors, their interconnections and their contribution to the overall output of a region. Future impacts of climate change, such as floods, and resulting policy reactions are a crucial example for socially and politically highly relevant regional challenges,¹ and they depend on local geographic and climatic conditions. In addition to adaptation to climate change, mitigation of greenhouse gas emissions, especially the transformation of the energy system with the expansion of renewable energies, is a major challenge that is in the spotlight in this article while climate change impacts cannot be evaluated due to missing data. It is subject to regional potentials and obstacles because different regions within countries often exhibit heterogeneity with regard to their renewable energy potentials, sectoral structures, focal points of production and natural resource endowments, particularly with fossil fuels.

In our policy analysis, we investigate Germany and the European Union (EU) because they are climate and energy policy front-runners and subject to economic and renewable-energy related heterogeneity. Since the EU “is currently undergoing a digital and green transition” that affects the heterogeneous European regions in different ways and may hinder regional coherence (Maucorps et al. 2023), it is important to study regional policy effects from an EU perspective. In particular, we compare the effects of the EU’s climate policy across EU countries and within Germany, the biggest economy within the EU. Our analysis includes the established EU Emissions Trading System (ETS) and the new EU Carbon Border Adjustment Mechanism

¹See, for example, Adeel et al. (2020) regarding regional effects of floods in the United States, Canada and Mexico.

(CBAM). Understanding the economic incentives and effects of such carbon-based tariffs can be an important step towards a global climate policy solution, possibly via a climate policy club (coalition) as an intermediate step. Because Germany is heavily involved in international trade, it can be significantly affected by these policies.

Whereas German regions with strong dependence on fossil fuel-based sectors, regions with in situ coal reserves, are presumably negatively affected by stricter climate/energy policy regimes and may therefore receive adequate financial support, other regions are more robust to stricter climate/energy policy settings or even benefit from them. Lower Saxony is a prominent expected beneficiary (cf. Pothen and Hübler 2018; Pothen and Hübler 2021) among the German federal states. Although wind power plants are common across Germany, the northern coastal federal states, particularly Lower Saxony, exhibit a large on-shore and off-shore wind power potential and a high economic dependency on the wind power industry compared to the rest of Germany. Consequently, power generators in Lower Saxony can provide renewable energy (electricity) and sell CO₂ emissions permits to earn revenues. Lower Saxony has less industrial and more rural areas with significant agricultural production compared to other German regions. Since agriculture is not included in the considered CO₂ emissions trading scheme, Lower Saxony is not severely affected by CO₂ pricing, which predominantly places a cost burden on energy-/CO₂-intensive industries. Against this background, the regional focus of our policy simulations is on Lower Saxony. In contrast, southern federal states have a large solar power potential and host important industries, such as automotive manufacturers and suppliers. Thus, climate policies striving for an increasing share of renewable energies will presumably result in (negative or positive) region-dependent economic effects that we explore leaving aside (reduced) climate change damages.

In particular, we ask the following research questions: How far do the economic effects of the current EU ETS and CBAM differ within the EU and within Germany? What are the conclusions for climate policy design and for improvements of regional data (especially from Germany) and the deployment of modelling methods (especially regional and advanced trade models)?

To address these questions, we review the relevant literature and data sources focusing on Germany to clarify the availability of regional data and their use in policy analysis. Furthermore, we compare the regional effects of the current European climate policy across EU countries and across regions within Germany as a prominent EU member country. Based on that, we derive research priorities and data requirements. The insights obtained can be relevant for modelers, data providers, funders and policy makers.

Different to the literature that mostly uses input-output methods or standard computable general equilibrium (CGE) models, for our policy analysis, we deploy a global CGE model with an advanced trade module and regional disaggregation to identify regional differences of policy impacts. In particular, we use a new quantitative trade model introduced by Pothen and Hübler (2018), building on the Ricardian trade theory

of Eaton and Kortum (2002) and quantitatively implemented by Caliendo et al. (2018) and Caliendo et al. (2023). Unlike conventional input-output methods, this allows us to compare policy scenarios to a benchmark scenario taking endogenous policy-induced general equilibrium effects into account. Arkolakis et al. (2012) have shown that different types of (advanced) trade models can be aligned in terms of policy-induced changes in welfare and emissions. In recent contributions, Sogalla (2023) and Sogalla et al. (2024) find that in models with heterogeneous firms (cf. Melitz 2003; Kreickemeier and Richter 2014), sufficiently strong reductions in firms' emission intensities or reallocation of production between firms with different productivities and emission intensities can reduce overall emissions. Accordingly, we evaluate how far the scrutinized Eaton and Kortum type advanced trade model generates relevant policy effects and whether differences across regions occur. Although the implemented trade module appears to contribute little to the scrutinized policy effects compared with Armington (1969) type models, regional differences in trade module-specific effects are visible.

As a contribution to the economic policy modeling literature, we simulate the *regional* effects of CBAM on Germany based on the EU ETS. In the related literature, Hübler et al. (2024) study the effects of the EU ETS, CBAM and so-called "climate clubs" on German household income groups at the German-wide level. They find significant differences between the policy effects, e.g., a positive effect on poor households but a negative effect on rich households. Other studies find regional differences of climate and trade policy on German regions (Pothen and Hübler 2018; Hübler and Herdecke 2020; Pothen and Hübler 2021). However, they do not study the effects of CBAM. Korpar et al. (2023) set up a multi-region, multi-sector structural gravity model to study the effects of CBAM and find small policy effects. So far, however, the model-based literature on carbon border adjustment policies (for example, Böhringer et al. 2012; Mattoo et al. 2013) has to our knowledge not examined *regional* policy effects within countries which we address in Section 3.

In general, our review of the literature and policy analysis reveal significant, policy-relevant regional differences in economic (policy) effects. According to our model simulations assuming a 44% reduction of CO₂ emissions in (vis-à-vis) 2014 mimicking a 55% by 2030 compared to 1990 as envisaged by the EU, the effect of the EU ETS on Lower Saxony in the North of Germany is positive (due to its large wind power potential) whereas the effect on the Rest of Germany is on average negative. (Note that benefits of reduced climate change impacts are not modeled in this cost effectiveness analysis). CBAM has small positive effects on both regions, but the effect is considerably larger Lower Saxony than in the Rest of Germany. Accordingly, regional policy advice based on results from aggregate regions (here, Germany or the EU) can be misleading.

While the small policy effects that we find are in accordance with Korpar et al. (2023), a sensitivity check provides additional new insights: Because the import tariff rates of CBAM are proportional to the current CO₂ price in the EU ETS, we obtain a typical "optimal tariff" relationship in which the terms-of-trade and hence welfare are improved in an inverted U-shaped manner (compare Weitzel et al. 2012). Under the 44%

CO₂ target, any welfare effect of CBAM on the entire EU is hardly measurable. A less stringent CO₂ target results in a lower CO₂ price and therefore lower tariff rates which creates a minor average welfare gain of the EU from CBAM compared with the EU ETS alone in accordance with Korpar et al. (2023). A more stringent CO₂ target results in a substantially higher CO₂ price and therefore higher tariff rates which creates an additional average welfare loss of the EU. A more stringent target, however, increases the effectiveness of CBAM in reducing carbon leakage and hence global emissions. According to a decomposition analysis of the CO₂ reductions in our model, the technique effect via Ricardian specialization of the Eaton and Kortum theory, reduces CO₂ emissions to a minor extent in Lower Saxony and a small extent in the Rest of Germany.

In contrast to the regionally different policy results, our review of data sources and the related literature reveals a lack of available regional data from Germany. Although researchers have constructed and compiled RIOTs of mainly Western German federal states and some comprehensive MRIO tables (Többen 2017a; Többen 2017b; Krebs 2020) (see Table 1 and Appendix Figure A1) covering all federal states, current official and publicly available data (from statistical offices) are largely missing. Consequently, we identify and discuss priorities of future research and data requirements aiming at providing a unified, official and publicly available country-wide regional data set of Germany and similarly from other countries.

This article proceeds as follows. Section 2 explores the availability of regional input-output data from Germany and reviews the literature on regional policy effects in Germany. Section 3 provides a model-based regional policy analysis of the current EU ETS and CBAM policies focusing on Lower Saxony compared with the rest of Germany and the EU with selected separated member countries. Section 4 discusses research challenges, research priorities and data requirements for regional policy analysis. Section 5 concludes.

2 Review of regional data and policy assessments

Considering the importance of regional economic (policy) analyses, this section reviews available regional data from Germany and policy studies using these data.

2.1 Availability and construction of regional datasets from Germany

This section summarizes the availability of regional data considering Germany at the federal state level as a prominent example. The availability of such data defines the technical boundaries of policy analyses (as summarized in Section 2.2) and identifies gaps that can be filled by statistical agencies and researchers. An example for an input-output table of a German federal state officially provided by a statistical agency is Baden-Wuerttemberg in the year 1990 (Pothen and Hübler 2018). Although approaches have been developed to create subnational time series data (Wang et al. 2017), regional input-output data remain scant. Therefore,

researchers have constructed recent input-output tables of further German federal states.

Table 1 summarizes the regional input-output tables of German federal states that have been constructed by scholars. As a notable contribution, using shipment data, Krebs (2020) constructs an interregional input-output table (IRIOT) containing 402 German counties, 26 foreign trading partners and 17 sectors.² In addition to Table 1, Schröder and Zimmermann (2014) construct regional output multipliers for the Baltic Sea region for different regionalization methods.

Regarding regionalization, the literature generally relies on non-survey methods with two common approaches being the Commodity Balance (CB) approach (also known as Supply-Demand Pool, SDP, approach) and the Location Quotient (LQ) approach. The CB method presupposes that regional intermediary transactions, along with interregional trade, can be inferred from national data by assessing the balance between regional supply and demand (Jin 1991). The LQ method, together with the more recent FLQ method developed by Flegg and Webber (2000) and Flegg and Tohmo (2013), estimates regional multipliers using national and regional employment data to derive regional input-output coefficients (Flegg et al. 1995).

However, as pointed out by Tohmo (2004) and Kronenberg (2009), both methods tend to produce tables that are systematically biased, primarily because they do not account for cross-hauling, i.e., intra-industry trade (the simultaneous exporting and importing of the same type of product). To address this shortcoming, Kronenberg (2009) has developed the Cross-Hauling Adjusted Regionalization Method (CHARM). In addition, some authors (e.g., Koch et al. 2019) adopt a hybrid approach that includes the use of original federal state-specific data. Based on a modified version of the CHARM method developed by Többen and Kronenberg (2015), Többen (2017a) creates a multi-regional input-output (MRIO) table of the year 2011 connecting single regional tables and covering all 16 German federal states (see Többen 2017b). The modified CHARM method addresses two limitations of the original approach: the assumption that cross-hauling in *interregional* trade is zero, and the outcome that estimates of interregional trade flows potentially violate accounting balances.

As summarized in Table 2, relevant data sources for these approaches include the Scientific Use Files of the Household Budget Survey (“Einkommens- und Verbrauchsstichprobe”, EVS, microeconomic household survey data from “Forschungsdatenzentren”, FDZ 2024) provided by the Research Data Centre (RDC) of the German Statistical Office, the German Statistical Office (“Statistisches Bundesamt”, Destatis 2022, macroeconomic German-wide non-survey data), the Regional Accounts of the Federal States (“Volkswirtschaftliche Gesamtrechnung der Länder”, VGRdL 2022b, macroeconomic non-survey data from the German federal states) as well as labor market statistics provided by the Federal Employment Agency (“Bundesagentur für Arbeit”, BfA 2022).

²The data and code used to construct the IRIOT are available via the author’s website: <https://sites.google.com/view/oliver-krebs/research?authuser=0>.

State	Author(s)	Year	Num. of sectors	Method	Publicly available
Baden-Wuerttemberg	Haigner et al. (2015)	2010	51	CHARM	no
Baden-Wuerttemberg	Heindl and Voigt (2012)	2006	72	CB/SDP	yes
Baden-Wuerttemberg	Koch et al. (2019)	2014	38	CHARM	no
Hamburg	Prognos (2009)	2005	12	?	no
Hamburg	Kronenberg (2011)	2003	71	CHARM	no
Hessen	Penzkofer (2002)	1995	?	?	no
Hessen	Koschel et al. (2006)	2000	18	LQ	no
Lower Saxony	Schröder (2012)	2007	71	CHARM	yes
Lower Saxony	Stöver (2018)	2013	20	CHARM	yes
Mecklenburg-Western Pomerania	Kronenberg (2010)	2003	16	CHARM	yes
North Rhine-Westphalia	Kronenberg and Többen (2011)	2007	59	CHARM	yes
North Rhine-Westphalia	Prognos (2007)	2000	12	?	no
Saxony	Lehr et al. (2013)	2006	16	CHARM	no
Thuringia	Dettmer and Sauer (2014)	2010	73	FLQ	no
All German federal states	Többen (2017a) and Többen (2017b)	2011	41	CHARM	no
All German federal states	Krebs (2020)	2010	17	Krebs (2020)	yes

Table 1: Regional input-output tables of German federal states (based on Kronenberg and Wolter 2017, and an own survey of the literature). CHARM: Cross-Hauling Adjusted Regionalization Method, CB: commodity balance, SDP: supply-demand pool, LQ: location quotient, FLQ: flegg location quotient.

Variable	Data source	Provider	Publication frequency	Publicly available
Intermediate demand	NIOT	Destatis	annual	yes
Private consumption	EVS	Destatis	quinquennial	no
Government final consumption expenditure	VGRdL	Federal states	annual	yes
Gross fixed capital formation	VGRdL	Federal states	annual	yes
Change in inventories	NIOT	Destatis	annual	yes
Exports and imports	CHARM/NIOT	-	-	-
Compensation of employees	VGRdL	Federal states	annual	yes
Employment by sectors	Labor data	BfA	monthly	yes

Table 2: Data sources for the construction of regional input-output tables (based on Stöver 2018; Koch et al. 2019). NIOT: national input-output table, Destatis: German Statistical Office, EVS: Household Budget Survey, VGRdL: Regional Accounts of the Federal States, CHARM: cross-hauling adjusted regionalization method, BfA: Federal Employment Agency.

In summary, as illustrated in Appendix Figure A1, the availability of RIOTs differs at the German federal state level. While Baden-Wuerttemberg, Hamburg, Hessen, North Rhine-Westphalia and Lower Saxony provide multiple RIOTs, less RIOTs are available for the eastern and than for the western federal states.³

2.2 Assessments of regional policy effects in Germany

In the previous subsection, we have identified a scarcity of regional data from Germany. Correspondingly, only a relatively small number of studies attempt to quantify regional policy impacts in Germany. Focusing on the German energy transition, our literature survey has identified only a few studies analyzing sub-national climate policy effects in Germany.

Többen (2017a) analyzes the regional and distributional effects of the German Renewable Energy Sources Act (EEG) in all 16 German federal states. He finds that most federal states benefit from an extended operation of renewable energies in terms of value added, particularly those states with large capacities for renewable energy generation. In addition, North Rhine-Westphalia and Baden-Wuerttemberg benefit from the production of renewable energy power plants and their components. Regarding distributional effects, the EEG has a negative impact on disposable income due to higher consumer prices, which is primarily challenging for low-income households.

Pothen and Hübler (2018) study the impacts of CO₂ pricing and renewable energy subsidies in Lower Saxony using a new quantitative trade model, i.e., a global CGE model including an elaborated trade module, with renewable energies in the electricity sector (see Section 3.1). In summary, they identify differences in the economic effects between Lower Saxony and the Rest of Germany induced by climate and/or trade policy, in particular, a welfare gain of 0.40% in Lower Saxony compared with 0.18% in the Rest of Germany. Pothen and Hübler (2021) calibrate the model introduced by Pothen and Hübler (2018) dynamically to future development scenarios until the year 2050. Their results confirm regional differences between Northwest Germany and the Rest of Germany caused by climate policy, for instance, a welfare loss of 0.11% in Northwest Germany compared with 0.59% in the Rest of Germany in 2040.

Hübler and Herdecke (2020) study the economic effects of US import tariffs against China and, as a reaction, increased Chinese import tariffs. They compare the Eaton and Kortum (2002) CGE model of Pothen and Hübler (2018) with an Armington (1969) CGE model for comparison. They find very small welfare effects on Germany. Depending on the targeted goods/sectors and tariff rates, regional differences of policy effects between Lower Saxony and the Rest of Germany are detected that can have opposite signs.

Bröcker et al. (2016) carry out an input-output analysis of the regional impacts of offshore wind energy

³We have counted two RIOTs for each federal state to account for the multi-regional input-output tables developed by Többen (2017a) and Krebs (2020).

expansion in Northern Germany on value added and employment. Assuming an additional offshore wind energy capacity of 15 gigawatts until 2030, the authors project an additional annual production value of 688 million Euros in 2029 and additional employment of 9,093 persons in Northern Germany.

Schröder (2010) investigates the production and employment effects of wind energy deployment in the Hanover region by using a RIOT for an input-output analysis of the Hanover region in the year 2009. He finds that wind energy use has small positive effects on regional employment and value added (1.6 million Euros via wind turbine construction and 2.3 million Euros via wind turbine operation). Likewise, Schröder (2012) estimates that offshore wind energy use is associated with a 0.007% increase in Lower Saxony's total production value and raises employment.

Due to the German coal phase-out, North Rhine-Westphalia is a hot spot area with regard to socio-economic repercussions (for related policy recommendations, see Göke et al. 2018; Kittel et al. 2020). González-Eguino et al. (2012) use a CGE model to investigate the effects of climate policy in North Rhine-Westphalia. They assume a 15% relocation of the iron and steel sector away from North Rhine-Westphalia and find that this relocation results in a decrease in regional GDP of 0.37% and a reduction in regional CO₂ emissions of approximately 2%. In a different study, Kronenberg et al. (2018) evaluate the economic impacts of increased investments in energy efficiency in North Rhine-Westphalia by using a biregional input-output table. They consider a target scenario, in which the investment ratio is increased to 18% of the regional GDP resulting in a 0.3 percentage point increase in the growth rate of gross value added and additional employment of about 98,000 people. Using a partial-equilibrium investment and dispatch model, Sgarciu et al. (2023) project an annual loss of 900 jobs in Lusatia due to the coal phase-out and an increase in CO₂ prices accelerated by the phase-out of Lusatian lignite-fired power generation.

Heindl and Voigt (2012) conduct an input-output analysis of the turnover and employment effects of the EEG in Baden-Wuerttemberg. With internal funding, the authors estimate net turnover and employment effects of approximately 2.4 billion Euros and -34,000 jobs until 2020, respectively, whereas investments from external funding are associated with turnover and employment effects of approximately 6.5 billion Euros and +24,000 jobs, respectively.

3 Simulation of regional climate policy effects

This section presents an exemplary regional policy analysis of Germany. It provides an overview of the model and its regional disaggregation, it defines climate policy scenarios and presents the simulation results. After the discussion of the regional results, it provides sectoral, decomposition and sensitivity analysis results.

3.1 Overview of the model

In our comparative static policy analysis, we apply the static global new quantitative trade model presented in Pothen and Hübler (2018) with an updated calibration to Global Trade Analysis Project (GTAP) version 10 data with the base year 2014.⁴ The trade module follows the Ricardian new trade theory of Eaton and Kortum (2002) (see Caliendo and Parro 2015; Caliendo et al. 2018, for a numerical implementation). Within Germany, it goes beyond GTAP by explicitly representing the federal state Lower Saxony separated from the Rest of Germany (ROG, for an overview of the regional disaggregation, see Section 3.2; for details, see Pothen and Hübler 2018). Additionally, it goes beyond standard (GTAP) data and models by disaggregating the electricity sector of the regions Lower Saxony (LSX), Rest of Germany (ROG), France (FRA), United Kingdom (GBR) and Italy (ITA).

Sector	Description
AGRI	Agriculture
COAL	Coal
CRUD	Crude oil
NGAS	Natural gas
PETR	Refined petroleum
FOOD	Food production
MINE	Mining
PAPR	Paper and pulp
CHEM	Chemicals, rubber and plastic
NMMS	Mineral products nec.
IRST	Iron and steel
NFMS	Non-ferrous metals
MANU	Manufacturing
ELEC	Electricity
TRNS	Transport
CONS	Construction
SERV	Services
INVS	Investment

Table 3: Sectors (goods and services) of Pothen and Hübler (2018).

The deployed aggregation of the global data set GTAP features 18 production sectors (various goods, services and investment, see Table 3) in each of the 19 model countries/regions (see Table 4).⁵ Production (output) is sold domestically or exported. Investments (INVS) are equal to savings and produced like other goods but not traded internationally (for details, see Pothen and Hübler 2018, Appendix D). Each model country/region features a representative consumer who absorbs domestic production and imports. Savings are a region-specific fixed fraction of the consumer’s income. The consumer’s expenditures are financed via income from providing the production factors labor, capital and natural resources and from receiving net transfers (tax revenues minus subsidies) in a lump-sum way. The production factors are perfectly mobile across sectors within countries/regions but internationally immobile. They enter the production sectors as

⁴<https://www.gtap.agecon.purdue.edu/>.

⁵ *EU27* (European Union) and *WRLD* (World) aggregate the results of the included countries but do not appear in the model.

inputs together with intermediate goods inputs that can be imported or produced domestically.

Consumption, production and trade are represented by constant elasticity of substitution (CES) functions. Details can be found in Pothen and Hübler (2018) (Figures 1, 2 and 3 and Appendix Table C1). In consumption, first, energy goods and non-energy goods are combined separately in a complementary way (CES elasticities of 0.4 and 0.25). Then, these two bundles are combined in a complementary fashion (CES elasticity of 0.25).

In the non-electricity sectors, fossil fuel inputs are combined in a Cobb-Douglas fashion (CES elasticity of 1). The fossil fuel bundle is combined with electricity in a complementary way (CES elasticity of 0.5). The resulting energy composite is combined with a capital-labor bundle in a complementary way (CES elasticity of 0.4), while capital and labor are combined in a Cobb-Douglas fashion. Thereafter, non-energy intermediate goods inputs are attached in a Leontief fashion (CES elasticity of 0), and finally natural resources are added in a complementary way (CES elasticity of 0.6). Similarly, the electricity sector first combines fossil fuels (CES elasticity of 0.3) as well as capital and labor (CES elasticity of 1) separately and then puts these two bundles together (CES elasticity of 0.4). The main difference to other sectors is that (in the regions LSX, ROG, FRA, GBR and ITA) the following energy sources/technologies are combined as substitutes (CES elasticity of 3): coal, oil, gas, nuclear, hydro, wind, solar, geothermal and biomass. Furthermore, inputs in overhead, energy transmission and distribution (CES elasticity of 0) and a technology-specific fixed factor (CES elasticities of 0.1–0.6) are attached.

The use of fossil fuels (coal, gas, crude and refined oil) releases CO₂ emissions according to their fossil-fuel-specific CO₂ contents (given by the benchmark year data). In sectors subject to carbon pricing, the cost of these emissions must be paid by purchasing emission allowances at their current market price; that is, CO₂ is proportionally (via a Leontief function, CES elasticity of 0) connected to fossil fuel inputs and then treated as any other production input; in particular, allowances are traded on the CO₂ market established by the emission trading system.

The reaction of trade flows to changes in tariffs or trade costs is based on a structural estimation of the parameter values of the trade module including iceberg trade costs and gravity model parameters, such as a common border, common language or free trade agreement (see Pothen and Hübler 2018). The GTAP data incorporate existing taxes/tariffs and subsidies. Hence, the model represents a sub-optimal second-best world.

The solution of the resulting set of optimality conditions yields a global general equilibrium of all goods and factor markets in all model regions assuming perfect competition without modeling externalities.

3.2 Regional disaggregation of the model

For the following policy analysis, the data underlying the model have been updated to GTAP 10. Within Germany, the model calibration separates Lower Saxony (LSX) from the Rest of Germany (ROG). To this end, following the literature summarized in Sections 2.1 and 2.2, Pothen and Hübler (2018) derive a regional disaggregation procedure which is detailed in Appendix E of their article.

First, using consumption/investment data from VGRdL (2022b) and assuming that consumer preferences are identical across German federal states, Lower Saxony’s consumption and investment shares are calculated and applied to the GTAP data.

Second, using employment and energy data from BfA (2016a), BfA (2016b), LAE (2016a), LAE (2016b), and WVEE (2012), Lower Saxony’s sectoral gross output shares are calculated.

Third, assuming that the pattern of intermediate goods inputs in production is the same across German federal states, Lower Saxony’s input shares are computed.

Fourth, the Cross-Hauling Adjusted Regionalization Method (CHARM, Kronenberg 2009), extended by Többen and Kronenberg (2015), is applied to approximate trade flows between Lower Saxony and the Rest of Germany as well as other countries and world regions.

3.3 Definition of the policy scenarios

For our exemplary regional policy analysis of German, we define two policy scenarios. As a reference point, we define a benchmark scenario that captures EU policies implemented in 2014 given by the data (see Pothen and Hübler 2018) including so-called “grandfathering” (a free allocation of 90% of the CO₂ allowances to firms) and a CO₂ price of approximately US-\$19 per ton of CO₂. We do not model any climate change impacts throughout the policy analysis.

Definition of EUETS:

To set the emission target of the European Emissions Trading System (EU ETS) for both policy scenarios, we follow the greenhouse gas emission target for the year 2030 envisaged by the European Commission (Climate Action) and translate it into a 44% reduction of CO₂ emissions within (vis-à-vis) the year 2014 (provided by the benchmark data) in the EU ETS sectors (see Pothen and Hübler 2018).⁶ This means, the total amount of CO₂ emissions in the EU ETS is given by the total amount of CO₂ allowances (which is lower in the

⁶“Our ambition for 2030: Under the European Climate Law, EU Member States will work collectively to become climate neutral by 2050. As a first milestone, the EU is aiming to reduce net emissions by at least 55% by 2030 compared to 1990. The revised EU ETS will contribute to achieving this target. To achieve the necessary emission reductions cost-effectively, the EU ETS has been strengthened, and its scope expanded to maritime transport. Altogether, the cap is tightened to bring emissions down by 62% by 2030 compared to 2005 levels,” https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/our-ambition-2030_en (accessed 03/2024).

policy scenario than in the benchmark scenario and fixed) while the CO₂ price adjusts endogenously and is determined by the market equilibrium of the market for CO₂ allowances. We do not explicitly model other climate or energy policies (such as carbon taxes) in non-ETS sectors or final consumption. The EU ETS includes the model regions Lower Saxony (LSX), Rest of Germany (ROG), France (FRA), United Kingdom (GBR), Italy (ITA), Rest of EU-27 (EUR) and Rest of ETS (non-EU, ROE) and the model sectors refined petroleum (PETR), paper and pulp (PAPR), chemical products (CHEM), mineral products nec (NMMS), iron and steel (IRST), non-ferrous metals (NFMS) and electricity (ELEC) (see Pothen and Hübler 2018, Appendix Tables A1 and A2). The initial regional endowments with CO₂ allowances are allocated according to the regional benchmark year CO₂ emissions (shares). Carbon pricing is not assumed in other model regions.

Definition of CBAM:

A novelty of our analysis is the examination of regional effects induced by the Carbon Border Adjustment Mechanism (CBAM) announced by the European Commission (Taxation and Customs Union).⁷ CBAM aims at leveling the carbon playing field between producers within the EU (subject to EU ETS carbon pricing) and those producing outside the EU (without or with lower carbon pricing) and exporting into the EU. In this way, fairer competition and reduced carbon leakage⁸ shall be achieved. Therefore, this scenario includes the EUETS policy defined above and adds import taxation according to the carbon contents of goods imported into the EU. The carbon contents of goods are taken from Hübler et al. (2024) and valued at the endogenous CO₂ price derived from the general equilibrium model solution. When the CO₂ price in the EU ETS rises endogenously, especially due to tighter emissions targets, the import tax rates of CBAM will increase proportionally.

3.4 Regional results of the policy scenario simulations

Table 4 reports the policy scenario simulation results focusing on the welfare effects of each policy scenario relative to the benchmark scenario. Welfare effects are measured as relative changes in consumption expenditures divided by the true-cost-of-living index (see Pothen and Hübler 2018) to obtain real effects (excluding price effects). Figure 1 summarizes the policy effects on Lower Saxony and the Rest of Germany.

⁷“CBAM: The EU’s Carbon Border Adjustment Mechanism (CBAM) is the EU’s tool to put a fair price on the carbon emitted during the production of carbon intensive goods that are entering the EU, and to encourage cleaner industrial production in non-EU countries. By confirming that a price has been paid for the embedded carbon emissions generated in the production of certain goods imported into the EU, the CBAM will ensure the carbon price of imports is equivalent to the carbon price of domestic production, and that the EU’s climate objectives are not undermined. The CBAM is designed to be compatible with WTO-rules. CBAM will apply in its definitive regime from 2026, while the current transitional phase lasts between 2023 and 2026. This gradual introduction of the CBAM is aligned with the phase-out of the allocation of free allowances under the EU Emissions Trading System (ETS) to support the decarbonisation of EU industry,” https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en (accessed 03/2024).

⁸Theoretically, emissions reductions in the EU can partly be compensated by emissions increases abroad via reductions of fossil fuel prices on international markets, relocation of EU producers to abroad or climate policy relaxation abroad.

Region	Description	EUETS	CBAM	CBAM -EUETS
LSX	Lower Saxony	0.17	0.42	0.25
ROG	Rest of Germany	-0.19	-0.05	0.14
FRA	France	0.10	0.19	0.08
GBR	United Kingdom	-0.21	-0.18	0.04
ITA	Italy	-0.23	-0.22	0.01
EUR	Rest of EU-27	-0.56	-0.69	-0.12
ROE	Rest of ETS (non-EU)	0.02	0.13	0.12
<i>EU27</i>	EU-27 (aggregate result)	-0.30	-0.31	0.00
FSU	Former Soviet Union	0.06	-0.14	-0.20
BRA	Brazil	0.00	-0.01	-0.01
CAN	Canada	0.02	-0.03	-0.05
USA	United States of America	-0.01	-0.02	-0.01
MEX	Mexico	0.01	-0.03	-0.04
CHN	China	0.00	0.00	0.00
IND	India	-0.01	-0.03	-0.02
JPN	Japan	0.01	0.02	0.02
KOR	South Korea	0.00	0.04	0.04
ROA	Rest of Asia	-0.03	-0.07	-0.04
OCE	Australia & Oceania	-0.05	-0.07	-0.02
ROW	Rest of the World	0.02	-0.12	-0.14
<i>WRLD</i>	World (aggregate result)	-0.08	-0.10	-0.02

Table 4: Policy effects of the European Emissions Trading System (EUETS) and the European Carbon Border Adjustment Mechanism (CBAM) on the model regions. The reported welfare effects are measured as relative changes between the scenario EUETS or CBAM compared with the benchmark scenario referring to the year 2014 (defined by GTAP 10) in percent. CBAM-EUETS reports the difference between CBAM and EUETS in percentage points.

Effects of EUETS:

The endogenous CO₂ price in the EU ETS reaches approximately US-\$190 per ton of CO₂. The renewable energy share in power generation (ELEC) increases to almost 46% compared with 30% in the benchmark in Lower Saxony (LSX) and to 42% compared with almost 21% in the benchmark in the Rest of Germany (ROG). In the production sectors of LSX and ROG, CO₂ emissions decline by approximately 55% and 41% compared to the benchmark. The leakage rate (endogenous increase in emissions abroad divided by the exogenous emissions reduction in the EU ETS) increases from 26% in the benchmark to 45%. EUETS reduces global CO₂ emissions by more than 1.1%. Changes in the price level (true-cost-of-living index) are minor and point in different directions across the model regions. Whereas total income increases to a minor extent in LSX, it decreases to a minor extent in ROG compared with the benchmark scenario.

While all resulting welfare losses across model regions are smaller than 0.6%, all welfare gains are smaller than 0.2% (see Table 4). Lower Saxony (LSX, 0.17%) and France (FRA, 0.10%) benefit most from EUETS

due to their large wind or nuclear potential, respectively. The Rest of Germany (ROG), the United Kingdom (GBR) and Italy (ITA) become worse off (by 0.19%, 0.21% and 0.23%, respectively). The remaining EU ETS countries that are not EU members (ROE) benefit slightly (0.02%). The remaining EU countries that are EU members (EUR) lose significantly (by 0.56%): while the model features renewable energies explicitly in the separate model regions/countries LSX, ROG, FRA, GBR and ITA, this feature is not available in the aggregate EU ETS regions EUR and ROE which renders decarbonization more difficult and costly. The aggregate EU (*EU27*) region suffers a moderate welfare loss (by 0.30%) because we do not model reduced climate change damages and climate policy creates a distortion.

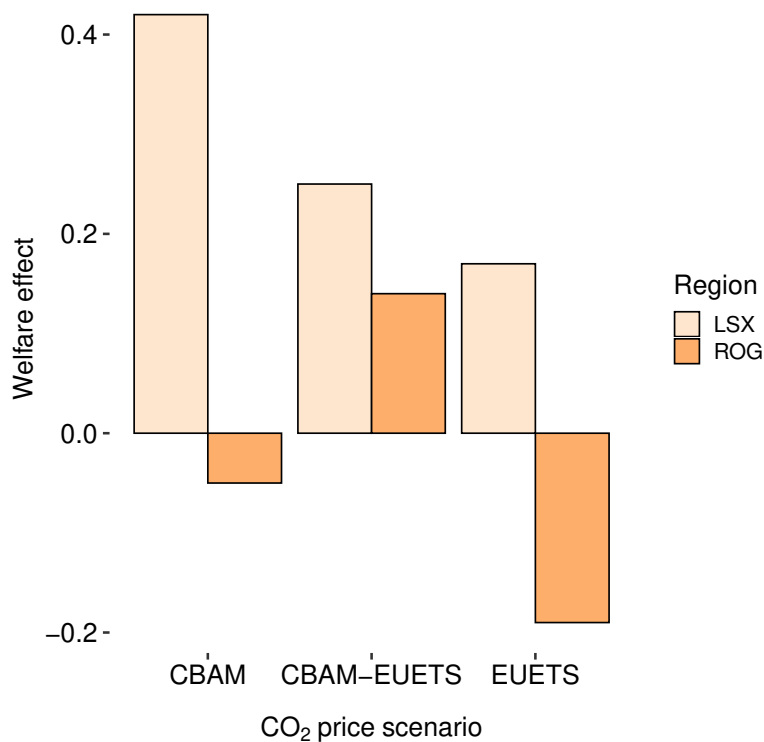


Figure 1: Policy effects of the European Emissions Trading System (EUETS) and the European Carbon Border Adjustment Mechanism (CBAM) on Lower Saxony (LSX) and the Rest of Germany (ROG). The welfare effects are measured as relative changes between the scenario EUETS or CBAM compared with the benchmark scenario in percent. CBAM-EUETS illustrates the difference between CBAM and EUETS in percentage points.

The former Soviet Union (FSU) countries benefit slightly from EUETS (by 0.06%); although fossil fuel imports into the EU are hindered, carbon-intensive production may be relocated from the EU to neighbour countries, such as FSU. Effects on the Rest of the World (ROW, a 0.02% gain) and the entire world (*WORLD*, a 0.08% loss) are small. Similar to the entire EU, the entire World loses due to carbon pricing because the benefits of less CO₂ in the atmosphere and hence reduced climate change are not taken into account and

carbon pricing creates an economic distortion (inefficiency). The large open economies USA and India (IND, both a 0.01% loss), Japan (JPN), Mexico (MEX, both a 0.01% gain) and Canada (CAN, a 0.02% gain) are affected to a minor extent, while Korea (KOR), China (CHN) and Brazil (BRA) are insignificantly affected.

Overall, EUETS has smaller effects than in the study by Hübler et al. (2024), because the model examined here provides more flexibility to reduce CO₂ emissions, especially to decarbonize power supply in the EU countries where energy sources/technologies are modelled explicitly. Particularly, France (FRA) benefits from its large nuclear power potential. The policy effect on the Rest of the EU-27 (EUR), however, is very similar in both models (approximately, -0.5%) despite different climate policy targets (a 10% reduction in 2014 in Hübler et al. 2024). The EU policy spillovers on other countries/regions in the world are also smaller in this study than in Hübler et al. (2024) which indicates that the advanced trade module of the model deployed here provides more flexibility as well. The qualitative pattern of the policy spillovers on other countries/regions in the world also differs from the results of Hübler et al. (2024).

In summary the EUETS results presented in Table 4 and illustrated in Figure 1 underline that regional disaggregation matters: the climate policy effects of the EUETS scenario on Lower Saxony and the Rest of Germany have similar magnitudes but opposite signs. Lower Saxony benefits from climate policy with emissions trading due to its large wind power potential. Further disaggregation of the Rest of Germany, e.g., in south, east and west, could reveal further differences between regions regarding their potential to expand renewable energies and hence to reduce emissions with relatively low marginal abatement costs. Furthermore, the policy effects differ significantly across European countries/regions.

Effects of CBAM:

In this policy scenario, the endogenous CO₂ price increases to approximately US-\$240 per ton of CO₂. Intuitively, due to the reduced imports, EU production expands which increases demand for CO₂ allowances putting upward pressure on the CO₂ price. The renewable energy share in power generation (ELEC) increases to more than 47% compared with 46% under EUETS in Lower Saxony (LSX) and to 46% compared with almost 42% under EUETS in the Rest of Germany (ROG). The leakage rate declines from 45% under EUETS to 25% under CBAM which is slightly below the benchmark rate; this means that CBAM is an effective instrument to reduce carbon leakage. CBAM reduces global CO₂ emissions by more than 1.8%, i.e., 0.7 percentage points more than EUETS alone. These effects are somewhat lower than those found by Sogalla (2023).

While EUETS reduces the average domestic supply of Lower Saxony (LSX) by almost 3%, CBAM slightly mitigates this decline. While EUETS slightly reduces the average domestic supply in the Rest of Germany (ROG) and the entire EU (EU27), CBAM eliminates this effect in the Rest of Germany and turns it into a

small increase in average domestic supply in the EU. Because CBAM hinders international trade, it reduces productivity gains from Ricardian selection (on average across sectors, derived from the Eaton Kortum theory) in the EU and the World. It decreases the Ricardian productivity gains compared with EUETS in ROG but increases them in LSX. These effects are, however, small. The overall price level (true cost-of-living index) slightly increases due to the import taxation of CBAM (by approximately 0.5 percentage points in LSX and ROG). Similarly, total income slightly increases in both considered German regions compared with the benchmark scenario (by approximately 1% in LSX and 0.5% in ROG). With CBAM, Lower Saxony (LSX) and the Rest of Germany (ROG) reduce CO₂ emissions in the EU ETS more than with EUETS only (almost 57% and almost 44% compared to the benchmark).

We are particularly interested in the differences in the welfare effects of CBAM (EUETS plus import tariffs) compared with those of EUETS alone (see above) as displayed in the right column of Table 4 in percentage points. All resulting welfare losses across the model regions are smaller than 0.7%, while welfare gains are smaller than 0.5%. CBAM intensifies the effects of the EUETS and creates typical trade policy effects: With power on international markets, EU ETS members can gain from import taxation by improving the terms-of-trade in their favor. From a global perspective, however, import taxation causes a distortion of international trade and hence a welfare loss. Additionally, carbon-based import taxation changes the allocation of emissions across countries/regions and sectors and the CO₂ price. This can create winners and losers. Finally, because the benchmark data contain existing taxes (tariffs) and subsidies, the model describes a second-best world, in which additional policies can have complex and unexpected effects.

According to Table 4, the EU is hardly affected (tiny negative effect) by CBAM compared with EUETS whereas the entire World (*WORLD*) slightly loses (by 0.02 percentage points) compared with EUETS. The Rest of the World (ROW) significantly loses (by 0.14 percentage points) due to CBAM.

CBAM significantly reduces the EUETS-induced loss of the Rest of Germany (ROG, 0.19%) by 0.14 percentage points (to 0.05%). Similarly, CBAM substantially increases the EUETS-induced gain of Lower Saxony (LSX, 0.17%) by 0.25 percentage points (to 0.42%). France (FRA), the United Kingdom (GBR) and Italy (ITA) benefit from CBAM (by 0.08, 0.04 and 0.01 percentage points, respectively). While the Rest of the EU (EUR) gets worse off (by 0.12 percentage points), the Rest of the EU ETS (ROE) becomes equally better off (also by 0.12 percentage points). The entire EU (*EU27*) is not significantly affected by CBAM compared with EUETS.

The Former Soviet Union (FSU) countries lose significantly due to CBAM (by 0.20 percentage points), because fossil fuel imports as well as imports of carbon-intensive goods into the EU are hindered. Japan (JPN) and Korea (KOR) gain slightly (by 0.02 and 0.04 percentage points) due to CBAM, while Canada (CAN) and Mexico (MEX) lose slightly (by 0.05 and 0.04 percentage points).

Large open economies, in particular, the USA (a 0.01 percentage point loss in CBAM compared with EUETS), China (CHN, approximately 0.00 percentage points) and India (IND, a 0.02 percentage point loss) are affected (negatively) to a minor extent. This result indicates that the USA's vulnerability to EU tariffs is low, especially when the tariff rates are moderate, because it is a large economy with many trading partners.

The qualitative pattern of the policy spillovers of CBAM on other countries/regions in the world derived from the new quantitative trade model is very similar to the pattern found by Hübler et al. (2024) derived from an Armington (1969) type trade model. Quantitatively, the magnitudes of the effects of CBAM compared to those of EUETS are also similar to those found by Hübler et al. (2024). One notable exception is the small welfare loss of the Rest of the EU due to CBAM displayed in Table 4 that contrasts with the small gain found by Hübler et al. (2024). Considering the entire EU-27 (*EU27*), according to Table 4, however, this negative effect is neutralized by the positive effects in the explicitly modeled EU countries such that an EU-wide effect of CBAM is hardly visible. This outcome highlights the relevance of modelling single countries within a larger political or geographic macro-region (here the EU) because the effects within a macro-region can be heterogeneous. The small magnitudes of the simulated effects of CBAM are also in line with Korpar et al. (2023) but smaller than in previous studies, e.g., by Mattoo et al. (2013).

In summary, the CBAM results confirm that regional disaggregation matters: the positive regional effects of CBAM on Lower Saxony are substantially stronger than those on the Rest of Germany.

3.5 Sectoral analysis

This section provides an analysis of the sectoral emission, sales and trade effects of EUETS and CBAM to illustrate the model mechanisms at the sectoral level and to derive insights in international competitiveness effects. We focus on the same German regions as before.

Appendix Figures A2 and A3 illustrate the relative reductions in CO₂ emissions from fossil fuel inputs coal (COAL), natural gas (NGAS), crude oil (CRUD) and refined petroleum (PETR) in the carbon-intensive EU ETS sectors electricity (ELEC), iron and steel (IRST), chemicals (CHEM), paper and pulp (PAPR), mineral products (NMMS) and non-ferrous metals (NFMS) (without PETR which is less relevant for the considered German regions). In both regions, the EU ETS sectors achieve the most substantial mitigation of CO₂ emissions via reductions in the COAL input which has the highest carbon content among fossil fuels. Overall, emission reductions are slightly larger under CBAM than under EUETS. Both policy scenarios result in an increase in emissions from PETR in all sectors except ELEC because of its low carbon content compared with COAL and NGAS. While LSX experiences a small decrease in emissions from CRUD in the ELEC sector, emissions from CRUD increase in ROG. In addition, relative emissions reductions in the ELEC

sector are significantly greater in LSX than in ROG due to its substantial renewable energy (especially wind power) capacity.

Let us now consider sectoral sales as a production and competitiveness indicator. In Lower Saxony (LSX) and the rest of Germany (ROG), the coal (COAL), electricity (ELEC) and natural gas (NGAS) sectors are by far most strongly affected by EUETS in terms of reductions in their sales (e.g., a reduction in coal sales by more than 55% compared to the benchmark in ROG). Crude oil (CRUD) and refined petroleum (PETR) sales are hardly affected or slightly decline (PETR in LSX) because they can replace more carbon-intensive fossil fuels, particularly coal. Energy-intensive and trade-exposed sectors (iron and steel, IRST, non-ferrous metals, NFMS, mining, MINE, chemicals, CHEM, paper and pulp, PAPR) in LSX and ROG suffer from sales reductions of two to three percent (compared with the benchmark) due to EUETS. Agriculture (AGRI) in LSX and ROG, crude oil (CRUD) in ROG (as a substitute for coal and gas), construction (CONS) in LSX and manufacturing (MANU) in ROG are slightly better off regarding their sales under EUETS. Other sectors, such as transport (TRNS), services (SERV), mineral products (NMMS) or food (FOOD), are barely affected.

CBAM supports some domestic sectors in terms of their sales (e.g., iron and steel, IRST, in LSX and ROG) but also creates some sectoral disadvantages (e.g., non-ferrous metals in LSX and ROG) and barely affects other sectors (e.g., paper and pulp, PAPR, in LSX and ROG). The magnitudes of these effects are small.

In the Eaton and Kortum trade model, international trade is reflected by international trade shares between two trading partners (see Appendix Equation 5). For each good (produced in each sector), it reflects the fraction of varieties that are delivered by one trading partner at the lowest cost among all trading partners.

Let us consider China (CHN) as a major trading partner of Germany with relatively carbon-intensive production as a case study and focus on energy-intensive, trade-exposed EU ETS sectors (IRST, CHEM, PAPR, NMMS, NFMS). According to the simulation results, EUETS leads to an increase in the import shares from China to Lower Saxony (LSX) or to the Rest of Germany (ROG) in these sectors (e.g., by 6.5% compared with the benchmark in the iron and steel, IRST, sector of LSX) because the considered carbon pricing makes domestic supply from these carbon-intensive sectors more expensive relative to Chinese production/imports. On the contrary, CBAM renders imports from China (due to their significant carbon contents) more expensive (relative to other countries/regions) and hence reduces the import shares from China (e.g., by 7.5% compared with the benchmark or 1.0 percentage points below EUETS in the IRST sector of LSX).⁹ However, leaving aside (carbon-based) export rebates, EUETS and CBAM also reduce the export shares from LSX or ROG to CHN (e.g., 7.9% under EUETS and 12.7% under CBAM compared to the benchmark) due to higher fossil fuel input costs and higher intermediate good import costs that reduce

⁹Except non-ferrous metals (NFMS) in the Rest of Germany (ROG).

the competitiveness of German producers on the international market.

3.6 Decomposition analysis

Figure 2 depicts a decomposition of the policy-induced CO₂ emission changes in the production sectors of Lower Saxony (LSX) and the Rest of Germany (ROG) based on Pothen and Hübler (2018), similar to Larch and Wanner (2017) and Sogalla et al. (2024) building on the seminal work by Grossman and Krueger (1993) and Copeland and Taylor (1994). Besides the usual scale and decomposition effects, it includes a technique effect capturing sectoral productivity gains via Ricardian selection emerging from the Eaton and Kortum trade model and an input substitution effect. It uses the multiplicative Log-Mean Divisia Index Method I (LMDI I) developed by Ang and Liu (2001).

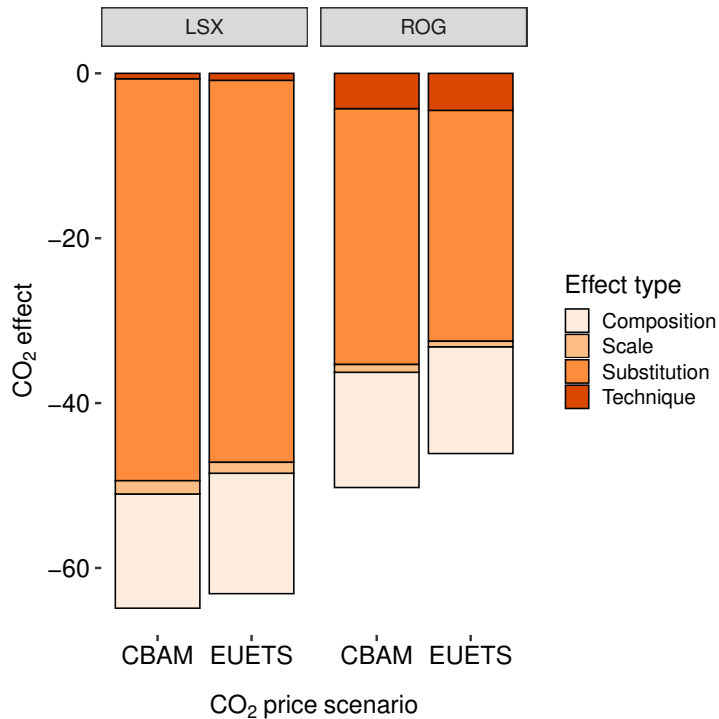


Figure 2: Decomposition of policy-induced changes in CO₂ emissions in Lower Saxony (LSX) and the Rest of Germany (ROG). The CO₂ effects are measured as relative changes between the scenario EUETS or CBAM compared with the benchmark scenario in percent.

According to the results, under EUETS, emission reductions are mainly achieved by replacing fossil fuel inputs by other inputs (substitution effect), to a much smaller extent by shifting production towards less CO₂-intensive sectors (composition effect) and to a minor extent via Ricardian productivity gains (technique effect) and output reductions (negative scale effect). This result shows that the additional mechanism of Ricardian

selection and resulting productivity gains provided by the Eaton and Kortum model has numerically little relevance for this analysis. Notwithstanding, according to the estimates, the technique effect is considerably stronger in the Rest of Germany (ROG) than in Lower Saxony (LSX) which underlines the relevance of regional differences, also for advanced trade modelling.

CBAM intensifies the predominant substitution effect in the EU ETS that reduces CO₂ emissions (see Figure 2). The magnitude of the composition effect is much smaller than in Larch and Wanner (2017). While CBAM slightly extends the composition effect in the Rest of Germany, it reduces it in Lower Saxony. Because CBAM hinders international trade, Ricardian productivity gains decline in LSX and ROG compared with EUETS.

In summary, Ricardian selection driven by the Eaton and Kortum theory differs between the two German regions under consideration. As before, the policy effects also differ across European countries/regions. Regarding the relevance of the Eaton and Kortum theory for modelling climate and trade policy, the contribution of Ricardian selection to CO₂ reductions is, however, small in the decomposition analysis, and the policy modelling results are similar to those derived from an Armington (1969) type trade model.

3.7 Sensitivity analysis

To check the robustness of our policy analysis and to obtain additional insights regarding the effect of model and scenario assumptions, we carry out a couple of sensitivity checks. First, we change the CO₂ emission target of the EU ETS which is the main determinant of the impacts of both policies, EUETS and CBAM. Second, we vary the sectoral trade elasticities of the Eaton and Kortum model because this is the key parameter governing the reaction of international trade to policy changes. A full sensitivity analysis of the underlying model including a Monte Carlo analysis with thousands of random draws of parameter values can be found in Pothen and Hübler (2018).

First, we vary our original 44% CO₂ reduction in the EU ETS sectors to 30%, 60% and 70%. The results are reported in Appendix Table A3. Under the 30% target, the welfare gain of Lower Saxony (LSX) compared with the benchmark scenario becomes much smaller (0.64%) than under 44% (0.17%); assuming 60% the gain further increases (0.25%) but under 70% it decreases (0.21%). Intuitively, gains from emission trading due to low marginal abatement costs have their limits and cannot compensate losses induced by ambitious emission targets. In the Rest of Germany, this relationship looks more straightforward, i.e., more stringent targets lead to higher welfare losses (between 0.16% under the 30% target and 0.30% under the 70% target). The welfare loss of the EU reaches 0.84% when assuming the 70% reduction. These qualitative and quantitative differences in the policy effects underline the relevance of regional analyses.

The scrutinized more stringent emission targets of the EU ETS render CBAM considerably more efficient regarding the reduction of carbon leakage so that global emissions decline by 2.5 to 2.9%, similar to the results found by Sogalla (2023). Regarding welfare effects on the EU, however, a typical “optimal tariff” relationship emerges, in which the terms-of-trade and hence welfare are improved in an inverted U-shaped manner. Under the 44% CO₂ target, CBAM has on average a negligible welfare effect on the entire EU. The less stringent 30% CO₂ target results in a lower CO₂ price and hence lower tariff rates which creates on average a minor welfare gain of the EU from CBAM compared to the EU ETS alone in accordance with Korpar et al. (2023). A more stringent CO₂ target, however, results in a substantially higher CO₂ price and hence higher tariff rates creating on average a higher welfare loss of the EU compared to EUETS alone (0.83% and hence an additional 0.23 percentage points loss under the 60% target and 1.43% and hence an additional 0.59 percentage points loss under the 70% target). While the global welfare loss (*WRLD*) due to EUETS amounts to 0.21% under the 70% target, CBAM more than doubles that loss reaching 0.46%.

In the decomposition of CO₂ reductions induced by EUETS or CBAM, sectoral shifts (decomposition effect) first become stronger in the Rest of Germany (ROG) with more stringent CO₂ targets as found by Sogalla (2023) but then become weaker. In Lower Saxony (LSX), they become overall weaker. This means, more stringent CO₂ reductions are mainly achieved by replacing fossil fuels by other inputs (substitution effect) and to a small extent by reducing output (negative scale effect).

Second, we vary all sector-specific trade elasticities, i.e., the inverse spread of productivity as defined by the Eaton and Kortum theory, in all sectors and regions simultaneously by $\pm 20\%$. Their initial values have been derived from a structural estimation as detailed in Pothen and Hübler (2018) (especially Table 3) and are displayed in our Appendix Table A2. The results are reported in Appendix Table A4. Interestingly, it is not evident whether lower/higher values of the trade elasticities result in larger/smaller magnitudes of the (positive or negative) welfare effects of EUETS or CBAM in the model regions. In any case, the welfare deviations are small so that the model specification is relatively robust with respect to uncertainty in the trade elasticities.

4 Regional data provision and modelling strategies

For regional analyses, several priorities of future research and data provision emerge from the reviewed literature, the available data and the limitations of our model and our policy simulations.

First, we have identified a lack of available RIOTs for several German federal states, especially in the eastern federal states. Official regional data from statistical offices seem to be exceptional and sometimes outdated. Considering the large differences in the economic importance of certain sectors across regions

(e.g., wind energy in Lower Saxony and Schleswig-Holstein versus coal mining in Lusatia and North-Rhine Westphalia), this discrepancy could be addressed by researchers in order to accurately quantify the regional impacts of climate policy measures. Consequently, the creation and public provision of an up-to-date standardized/harmonized German regional database with federal state level resolution covering all federal states (following the multi-regional input-output (MRIO) tables created by Többen 2017a; Többen 2017b; Krebs 2020) and providing further region-specific information, as discussed in the following, should be supported by public funding to allow cooperation between scholars and statistical offices. Then it should be updated regularly and, as far as possible, aligned with existing standard databases, such as GTAP, regarding available sectors, years and variables to facilitate policy modelling.

Second, further disaggregation of RIOTs within federal states to individual regions is required to narrow down specific policy effects. The evaluation of such effects at a more granular level can be crucial for regions that are strongly affected by climate change impacts or climate/energy policy measures. In this regard, the German district level (“Kreisebene”) data (VGRdL 2022a) containing the gross domestic product, (sectoral) value added, (sectoral) employment and further information provide a relevant data basis. This includes regions whose production depends on energy- or greenhouse gas-intensive production sectors or production chains with the resulting negative effects of carbon pricing but also regions that benefit from the subsidization of climate-friendly technologies or from financial compensation, such as Lower Saxony or Lusatia (see Seibert et al. 2018; Stürmlinger and Fuchs 2021; Sgarciu et al. 2023).

Third, a conceptual challenge emerges because trade and factor mobility between regions within a country differ from *international* trade and factor mobility. The required trade on migration, capital mobility and inter-regional trade are not monitored and reported in official statistics like their international counterparts either. A reasonable assumption could be perfect factor mobility across regions within the same country, but no factor mobility across countries or world regions. However, in this case, the definition of a model region based on a representative consumer with region-specific factor endowments becomes a technical challenge. Consequently, imperfect factor mobility within a country could be a solution. Then, factor mobility across countries with a lower degree of mobility, particularly within the EU, could be a logical next step, considering the increasing relevance of international migration, foreign direct investment (FDI) and international financial transfers (portfolio investments). These mechanisms, however, require a suitable and tractable theoretical foundation, model implementation and calibration data to represent regionally different degrees of factor mobility (where the latest GTAP versions make a step forward). Similarly, scholars need to find an adequate representation of within-country trade, especially regarding data assumptions, in contrast to the standard case of international trade, for which theories, model implementations and data exist.

Furthermore, in the context of international trade and international investments, multinational enterprises

and “global players” play a central role. Within a country, however, they reside within specific federal states or regions and there is likely regional concentration of producers and suppliers making use of supplier-customer relations within the supply chain, business relations, exchange of workers and ideas, i.e., knowledge spillovers, and so forth (e.g., in the Silicon Valley). Consequently, domestic, foreign or international policies affecting multinational enterprises have strong effects on their regions of residence and smaller effects on other regions. A profound regional policy analysis in a globalized world would need to take this into account.

Fourth, the sectoral structures of federal states or regions can significantly differ (e.g., the relevance of agriculture or the automotive industry). However, these structures may not be perfectly covered by constructed data sets, and data on (sectoral) intermediate goods inputs are often missing. Inadequate approximations of input patterns, in particular fossil fuels, however, affect sectoral CO₂ emissions and hence climate policy effects. Furthermore, the available sectoral resolution can be insufficient. For the purpose of climate/energy policy analysis, Pothen and Hübler (2018) and Pothen and Hübler (2021), for example, combine the regional disaggregation with the disaggregation of the power sector distinguishing different energy sources/technologies (and the latest GTAP data make a step forward in this regard). Depending on the policy question, such a sectoral disaggregation can also be relevant for other sectors. In the climate/energy policy context, the representation of specific energy-/CO₂-intensive industries (cf. Hübler and Löschel 2013), such as cement, possibly including process emissions, can be relevant (in combination with regional disaggregation). Other examples for sectors that are important (for Germany) but not separately visible in common data, are the automotive industry and specific types of machinery or information and communication technologies. Consequently, a better sectoral resolution of regional data is recommendable, and the sectoral structures of regional data should match those of standard country-wise datasets, such as GTAP.

Fifth, for regional climate and energy policy analysis, the transfer of electricity (and other types of energy carriers, such as gas or hydrogen) is of particular interest. Due to elaborated within-country grids, energy exchange between regions within countries is presumably larger than between countries. Improvements and extensions of energy transfer and storage that are necessary for the expansion of renewable energy, such as the North-South transmission line in Germany, need to be considered. In this regard, links to power grid models or their results and insights can be helpful, for example, considering decentralization of power supply, high-voltage grids, electricity-heat coupling, renewable energy fluctuations and storage (e.g., Böing et al. 2018). For this purpose, the design of a comprehensive modeling framework, for instance, within an interdisciplinary project, can be helpful (see, for example, the interdisciplinary NEDS – Nachhaltige Energieversorgung Niedersachsen – project on Northwest Germany; Blaufuß et al. 2019). For practical policy modelling, simplified approaches to the integration of engineering aspects into economic models would be helpful, especially in the field of energy supply, storage, transfer and demand with an increasing share of

energy from renewable sources.

Sixth, the available regional data (from Germany) may not contain the required detailed patterns of income sources and consumption expenditures on different goods/services. In the absence of these data, the standard assumption (also adopted in our analysis in Section 3) is that the income and consumption patterns of the representative consumer of each federal state mimic those of the average nation-wide consumer. This assumption, however, neglects discrepancies in income and inequality within a country (here, Germany) that are related to differences in income sources. Income sources are in turn related to region-specific (in-situ) natural resource endowments, including fossil fuels. Climate/energy policy, however, significantly devaluates fossil fuels and thus has significant negative income effects on fossil fuel owners (cf. Hübler et al. 2024) which can be expected to show up as region-specific losses. Additionally, capital ownership may differ across regions. Hence, further data and research are required.

Seventh, the distinction of household/consumer income groups is another relevant dimension of disaggregation. While disaggregated income groups have been implemented at the German-wide level (Hübler et al. 2024) and led to significant differences in policy effects across income groups, the investigation of inequality effects at the regional within-country level is missing. Because average income differs regionally between rural and urban areas and, particularly, across federal states in Germany, regional differences in the inequality effects of policies can be expected. Therefore, the combination of regional data with household income group data can provide new insights. The required data are basically available within the German Household Budget Survey (EVS, FDZ 2024).

Eighth, like most model and input-out data analyses, our policy assessment does not consider climate change impacts that are often region-specific. Therefore, as far as possible, the new generation of regional data should also contain climate change impacts linked to (global budgets of) greenhouse gas emissions or concentrations.

5 Conclusion

We have reviewed the literature on regional policy effects in Germany and carried out a new policy analysis of the European Carbon Border Adjustment Mechanism (CBAM) that is currently being implemented regarding its regional effects within Germany as a new aspect.

According to our policy simulation results, CBAM is an effective instrument to reduce carbon leakage. Under the EU ETS CO₂ emission reduction target envisaged for the year 2030, CBAM has on average a negligible welfare effect on the EU. Whereas a less stringent CO₂ target creates a minor average welfare gain of the EU from CBAM compared with the EU ETS alone, more stringent targets applicable towards the

year 2050 lead to an additional average welfare loss of the EU due to substantially higher CO₂ prices. More stringent targets, however, also improve the effectiveness of CBAM in reducing carbon leakage and, therefore, global emissions.

While CBAM enhances the emission reductions of energy-intensive, trade-exposed sectors, CBAM affects the competitiveness of these sectors in terms of their sales to different degrees. Consequently, there is no guarantee that such policies are beneficial for all producers or industries.

Large open economies, in particular, the USA, China and India are affected negatively by CBAM but to a minor extent. With regard to reactive tariff increases of the EU against the USA, this result indicates that the USA's vulnerability to EU tariffs is relatively low, because it is a large economy with many trading partners. This insight questions the effectiveness of CBAM in incentivizing climate action of large CO₂ emitters, especially the USA when carbon-based tariffs are dominated by a new wave of strategic tariffs. Nonetheless, our results and considerations point to significant regional and sectoral differences of policy effects. For example, high US tariffs on EU automobiles can significantly hurt German regions where automotive industries are located although these local effects average out at moderate effects at the German or European economy-wide level.

Like other computable general equilibrium assessments, our policy analysis is subject to uncertainty of parameter values, in particular those governing the reaction of inputs, outputs, trade and consumption (i.e., elasticities of substitution and trade elasticities) to policies. More flexibility in the modelling system (reflected by higher elasticity values) basically allows stronger adjustments to policies, including easier replacements of fossil fuels to reduce CO₂ emissions, and hence smaller welfare effects. Our sensitivity test and the detailed sensitivity analysis in Pothen and Hübler (2018), however, indicate that the model results are relatively robust to changes in such parameter values. Nonetheless, all specific numerical results, especially those from the regional analysis, should be treated with caution.

Regarding the relevance of the Eaton and Kortum theory for modelling climate and trade policy, our analysis indicates that the contribution of Ricardian selection to CO₂ reductions is small and the policy modelling results are similar to those derived from an Armington (1969) type trade model. An Armington specification also eases the computation of basic trade indicators, such as import and export volumes, average import and export prices and the terms-of-trade based on import and export bundles. Hence, an Armington-type trade model (see, for instance, Böhringer et al. 2012; Larch and Wanner 2017) appears to be sufficient for climate and trade policy assessments, such as carbon-based tariffs, especially for providing qualitative policy advice. For understanding the delicate theoretical mechanisms driving emission changes in the international trade context, advanced trade models are nonetheless relevant and insightful tools.

In summary, our analysis combined with a literature review highlights relevant regional differences in policy

effects. It underlines that world region-wide (e.g., the EU) or country-wide (e.g., Germany) policy results can be misleading for giving reliable national region-wide (e.g., Lower Saxony) policy advice. Consequently, more regional data and practical modelling approaches are required.

In contrast to these insights, our review of available regional data within Germany reveals a dearth of publicly available official and constructed data. Therefore, the overarching goal is the provision of an up-to-date, standardized, country-wide multi-regional input-output (MRIO) table (as developed by Többen 2017a; Többen 2017b; Krebs 2020). It shall cover all regions (e.g., federal states) within the country and contain the required information for various policy modelling purposes, for example, CO₂ emissions. Such a comprehensive data set could be officially and publicly provided by the country-wide or federal state-specific statistical offices (such as Statistisches Bundesamt) in an easily accessible way (online access). It should be updated regularly and, as far as possible, aligned with broader standard databases (such as GTAP) regarding sectors, years and variables/indicators.

With such a database, researchers could verify how far the results found in the literature and in our own analysis are robust to the choice of the regional disaggregation procedure and the availability of accurate and comprehensive data. Results can also differ when more regions (federal states) within countries are modeled separately/explicitly, which requires further research.

Importantly, interactions across regions via interregional trade (compared to international trade) and interregional factor movements (labor mobility, i.e., migration, capital mobility, i.e., geographic flexibility of investments) are conceptually different within countries compared with the mechanisms across countries, for which established theories and (numerical) models exist. Therefore, better practical modelling solutions are required that describe interregional trade and flexible factor mobility across regions within countries.

In the context of climate/energy policy and energy transition, interregional power grids and transmission lines (together with energy storage) create important interregional linkages and require an interdisciplinary economics-engineering approach (Böing et al. 2018; Göke et al. 2018; Blaufuß et al. 2019).

On the production side, the combination of regional with further sectoral disaggregation can be advisable, especially in the power sector and in energy-intensive sectors. In this way, process emissions can also be considered. On the consumption side, the distribution of income as well as land/resource ownership is regionally different. Therefore, the combination of regional disaggregation with consumer disaggregation can provide new insights in regional inequality effects.

Considering that shocks or policies can have a restricted local/regional scope and country-wide policies can have extraordinary local/regional effects due to local/regional circumstances (e.g., coastal off-shore wind power expansion in Northern Germany or the coal phase-out in Lusatia), a more detailed geographic resolution of the provided data than the federal state level is useful, at least for selected relevant areas.

In this context, multinational enterprises and “global players” play a crucial role in the determination of local/regional policy impacts, such as production and employment effects of trade policy or electromobility expansion. They are not only affected by local policies but also by policies abroad or changes in international regulation or on international markets. Because such enterprises are located or concentrated in certain areas, economic effects can be locally significant but average out at the country-wide level. This requires more granular data.

Overall, we have identified a number of modelling and data challenges and corresponding improvements. We believe that this regional analysis of Germany embedded in the EU provides insights that are relevant for other countries as well. In a world with increasing strategic trade barriers at arbitrary rates, environmental taxation, such as CBAM, provides an alternative strategy, setting well-grounded, transparent, reliable, beneficial, peaceful and hopefully broadly acceptable tariffs.

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Supplementary online appendix

This technical model summary follows closely Pothen and Hübler (2018). The general equilibrium model is summarized in Table A1. The corresponding model equations (MQs) are detailed below. The model features n^r regions indexed r or s and n^i goods (including services) produced in corresponding sectors indexed i or j that are traded from r to s . Normally, variables and parameters are written in Latin upper-case letters. Variables or parameters representing sectoral varieties $z_{i,r}$ are written in Latin lower-case letters. Greek lower-case letters indicate relative values.

A general equilibrium is reached if all relevant equilibrium conditions are met. The general equilibrium model is programmed in GAMS (General Algebraic Modeling System; Bussieck and Meeraus 2004) as a Mixed Complementarity Problem (MCP) and solved with the algorithm PATH (Dirkse and Ferris 1995). It uses the calibrated share form (Böhringer et al. 2003) that normalizes benchmark variables to unity to ease the model solution and interpretation of counterfactual values.

Variable	Equation	Symbol	Dimension
<i>Income balance condition:</i>			
Consumer income	MQ (1)	Y_r	n^r
<i>Zero-profit conditions:</i>			
Intern. transport services	MQ (2)	X_h^{ITR}	n^h
Per-unit input costs	MQ (3)	$c_{i,r}$	$n^i \times n^r$
Sectoral goods price index	MQ (4)	$P_{i,s}$	$n^i \times n^r$
<i>Trade flows:</i>			
Bilateral trade shares	MQ (5)	$\pi_{i,r,s}$	$n^i \times n^r \times n^r$
<i>Market clearing conditions:</i>			
Primary factor prices	MQ (6)	P_r^K, P_r^L	$2 \times n^r$
Natural resource prices	MQ (7)	$P_{i,r}^R$	$4 \times n^r$
Prices of the specific factors	MQ (8)	$P_{g,r}^F$	$n^g \times n^r$
Prices of intern. transp. serv.	MQ (9)	P_h^{ITR}	n^h
Total expenditures (demand)	MQ (10)	$D_{i,r}$	$n^i \times n^r$
Output of goods (sectors)	MQ (11)	$X_{i,r}$	$n^i \times n^r$
Emission price	MQ (12)	P^{ETS}	1
<i>Optional policy:</i>			
Subsidy (free allowances)	MQ (13)	$\phi_{i,r}^{ETS}$	$n^i \times n^r$

Table A1: Equilibrium conditions and variables from Pothen and Hübler (2018) (Table 1).

MQ = model equation, r/s = region, i/j = sector, h = transport service sector, g = electricity generation technology, c = per-unit cost, π = trade share, K = capital, L = labor, R = natural resources, F = technology-specific factor, P = price, Y = consumption (income), X = sales (production output), D = demand (expenditures), ϕ = subsidy, ITR = international transport services, ETS = emissions trading system, n^r = number of regions, n^i = number of sectors, n^h = number of transport service sectors, n^g = number of technologies.

The following stylized equation **MQ (1)** describes the income of the representative consumer in each region s (see Pothen and Hübler 2018). \bar{K}_s and \bar{L}_s are region-specific endowments with the primary factors capital

and labor; $\bar{R}_{i,s}$ are sector-specific natural resource stocks and $\bar{F}_{g,r}$ technology-specific factor endowments. P_s^K , P_s^L , $P_{i,s}^R$ and $P_{g,s}^F$ are the corresponding factor prices. Factors are supplied inelastically and provide factor income Θ_s . Ξ_s are (endogenous) transfers (tax revenues and revenues from selling CO₂ allowances minus subsidies). Δ_s is the exogenous current account deficit that is constant across scenarios. $\frac{\xi_s Y_s}{c_s^C}$ is real consumption and used as the welfare measure of the policy analysis, where c_s^C denotes the true-cost-of-living index, i.e., the price of the (optimal) consumption bundle. (The consumption function can be found in Pothen and Hübler 2018, Figure 1.)

$$Y_s = \Theta_s + \Xi_s + \Delta_s \quad (1)$$

$$\Theta_s = P_s^K \bar{K}_s + P_s^L \bar{L}_s + \sum_i P_{i,s}^R \bar{R}_{i,s} + \sum_g P_{g,s}^F \bar{F}_{g,s}$$

The following zero-profit condition **MQ (2)** refers to the provision of global international transport services Q_h^{ITR} aggregating transport services from sectors h in regions r , where $\zeta_{h,r}$ denotes the constant input share of r in international transport services (see Pothen and Hübler 2018). The corresponding prices for transport services P_h^{ITR} must cover their per-unit costs.

$$P_h^{ITR} = \prod_r \left(\frac{P_{h,r}}{\zeta_{h,r}} \right)^{\zeta_{h,r}} \quad (2)$$

According to Pothen and Hübler (2018), assuming a CES (constant elasticity of substitution) function that combines inputs with constant returns to scale and including intermediate goods inputs $Z_{j,i,r}$, cost minimizing production (see Pothen and Hübler 2018, Equation 3 and Figures 2 and 3) yields the per-unit production costs $c_{i,r}$ of varieties $z_{i,r}$ that define **MQ (3)**.

$$c_{i,r} = C\tilde{E}S^Q(K_{i,r}, L_{i,r}, R_{i,r}, Z_{j,i,r}|_j) \quad (3)$$

The domestic sectoral price of a good $P_{i,s}$ can be expressed as **MQ (4)** with the constant γ_i . For details see Pothen and Hübler (2018), particularly, Appendix O, and Caliendo et al. (2018). The trade elasticity θ_i (explained below) is a key parameter of the Eaton and Kortum model.

$$P_{i,s} = \gamma_i \left[\sum_r T_{i,r}^{\theta_i} (1 - \tau_{i,r}^x)^{\theta_i} (c_{i,r} \delta_{i,r,s})^{-\theta_i} \right]^{-\frac{1}{\theta_i}} \quad (4)$$

Table A2 reports the sector-specific values of the trade elasticity θ_i taken from Pothen and Hübler (2018). θ_i determines the shape of the Fréchet distribution assumed by the Eaton and Kortum theory. According to

Sector	Description	Trade elasticity
AGRI	Agriculture	2.69
COAL	Coal	10.02
CRUD	Crude oil	7.89
NGAS	Natural gas	7.94
PETR	Refined petroleum	9.67
FOOD	Food production	3.80
MINE	Mining	2.43
PAPR	Paper and pulp	5.18
CHEM	Chemicals, rubber and plastic	4.45
NMMS	Mineral products nec.	6.39
IRST	Iron and steel	4.21
NFMS	Non-ferrous metals	4.43
MANU	Manufacturing	5.05
ELEC	Electricity	18.66
TRNS	Transport	6.21
CONS	Construction	15.07
SERV	Services	6.43

Table A2: Parameter values of the sector-specific trade elasticities θ_i (inverse spread of Ricardian productivity) of the Eaton and Kortum theory estimated by Pothen and Hübler (2018) (reported in their Table 3).

this theory, it reflects the inverse spread of productivity in the production of varieties of a good in a sector i . A higher value of θ_i results in a narrower distribution of variety productivities resulting in less scope for productivity gains from Ricardian specialization (Pothen and Hübler 2018). Table A4 reports the results of a sensitivity check that simultaneously varies all sector-specific trade elasticities θ_i by $\pm 20\%$.

MQ (5) characterizes the international trade share of shipping good i from r to s . According to the Eaton and Kortum theory, $\pi_{i,r,s}$ represents the part of all varieties of good i that region r delivers because it can produce it at the lowest cost among all regions. (See Pothen and Hübler 2018, for further explanations.)

$$\pi_{i,r,s} = \left[\frac{T_{i,r}(1 - \tau_{i,r}^x)P_{i,s}}{\gamma_i c_{i,r} \delta_{i,r,s}} \right]^{\theta_i} \quad (5)$$

Each region is endowed with given amounts of the production factors labor \bar{L}_r , capital \bar{K}_r , sector-specific resource stocks $\bar{R}_{i,r}$, particularly fossil fuels and mining, as well as technology-specific fixed factors $\bar{F}_{g,r}$ in the electricity sector that are all attributed to the region's representative consumer. The corresponding market clearing conditions **MQ (6)–(8)** define the corresponding factor prices P_r^K , P_r^L , $P_{i,r}^R$ and $P_{g,r}^F$ in equilibrium when factor supply equals demand from all production sectors of the region (Pothen and Hübler 2018).

$$\bar{K}_r = \sum_i K_{i,r}, \quad \bar{L}_r = \sum_i L_{i,r} \quad (6)$$

$$\bar{R}_{i,r} = R_{i,r} \quad \forall i \in \{COAL, NGAS, CRUD, MINE\} \quad (7)$$

$$\bar{F}_{g,r} = F_{g,r} \quad (8)$$

In addition, the market for international transport services h must clear in equilibrium **MQ (9)**. It defines the price P_h^{ITR} so that the global transport supply Q_h^{ITR} matches regional demands $Z_{h,i,r,s}^{ITR}$ (Pothen and Hübler 2018).

$$Q_h^{ITR} = \sum_{i,r,s} Z_{h,i,r,s}^{ITR} \quad (9)$$

Expenditures $D_{i,s}$ cover imported and domestically produced varieties of good i in region s including final $C_{i,r}$ and intermediate $Z_{i,j,r}$ goods (used in sectors j in s) which yields **MQ (10)** (Pothen and Hübler 2018).

$$D_{i,s} = P_{i,s}(C_{i,s} + \sum_j Z_{i,j,s}) \quad (10)$$

Similarly, market clearance of all goods markets requires that the sales $X_{i,r}$ of a region r match the corresponding expenditures $\pi_{i,r,s}D_{i,s}$ of all regions s which results in **MQ (11)** where $\tau_{i,r,s}^t$ denotes observable policy- and transport-related trade costs (Pothen and Hübler 2018).

$$X_{i,r} = \sum_s \frac{\pi_{i,r,s}D_{i,s}}{\tau_{i,r,s}^t} \quad (11)$$

This completes the trade model. For modeling climate policy, for example, in the European Emissions Trading System (EU ETS), at least one additional equation is required that defines the market for CO₂ allowances. The following market clearing condition **MQ (12)** determines the CO₂ price P^{ETS} by equating the exogenous supply of allowances given by the emission target \bar{ETS} with the actually released CO₂ emissions from burning fuels $A_{j,i,r}^{CO_2}$, $j \in \{COAL, CRUD, NGAS\}$ (Pothen and Hübler 2018). Υ^{ETS} symbolizes the set of all sectors and Ψ^{ETS} the set of all regions covered by the emission pricing system.

$$\bar{ETS} = \sum_{i \in \Upsilon^{ETS}, r \in \Psi^{ETS}} \sum_j A_{j,i,r}^{CO_2} \quad (12)$$

When part of the CO₂ allowances is allocated to producers for free (called “grandfathering” as implemented in the second phase of the EU ETS), an additional equation **MQ (13)** will be required. $\alpha_{i,r}^{fa}$ denotes the share of freely allocated allowances and $\phi_{i,r}^{ETS}$ an endogenous output subsidy that compensates producers in a particular sector for the corresponding part of their initial expenditures on allowances (Pothen and Hübler 2018).

$$\phi_{i,r}^{ETS} X_{i,r} = \alpha_{i,r}^{fa} \sum_j P^{ETS} A_{j,i,r}^{CO_2} \quad (13)$$

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	EUETS				CBAM			
	30%	44% (default)	60%	70%	30%	44% (default)	60%	70%
LSX	0.0638	0.1703	0.2538	0.2128	0.1498	0.4205	1.3485	2.6776
ROG	-0.1637	-0.1885	-0.1914	-0.2798	-0.1230	-0.0481	0.5231	1.3776
FRA	0.0654	0.1035	0.1255	0.1045	0.0952	0.1880	0.4855	0.8933
GBR	-0.1169	-0.2145	-0.2515	-0.2451	-0.1050	-0.1760	0.2236	0.7612
ITA	-0.1050	-0.2309	-0.4378	-0.5949	-0.0890	-0.2195	-0.3334	-0.1346
EUR	-0.2263	-0.5638	-1.2401	-1.7606	-0.2155	-0.6851	-2.5219	-4.9503
ROE	0.0084	0.0165	0.0371	0.0443	0.0583	0.1324	0.6224	1.7164
<i>EU27</i>	-0.1392	-0.3030	-0.5995	-0.8408	-0.1192	-0.3062	-0.8305	-1.4267
FSU	0.0133	0.0584	0.2019	0.3714	-0.0842	-0.1422	-0.2869	-0.4635
BRA	0.0012	0.0021	0.0041	0.0067	-0.0042	-0.0087	-0.0248	-0.0518
CAN	0.0028	0.0197	0.0783	0.1442	-0.0203	-0.0342	-0.0751	-0.1295
USA	-0.0056	-0.0102	-0.0186	-0.0254	-0.0096	-0.0179	-0.0421	-0.0795
MEX	0.0061	0.0138	0.0327	0.0524	-0.0146	-0.0284	-0.0733	-0.1417
CHN	0.0003	-0.0019	-0.0091	-0.0166	-0.0009	-0.0031	-0.0119	-0.0294
IND	-0.0014	-0.0140	-0.0497	-0.0869	-0.0133	-0.0330	-0.0938	-0.1828
JPN	0.0072	0.0056	-0.0076	-0.0246	0.0155	0.0239	0.0369	0.0423
KOR	0.0111	0.0008	-0.0403	-0.0879	0.0277	0.0370	0.0436	0.0337
ROA	-0.0185	-0.0313	-0.0529	-0.0700	-0.0377	-0.0685	-0.1505	-0.2620
OCE	-0.0409	-0.0497	-0.0473	-0.0365	-0.0529	-0.0741	-0.1115	-0.1585
ROW	0.0014	0.0235	0.1005	0.1887	-0.0671	-0.1206	-0.2618	-0.4377
<i>WRLD</i>	-0.0394	-0.0825	-0.1560	-0.2123	-0.0444	-0.1046	-0.2713	-0.4650

Table A3: Sensitivity check assuming different CO₂ emission reductions (vis-à-vis 2014 emissions) in the EU ETS; the numbers display welfare changes compared with the benchmark scenario in percent.

	EUETS			CBAM		
	$0.8\theta_i$	θ_i (default)	$1.2\theta_i$	$0.8\theta_i$	θ_i (default)	$1.2\theta_i$
LSX	0.2085	0.1703	0.1440	0.4413	0.4205	0.4102
ROG	-0.2190	-0.1885	-0.1652	-0.0939	-0.0481	-0.0082
FRA	0.1257	0.1035	0.0864	0.2052	0.1880	0.1748
GBR	-0.2352	-0.2145	-0.1956	-0.2030	-0.1760	-0.1461
ITA	-0.2332	-0.2309	-0.2267	-0.2108	-0.2195	-0.2241
EUR	-0.5827	-0.5638	-0.5434	-0.6471	-0.6851	-0.7193
ROE	-0.0024	0.0165	0.0294	0.1041	0.1324	0.1567
<i>EU27</i>	-0.3157	-0.3030	-0.2901	-0.2994	-0.3062	-0.3109
FSU	0.0374	0.0584	0.0754	-0.1520	-0.1422	-0.1361
BRA	0.0019	0.0021	0.0021	-0.0090	-0.0087	-0.0086
CAN	0.0167	0.0197	0.0216	-0.0359	-0.0342	-0.0332
USA	-0.0103	-0.0102	-0.0102	-0.0183	-0.0179	-0.0177
MEX	0.0116	0.0138	0.0157	-0.0296	-0.0284	-0.0273
CHN	-0.0017	-0.0019	-0.0019	-0.0035	-0.0031	-0.0025
IND	-0.0118	-0.0140	-0.0159	-0.0317	-0.0330	-0.0341
JPN	0.0080	0.0056	0.0038	0.0256	0.0239	0.0228
KOR	0.0058	0.0008	-0.0030	0.0411	0.0370	0.0341
ROA	-0.0319	-0.0313	-0.0309	-0.0699	-0.0685	-0.0675
OCE	-0.0543	-0.0497	-0.0464	-0.0782	-0.0741	-0.0716
ROW	0.0127	0.0235	0.0312	-0.1308	-0.1206	-0.1134
<i>WRLD</i>	-0.0873	-0.0825	-0.0780	-0.1041	-0.1046	-0.1048

Table A4: Sensitivity check simultaneously varying all sector-specific trade elasticities θ_i (inverse spread of Ricardian productivity) of the Eaton and Kortum theory; the numbers display welfare changes compared with the benchmark scenario in percent.

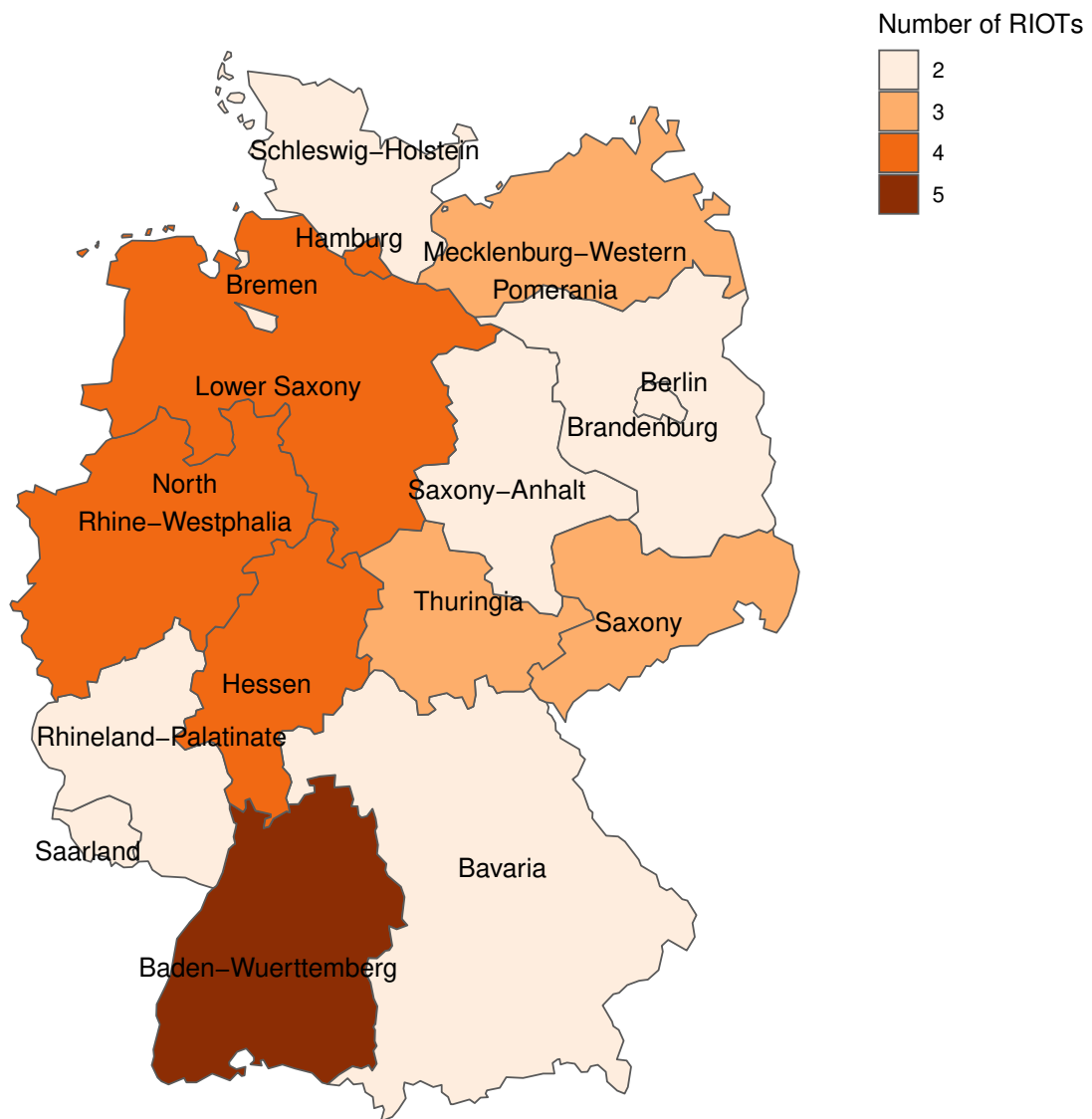
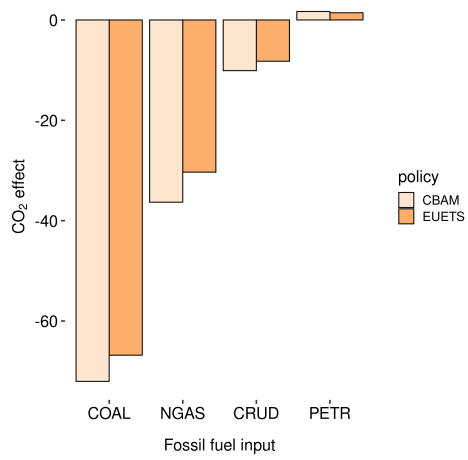
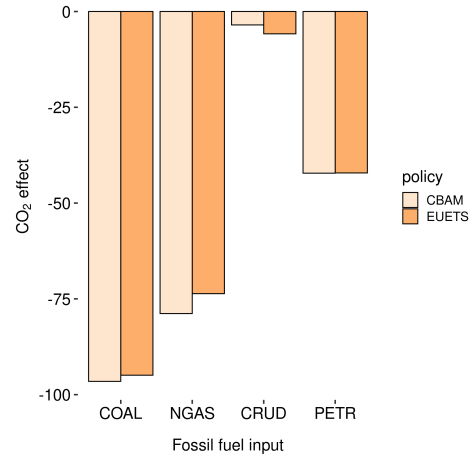


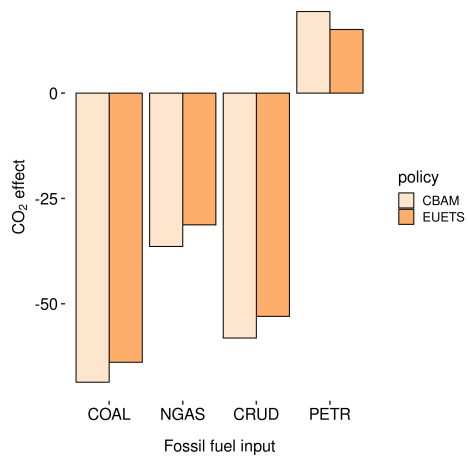
Figure A1: Availability of regional input-output tables (RIOTs) of single German federal states.



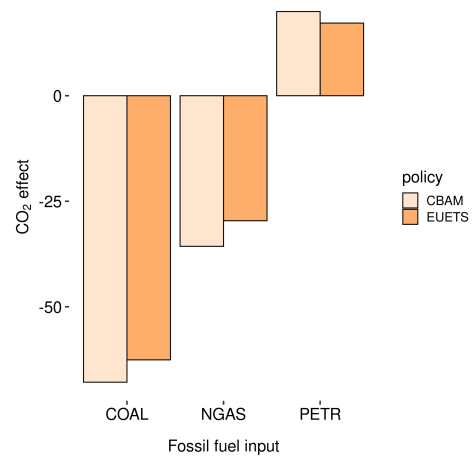
(a) Chemicals, rubber and plastic



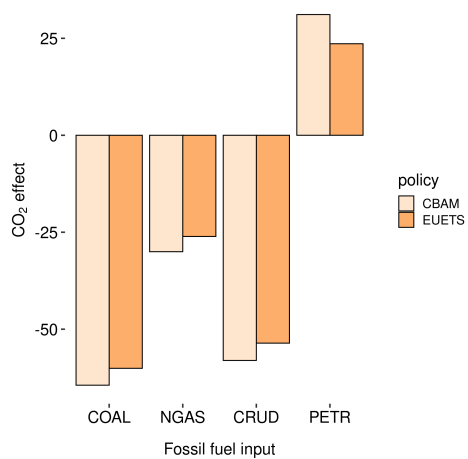
(b) Electricity



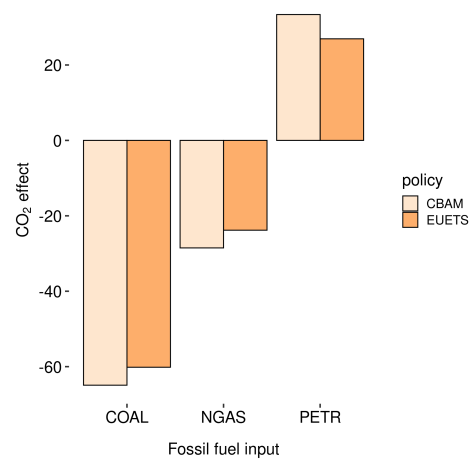
(c) Iron and steel



(d) Non-ferrous metals

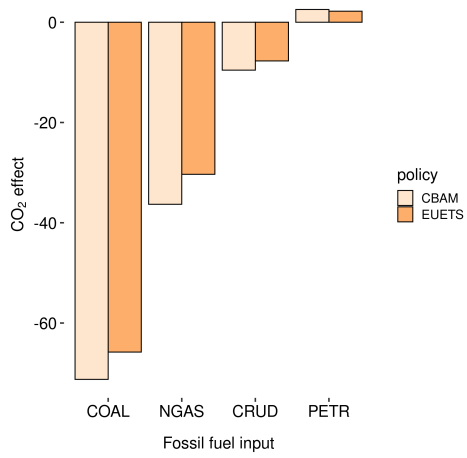


(e) Mineral products nec.

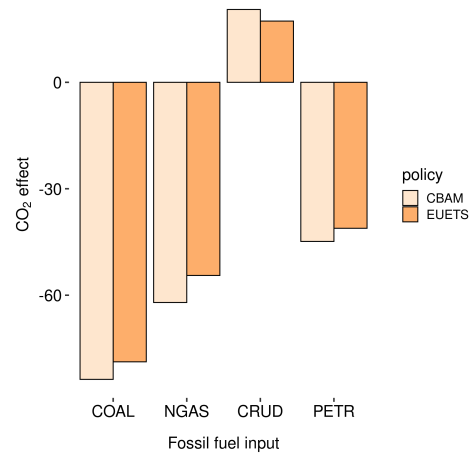


(f) Paper and pulp

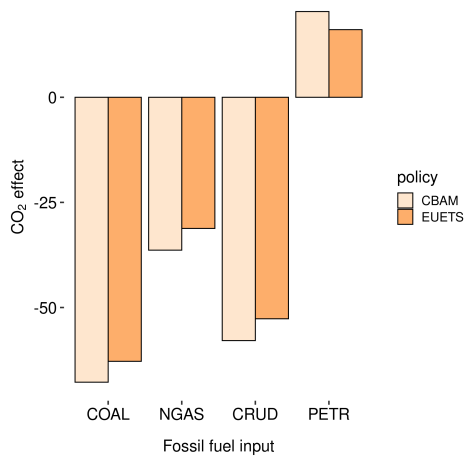
Figure A2: Policy-induced CO₂ effects in Lower Saxony's (LSX) energy-intensive and trade-imposed EU ETS sectors.



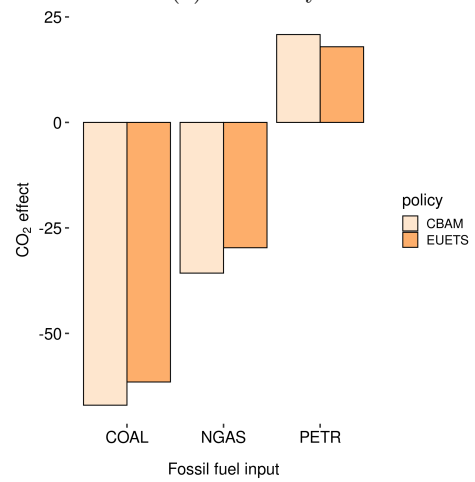
(a) Chemicals, rubber and plastic



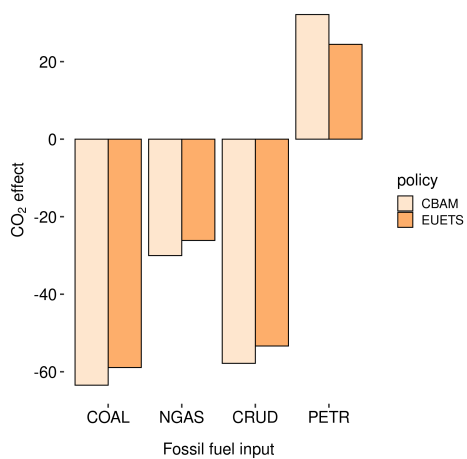
(b) Electricity



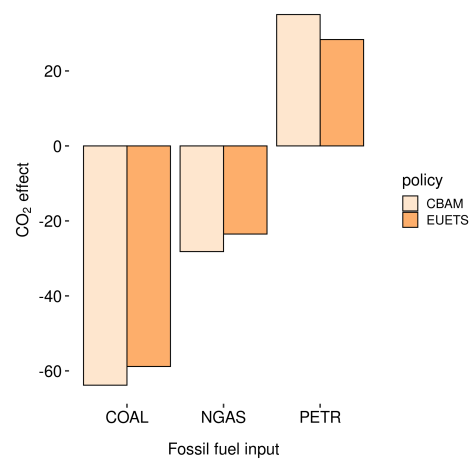
(c) Iron and steel



(d) Non-ferrous metals



(e) Mineral products nec.



(f) Paper and pulp

Figure A3: Policy-induced CO₂ effects in the Rest of Germany's (ROG) energy-intensive and trade-imposed EU ETS sectors.

Chapter 6

Differences in Labour Mobility Between Immigrant Generations: Evidence From the European Debt Crisis

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- 7th Annual Conference on Migration Research in Austria, September 26 – 28, 2022, Krems an der Donau, Austria

RESEARCH ARTICLE OPEN ACCESS

Differences in Labour Mobility Between Immigrant Generations: Evidence From the European Debt Crisis

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ABSTRACT

Immigrants' higher responsiveness to regional differences in labour market conditions has been recognised as a potentially important adjustment mechanism to labour market shocks. This paper investigates an aspect less explored by previous research, namely how labour mobility patterns are passed on across immigrant generations. Using Euro Area household-level data, we compare mobility patterns of first- and 1.5-generation immigrants and natives. We observe that 1.5-generation immigrants have a significantly lower interregional and international mobility compared to first-generation immigrants but are more mobile than natives. Our results suggest that not only first-generation immigrants but also their descendants contribute to labour market flexibility.

JEL Classification: F22, J61, R23

1 | Introduction

For the functioning of labour markets the mobility of individuals is an important channel through which wage signals attract and reallocate workers. When labour markets experience shocks, a high level of labour mobility contributes to the adjustment process in the labour market and to the recovery of the economy as a whole.

Currency areas such as the Euro Area (EA) represent a set of national labour markets which share a common currency and have freedom of movement for workers between the different member states. Because of the integration of national labour markets in currency areas, labour mobility is necessary as an adjustment process to country-specific labour market shocks. The role of labour mobility as an adjustment process was first recognised by the seminal work by Mundell (1961) in the context of currency areas.

A recent labour market shock in a currency area was caused by the European debt crisis which started in the beginning of 2010.

The crisis occurred after different EA member states that heavily relied on lending foreign capital experienced an unexpected lending stop followed by a recession with high unemployment rates and declining wages. These EA member states include Cyprus, Greece, Ireland, Portugal and Spain. Contrary to these economies, other Euro countries' labour markets were not as strongly affected, which led to high wage and unemployment differentials between the EA member states. This becomes clear when looking at the unemployment rates in 2012: Greece and Spain experienced unemployment rates of around 24.8% while the unemployment rates in France and Germany remained relatively low around 9.8% and 5.1%, respectively (the average unemployment rate in the Euro Area was around 11.5%) (OECD 2024). Standard neoclassical theories of migration suggest that when wage differentials between regions or countries are observed, migration occurs if the benefits of migrating compensate the costs of doing so (Sjaastad 1962). In light of previous literature documenting widening labour market differentials in the wake of the European debt crisis

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(Boeri, Garibaldi, and Moen 2012; Anderton et al. 2015; Boeri and Jimeno 2016), we believe the crisis represents an appropriate context to empirically investigate whether labour market differentials lead to migration.

This paper analyses differences in mobility patterns between immigrants and natives for the EA using the context of the European debt crisis. For this purpose, we use household-level data from the European Labour Force Survey (EU-LFS) (Eurostat 2020) from 2007 to 2014 and estimate binary logit models. We contribute to two strands of existing literature. First, to the literature on labour mobility as one channel through which shocks can be absorbed in currency areas. Second, to the literature on labour market mobility of immigrants versus natives.

Earlier empirical literature identifies a lack of labour mobility in Europe when compared to the United States that reduces European countries' ability to adjust to shocks (Blanchard et al. 1992; Decressin and Fatás 1995). More recent studies confirm this result but also find that the labour market mobility gap between European Countries and the United States has narrowed (Beyer and Smets 2015; Arpaia et al. 2016; Jauer et al. 2019). According to these studies, the improvement in European labour mobility can be partially attributed to the EU enlargements in 2004 and 2007 as well as migration from non-EU countries. This finding is consistent with Borjas (2001) who argues that immigrants 'grease the wheels' of their host countries' economies, that is, contribute to labour markets' capacity to adjust to shocks due to their higher propensity to migrate when compared to natives. These differences in internal mobility between foreign-born and natives have been observed by a number of studies. For instance, Schündeln (2014) shows that immigrants are significantly more likely than natives to migrate within Germany. Using panel data for Norway, Røed and Schöne (2012) and Røed and Schöne (2015) observe similar differences in mobility. Basso and Peri (2020) find a higher responsiveness of foreign-born workers to regional differences in labour market conditions for the United States.

The study most closely related to our paper is Basso, D'Amuri and Peri (2019). Using EU-LFS data from 2007 to 2016, they analyse the role of interregional labour mobility of foreign-born and native workers in absorbing shocks in the Euro Area. They find foreign-born workers' mobility to be similar between the United States and the Euro Area; however, when comparing European natives with their US counterparts, they find that US natives show a higher mobility in response to labour market shocks. Our paper offers an interesting extension to this research: Immigrants constitute a self-selected group which have chosen to undertake the migration to their host country. Thus, they may differ systematically from residents in their host country with respect to characteristics such as risk aversion, which potentially explains their higher responsiveness to regional labour market differences (Borjas 1987; Chiswick 2000). To shed some light on whether such characteristics can be passed on across generations or are lost as immigrants assimilate, we compare the labour mobility of immigrant generations, an issue that has been somewhat neglected by previous literature (with some notable

exceptions, for example, Ellis and Goodwin-White 2006; Goodwin-White 2007, 2018).

More specifically, we analyse differences in labour market responsiveness between first- and 1.5-generation immigrants (i.e., immigrants who arrived in their host country at age 10 or younger), which serve as a proxy for immigrants' descendants. The use of this proxy is necessary because the EU-LFS does not provide any information on individuals' parents' country of origin and thus does not allow us to directly identify second-generation immigrants. As these individuals received most of their educational attainment in their host country and are likely to have acquired substantial cultural experience, they are most likely more assimilated than their parents, which should ultimately result in greater access to labour market opportunities. We therefore believe that the 1.5 generation serves as a suitable proxy for second-generation immigrants. Thus, we expect 1.5-generation immigrants to exhibit lower labour mobility than first-generation immigrants due to their assimilation but higher labour mobility than natives as labour mobility characteristics are passed on from their parents' generation.

The remainder of this paper is structured as follows: Section 2 discusses theoretical background and reviews the empirical literature. In Section 3 we describe our data and empirical strategy. Section 4 discusses our empirical results. Section 5 presents some robustness checks. Section 6 concludes.

2 | Theoretical Background

2.1 | Neoclassical Theories of Migration

Much of the economic literature on international and regional migration builds on Sjaastad (1962), who argues that the individual migration decision can be viewed as a human capital investment decision, whereby the individual seeks to maximise her utility by choosing the location that offers the highest return to the skill-set offered by her whilst accounting for migration costs. This basic framework encompasses four key factors influencing the migration decision: First, discrepancies in timing between the benefits and costs of migration; second, variations in earnings between the origin and destination areas; third, discrepancies in the cost of living between these locations and fourth, the migrant's personal rate of time preference.

Subsequent literature has addressed some of the limitations of the basic Sjaastad model (see Bodvarsson, Simpson and Sparber (2015) for a comprehensive review). For instance, the basic model considers migration decisions at the individual level, implicitly assuming that the individual migration decision has no effect on the welfare of their family. However, most migration decisions occur at the family level, as households use migration as an informal insurance mechanism by diversifying family members' locations (Anam, Chiang, and Hua 2008; Bushin 2009), which is one of the main contributions of the New Economics of Labour Migration (NELM). Furthermore, the basic model assumes perfect information. However, many aspects of the migration decision, such as

economic conditions in the destination country, may be subject to uncertainty. Burda (1995) and O'Connell (1997) extend the basic model by applying real-options analysis to incorporate uncertainty into the migration decision. Moreover, the basic model does not account for the influence of the individuals' age. However, the age of a migrant at the time of the migration decision influences the expected net present value of the returns to migration (Becker 1964). In addition, the psychological cost of leaving friends and family members behind increases with age (Schwartz 1976). On the other hand, having a network of family members and friends present at the destination region reduces the psychological and information costs of migration such as language barriers, local employment opportunities as well as access to the social security system and other local amenities (Massey and España 1987; Carrington, Detragiache, and Vishwanath 1996; McKenzie and Rapoport 2010).

Another aspect particularly relevant to our paper is the self-selection of immigrants. On one hand, observable and unobservable characteristics of individuals—such as ambition, risk aversion and entrepreneurial spirit—influence wage differentials between the origin and destination region and thus the net present value associated with the migration decision (Borjas 1987). On the other hand, higher migration costs intensify selectivity of immigrants, as only those individuals that can expect to earn sufficiently high wages in the destination region will be able to recoup those costs (Chiswick 2000).

2.2 | New Economics of Labour Migration

An alternative theoretical approach to explaining migration patterns is the New Economics of Labour Migration (NELM) which dates back to the seminal work of Stark and Bloom (1985). Contrary to the basic neoclassical framework, NELM views the household rather than the individual as the main decision making unit. In particular, this theory argues that households use migration by one or more of its members as an income diversification and self-insurance strategy (Katz and Stark 1986; Lauby and Stark 1988). Remittances play a central role in this strategy, as they allow households to overcome market constraints and invest in productive activities (Stark 1980; De Haas 2010).

Another central insight of NELM is the emphasis on relative deprivation—that is, the wish to improve their income relative to other individuals people in their respective social settings—as a determinant of the migration decision-making process (Stark and Taylor 1989; Stark and Taylor 1991). However, a key implication of the relative deprivation model is that given a sufficiently large gain in utility from a reduction in relative deprivation, individuals will migrate from a high-income country to a low-income country, which is not consistent with empirical evidence on migration behaviour (Bodvarsson, Simpson, and Sparber 2015). In addition, NELM interprets migration as a process of innovation, adoption and diffusion (Stark and Bloom 1985). Thus, individuals that first migrate into a new region can be viewed as innovators to their network. The information provided by these innovators reduces future uncertainty for potential migrants and can thus potentially increase the speed of adoption of migration decisions.

2.3 | Spatial Assimilation Theory

A fundamentally different theoretical approach to migration patterns is provided by the spatial assimilation theory going back to Massey (1985) and Massey and Denton (1985) and Massey and Denton (1988), which originally attempted to explain intrametropolitan mobility patterns of migrants. This theory argues that spatial and socioeconomic mobility are related: As immigrants become more accustomed to their host society, for example, via labour market participation, better educational attainment and improved language proficiency, they become less depended on their immigrant network and thus have a higher propensity to leave their initial concentrated immigrant communities. As a result, they tend to leave for communities with better employment prospects, improved housing, a higher rate of home-ownership, lower crime rates and better public services (Hall 2009).

On the other hand, while these initial immigrant communities may provide employment opportunities and valuable networks (Model 1988; Jargowsky 2009), those immigrants remaining in these communities over time are often thought to make limited progress toward integration due to a concentration of limited education and labour force skills (Goodwin-White 2018). More recent scholars have extended this framework to larger regional scales to explain immigrants' mobility patterns at the regional and state level (Alba and Nee 1997; Hall 2009; Kritz and Gurak 2018). These authors note the importance of local as well as extralocal contexts, such as regional housing markets and the political environment, in shaping the assimilation process.

Another strand of the spatial assimilation literature particularly relevant for our paper assesses the assimilation trajectories of the children of immigrants. Their assimilation prospects are shaped by their parents' mobility patterns: As they move away from concentrated immigrant communities, they create avenues for their children's structural assimilation, primarily by residing closer to native populations. (Ellis and Goodwin-White 2006; Goodwin-White 2007). However, there is some disagreement in the literature on how strongly the second generation's assimilation trajectories depend on their parents' relocation choices on the one hand (e.g., Massey 1995) and social mobility through education on the other hand (e.g., Hirschman 2001).

3 | Data and Empirical Strategy

3.1 | Data Description

For our empirical analysis we use annual microdata from the EU-LFS. The EU-LFS provides detailed household level information on labour market participation and related issues of approximately 1.8 million people per year for the member states of the European Union. Table 1 shows the number of observed individuals by country and year. Following Basso, D'Amuri and Peri (2019) we look at all people aged 15 to 64 living in a country which joined the Euro Area in 2007 or earlier. To study labour mobility as a mechanism to adjust to the Euro crisis we consider the waves of 2007, 2011 and 2014. In doing so, we choose to look at one cross-section prior to the

TABLE 1 | Number of observed individuals by country and year in the EU-LFS.

Country	2007	2011	2014
AT	134,016	120,696	117,567
BE	77,733	66,760	69,230
CY	26,142	29,760	27,239
DE	32,216	31,239	309,474
EE	17,170	15,515	16,969
ES	71,205	71,600	71,030
FI	41,536	37,653	34,835
FR	226,711	328,446	326,124
GR	186,256	171,442	146,484
IE	212,616	146,749	134,153
IT	427,708	400,971	363,655
LT	43,967	45,137	42,523
LU	14,030	13,503	9246
LV	25,035	23,181	26,087
NL	76,780	64,820	56,446
PT	111,686	102,471	107,128
SI	49,105	43,759	43,004
SK	76,050	71,770	65,447
Total	1,849,962	1,785,472	1,966,641

Euro crisis, one shortly after the onset and one during the recovery process of the Euro Crisis. We choose 2014 as our last cross-section in order to exclude potential confounding effects of the large migration inflows Europe experienced in 2015 and 2016.

The EU-LFS allows us to study differences in labour mobility between immigrants and natives using a rich set of household-level characteristics. Mobility across countries is measured by comparing the country of residence in the year of survey to the country of residence 1 year prior to the survey. Analogously, mobility across regions is measured by comparing the NUTS-2 region of residence in the year of the survey to the NUTS-2 region of residence 1 year prior to the survey¹. In order to control for network effects we include the share of immigrants residing within a NUTS-2 region. We distinguish between natives, EU-born and non-EU-born immigrants. Therefore, we define natives as individuals born in the same country as their country of residence in the year of the survey, EU-born immigrants as individuals born in the EU but not in the country in which they resided in the year of the survey and non-EU-born immigrants as those born outside the EU. To study whether mobility can be passed on across immigrant generations or is lost over time we compare first-generation immigrants' mobility with the mobility of 1.5-generation immigrants. The EU-LFS does not include information on individuals' parents' country of birth. Therefore, we follow Ellis and Goodwin-White (2006) and Goodwin-White (2018) and proxy for second-generation immigrants as those born outside their host country but who arrived before they were 10 years old. As a robustness

check, we also conduct our analysis using alternative age thresholds of 7 and 13 years.

Furthermore, we include a number of control variables such as age, marital status, gender, education and employment status. Information on age is only available in 5-year age bands (15–19, 20–24 etc.). Thus, we include a set of dummy variables corresponding to the age bands. Marital status is measured using a dummy variable (1 corresponding to an individual being married and 0 otherwise). As for gender, a value of 1 indicates a female and 0 a male individual. Educational attainment is measured by three dummy variables indicating primary, secondary and tertiary levels of education². Employment status is measured using a dummy variable (1 corresponding to being unemployed in the year of the survey and 0 otherwise).

Table 2 presents descriptive statistics for our main variables. Natives comprise the largest part of our samples with around 1.6 to 1.7 million individuals, followed by non-EU-born immigrants and EU-born immigrants. For all 3 years the share of married individuals is higher among non-EU-born immigrants than among EU-born immigrants and natives. The labour market effects of the Euro Crisis can be most clearly observed by the unemployment share: Across all three groups, the share of unemployment increased between 2007 and 2011 and continued to increase between 2011 and 2014, with non-EU-born immigrants exhibiting the highest unemployment. Shares of individuals with secondary education are similar across all three groups for all years. However, the share of tertiary education is highest for EU-born individuals for all 3 years. This is interesting insofar as EU-born immigrants also exhibit the highest mean national migration rates, which is in line with previous literature (e.g., Basso and Peri 2020) observing a positive relationship between education and mobility.

In Table A1 in the Appendix, we also present some descriptive statistics for natives, first-generation and 1.5-generation immigrants. 1.5-generation immigrants only account for a relatively small part of our samples, comprising around 2% of individuals in 2011 and 2014. The 1.5 generation has the lowest share of married individuals of all three groups in both years. In addition, the 1.5 generation exhibits the highest share of individuals with secondary education, while tertiary education shares are similar across the three groups.

Figure 1 shows immigrant shares for NUTS-2 regions in the Euro Area based on data from the 2011 census. Unfortunately, data is not available for some Euro Area countries (Cyprus, Finland, Greece, the Netherlands and Slovakia). The highest immigrants shares are observed in Brussels and Luxembourg with 40% and 39.3%, respectively. The lowest shares are both observed in Italy, namely Sardinia and Puglia, with 3.2% and 3.7% respectively. The map shows that large regional differences in immigrant shares exist within some countries that in part coincide with structural differences, for example, between East and West Germany, Paris and its surrounding regions as well as North and South Italy.

Figures 2 and 3 respectively show interregional and international migration rates on the NUTS-2 level for 2007 and 2014. Note that

TABLE 2 | Descriptive statistics.

Variables	Natives	EU-born	Non- EU-born
2007			
Female (share)	0.507	0.541	0.522
Married (share)	0.544	0.566	0.641
Unemployed (share)	0.062	0.059	0.088
Secondary education (share)	0.663	0.606	0.642
Tertiary education (share)	0.182	0.266	0.187
Mean migration rates			
National	0.001	0.024	0.013
Regional	0.004	0.006	0.006
<i>N</i>	1,675,620	63,561	110,781
2011			
Female (share)	0.509	0.552	0.528
Married (share)	0.520	0.565	0.632
Unemployed (share)	0.093	0.113	0.145
Secondary education (share)	0.668	0.631	0.639
Tertiary education (share)	0.212	0.260	0.195
Mean migration rates			
National	0.001	0.024	0.013
Regional	0.004	0.008	0.006
<i>N</i>	1,578,982	73,102	133,388
2014			
Female (share)	0.507	0.557	0.535
Married (share)	0.497	0.551	0.620
Unemployed (share)	0.114	0.124	0.178
Secondary education (share)	0.670	0.616	0.642
Tertiary education (share)	0.238	0.301	0.210
Mean migration rates			
National	0.001	0.022	0.017
Regional	0.005	0.007	0.007
<i>N</i>	1,722,477	68,778	175,386

the migration rates represent the stock of individuals who were not living in the respective region or country 1 year prior relative to the total number of individuals in the survey living in that region. In Spain and Portugal, both types of mobility appear to have decreased during the considered period. Furthermore, interregional mobility appears to have decreased in some regions of Finland, France and Germany during the same time span. On the other hand, international mobility appears to have increased in French regions

neighbouring Spain. Finally, international mobility appears to have decreased in Italy and the Baltic countries.

3.2 | Empirical Strategy

In order to quantify differences in labour mobility between immigrants and natives we estimate the following logit model:

$$P(Y_i = 1) = \frac{\exp(\beta_0 + \beta_1 \text{EUborn}_i + \beta_2 \text{NonEUborn}_i + \beta_3 X_i)}{1 + \exp(\beta_0 + \beta_1 \text{EUborn}_i + \beta_2 \text{NonEUborn}_i + \beta_3 X_i)} \quad (1)$$

where Y_i is a dummy variable that alternatively indicates whether an individual changed their region or country of residence during the year prior to the survey. The dummy variables EUborn_i and NonEUborn_i indicate whether an individual was born outside their country of residence but inside the EU or outside the EU, respectively. X_i represents a vector of controls mentioned in the previous section. The logit model is estimated using maximum likelihood.

Furthermore, in order to analyse the differences in labour mobility between first- and 1.5-generation immigrants and natives, we estimate the following logit models:

$$P(Y_i = 1) = \frac{\exp(\beta_0 + \beta_1 1.5\text{Gen}_i + \beta_2 \text{NonEUborn}_i + \beta_3 X_i)}{1 + \exp(\beta_0 + \beta_1 1.5\text{Gen}_i + \beta_2 \text{NonEUborn}_i + \beta_3 X_i)} \quad (2)$$

and

$$P(Y_i = 1) = \frac{\exp(\beta_0 + \beta_1 1.5\text{Gen}_i + \beta_2 \text{EUborn}_i \beta_3 X_i)}{1 + \exp(\beta_0 + \beta_1 1.5\text{Gen}_i + \beta_2 \text{EUborn}_i \beta_3 X_i)} \quad (3)$$

where Equation (2) compares first- and 1.5-generation immigrants and Equation (3) compares 1.5-generation immigrants and natives.

4 | Results

4.1 | Baseline Results

Tables 3 and 4 show our baseline results for interregional and international mobility. All regression tables present raw estimated coefficients from the logit models. We observe for both types of mobility that immigrants are more mobile than natives. Evaluated at the mean of the explanatory variables, EU-born immigrants are between 0.1 and 0.2 percentage points more likely than natives to have migrated interregionally during the year prior to before the survey. Similarly, across all three survey years the probability of migrating internationally over a 1-year time horizon is between 1.5 and 1.6 percentage points higher for EU-born immigrants than for natives.

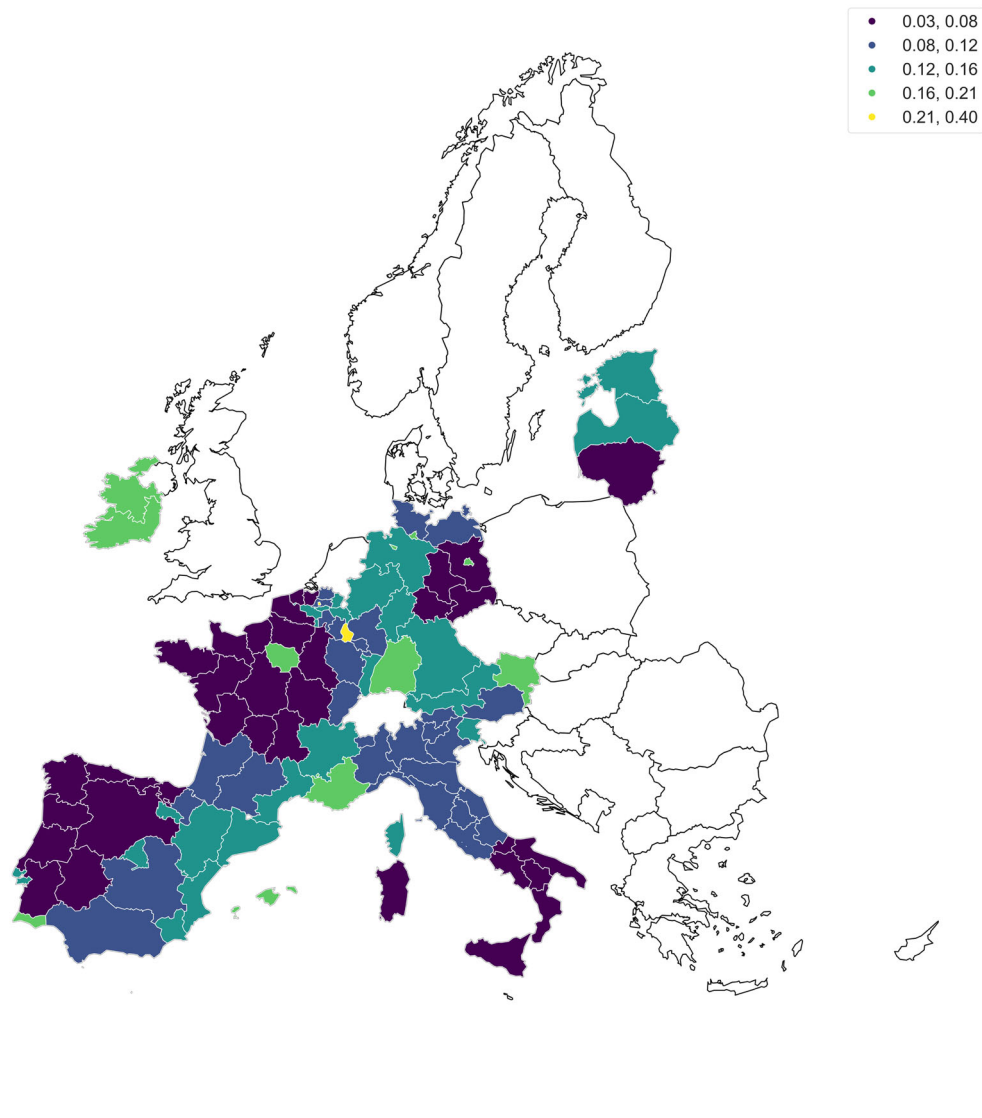


FIGURE 1 | Immigrant shares for NUTS-2 regions.

Two observations are of particular interest. First, differences between immigrants and natives are larger for international mobility than for interregional mobility. Following Borjas (1987) and Chiswick (2000), a possible interpretation for this finding would be that immigrants are less risk-averse when compared to natives, and thus their mobility response to international differences in labour market conditions is greater than for interregional labour market differences. Second, differences in international mobility are somewhat smaller for non-EU-born immigrants: Evaluated at the mean of the covariates, they are between 0.1 and 0.2 (between 0.7 and 0.9) percentage points more likely to have migrated interregionally (internationally) over a 1-year time horizon compared to natives. This finding is consistent with Røed and Schöne (2015) who argue that many non-Western immigrants are refugees and are thus less mobile internationally than Western immigrants due to immigration restrictions. The extent to which non-EU-born immigrants enjoy freedom of movement particularly depends on their status as family members of EU citizens as well as whether their country of origin has an agreement on freedom of movement with the EU (Carrera 2005). However,

due to data limitations, we are unable to observe individuals' family members' country of origin as well as their citizenship status. Nevertheless, despite such restrictions for non-EU-born immigrants, our results show higher mobility for these individuals compared to natives, which underlines our hypothesis of immigrants' higher responsiveness to labour market differentials. We observe that individuals residing in a NUTS-2 region with a higher immigrant share are more likely to have migrated during the year prior to the survey. The same results can be observed on a national level. This observation is consistent with the idea of network effects in the literature (Røed and Schöne 2012). Moreover, the effect appears to have increased in magnitude over time for both types of mobility.

In addition, we find positive effects of unemployment and tertiary education on both interregional and international mobility. We also find negative effects of secondary education on international mobility. With respect to secondary and tertiary education, our findings are in line with previous research (e.g., Bauernschuster et al. 2014; Aydemir, Kırdar, and Torun 2022). In particular, Bauernschuster et al. (2014) suggest that more

2007

2014

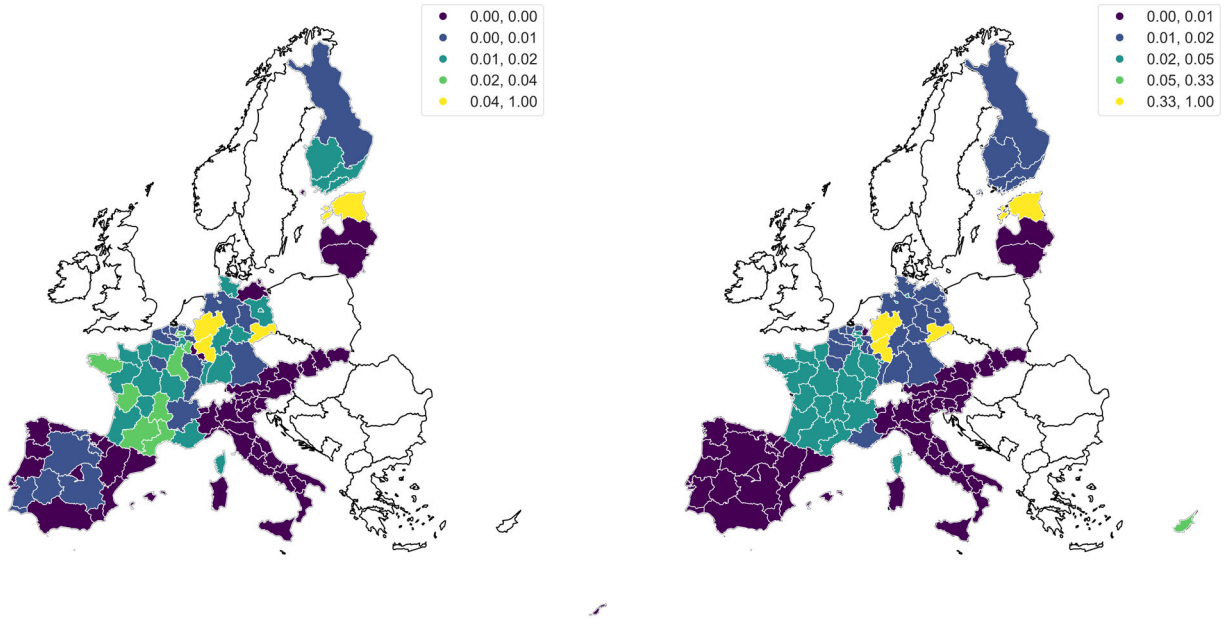


FIGURE 2 | Interregional migration rates for NUTS-2 regions for 2007 and 2014.

2007

2014

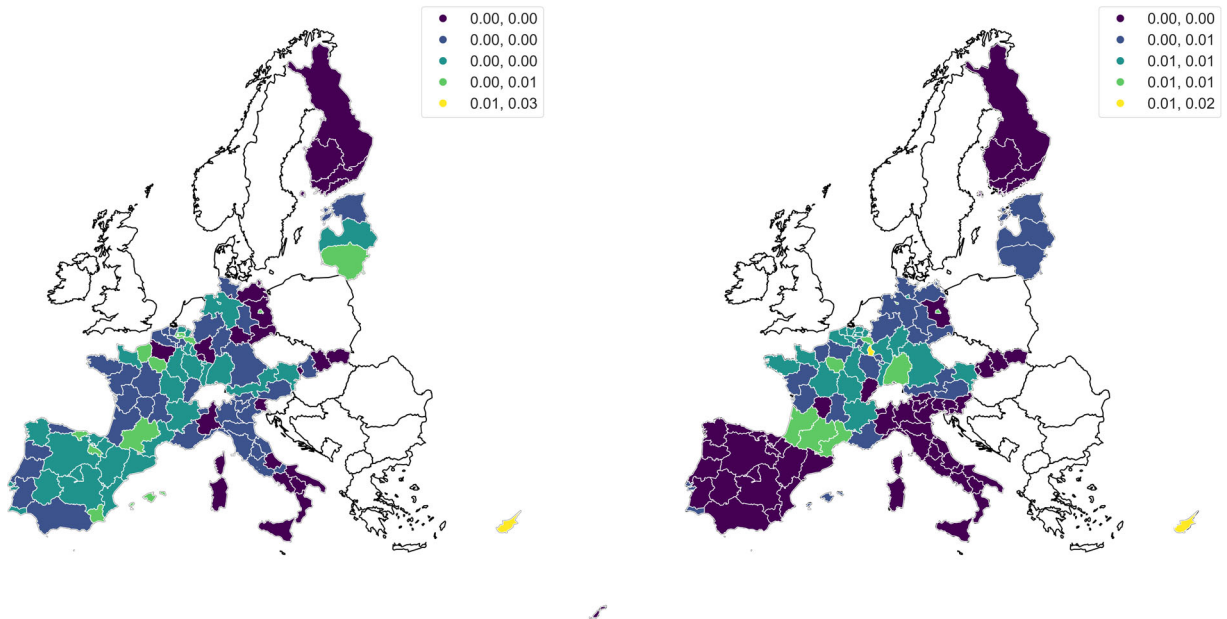


FIGURE 3 | International migration rates for NUTS-2 regions for 2007 and 2014.

educated individuals tend to be less sensitive to the cultural costs of migration. The relationship between unemployment and mobility also has the expected sign, as a move (interregional or international) is often accompanied by a spate of unemployment (Schündeln 2014). Additionally, gender is found to have no statistically significant effect on both types of mobility with the exception of international mobility for 2007.

The findings also indicate an inverted U-shaped relationship between age and both types of mobility, while being married is found to negatively affect interregional mobility. This is consistent with existing literature suggesting that the opportunity

costs of migration increase with age due to life-cycle changes such as marriage and family formation: Hunt (2006), for instance, finds for Germany for the 1990–2000 period that younger individuals are more responsive to wage differentials than older ones. This result likely reflects the fact that older individuals have less time to recover the costs of migration than younger individuals and also have more location-specific human capital (Newbold 2018). With respect to marriage, our findings are in line with, for example, David, Janiak and Wasmer (2010), who use data on 15 European countries for the 1994–2001 period and observe that married individuals are significantly less mobile than unmarried ones.

TABLE 3 | Interregional mobility.

Variable	2007		2011		2014	
	(1)	(2)	(3)	(4)	(5)	(6)
Foreign-born EU	0.4973*** (0.0729)	0.3906*** (0.0767)	0.8380*** (0.0553)	0.6323*** (0.0589)	0.3799*** (0.0590)	0.5791*** (0.0719)
Foreign-born non-EU	0.4364*** (0.0504)	0.5084*** (0.0542)	0.5146*** (0.0442)	0.6250*** (0.0477)	0.3400*** (0.0355)	0.5220*** (0.0651)
Immigrant share		2.1619*** (0.2142)		3.8594*** (0.1830)		5.9831*** (0.2090)
Unemployed		0.3703*** (0.0466)		0.3943*** (0.0418)		0.3190*** (0.0544)
Age						
20–24		0.7483*** (0.0594)		0.8561*** (0.0643)		0.6758*** (0.0100)
25–29		0.4993*** (0.0625)		0.6899*** (0.0667)		1.0466*** (0.0970)
30–34		0.2196*** (0.0672)		0.3834*** (0.0708)		0.7852*** (0.1011)
35–39		−0.2284*** (0.0747)		0.0058 (0.0758)		0.4388*** (0.1058)
40–44		−0.5684*** (0.0818)		−0.3626*** (0.0818)		0.0371 (0.1124)
45–49		−0.7680*** (0.0883)		−0.6218*** (0.0880)		−0.2992** (0.1204)
50–54		−0.9081*** (0.0962)		−0.7031*** (0.0927)		−0.4000*** (0.1249)
55–59		−0.8202*** (0.0959)		−0.7354*** (0.0977)		−0.3817*** (0.1275)
60–64		−0.9106*** (0.1040)		−0.5830*** (0.0955)		−0.5083*** (0.1355)
Married		−0.5603*** (0.0403)		−0.6105*** (0.0394)		−0.5993*** (0.0516)
Secondary education		0.0771 (0.0585)		−0.0393 (0.0616)		−0.5076*** (0.0736)
Tertiary education		1.1460*** (0.0612)		0.9127*** (0.0640)		0.1728** (0.0775)
Female		−0.0470 (0.0304)		−0.0167 (0.0306)		−0.0216 (0.0416)
N	1,323,469	1,136,348	1,333,279	1,061,611	1,417,389	815,063
Log-likelihood	−33,183.03	−26,915.57	−33,652.3	−26,344.05	−47,482.59	−14,990.12

Note: Dependent variable = 1 if individual changed their region of residence during the year prior to the survey. The reference category for the 'Foreign-born EU' and 'Foreign-born non-EU' dummies is 'Native'. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

4.2 | Mobility of First- and 1.5-Generation Immigrants

In the previous section, we demonstrated that compared to natives, immigrants are more likely to migrate both between regions and across Euro Area member states, confirming the findings of

previous research (e.g., Schündeln 2014; Røed and Schöne 2012; Røed and Schöne 2015; Basso, D'Amuri, and Peri 2019). In this section, we focus on differences in mobility within the group of foreign-born individuals. In particular, we compare the inter-regional and international mobility, respectively, of 1.5-generation immigrants to first-generation immigrants.

TABLE 4 | International mobility.

Variable	2007		2011		2014	
	(1)	(2)	(3)	(4)	(5)	(6)
Foreign-born EU	3.0208*** (0.0419)	2.7880*** (0.0507)	3.3548*** (0.0420)	3.1282*** (0.0519)	2.9940*** (0.0415)	3.1921*** (0.0584)
Foreign-born non-EU	2.4062*** (0.0386)	2.1320*** (0.0465)	2.7620*** (0.0398)	2.6819*** (0.0490)	2.770*** (0.0333)	2.6806*** (0.0587)
Immigrant share		-0.7826*** (0.2871)		2.3708*** (0.2110)		3.4019*** (0.2345)
Unemployed		0.5059*** (0.0565)		0.2273*** (0.0558)		0.1035* (0.0627)
Age						
20–24		0.5985*** (0.0742)		0.4212*** (0.0778)		0.5093*** (0.0947)
25–29		0.1700** (0.0788)		0.0113 (0.0811)		0.2593*** (0.0963)
30–34		-0.3821** (0.0862)		-0.5292*** (0.0876)		-0.3326*** (0.1043)
35–39		-0.7734*** (0.0922)		-1.1176*** (0.0962)		-0.8505*** (0.1125)
40–44		-1.3122*** (0.1046)		-1.2258*** (0.0981)		-0.9544*** (0.1134)
45–49		-1.4181*** (0.1102)		-1.6938*** (0.1125)		-1.1730*** (0.1206)
50–54		-1.5271*** (0.1192)		-1.7377*** (0.1181)		-1.3193*** (0.1294)
55–59		-2.2075*** (0.1562)		-1.9752*** (0.1343)		-1.7673*** (0.1557)
60–64		-1.6796*** (0.1365)		-1.8913*** (0.1368)		-2.0202*** (0.1813)
Married		0.2291*** (0.0484)		0.0083 (0.0472)		-0.0915* (0.0542)
Secondary education		-0.1234** (0.0629)		-0.4892*** (0.0638)		-0.3798*** (0.0822)
Tertiary education		0.7079*** (0.0694)		0.6995*** (0.0673)		0.5588*** (0.0862)
Female		-0.0843** (0.0389)		-0.0600 (0.0395)		-0.0430 (0.0454)
<i>N</i>	1,448,047	1,157,872	1,446,100	1,079,926	1,522,429	833,945
Log-likelihood	-22,894.82	-16,723.55	-22,437.01	-15,042.69	-28,233.67	-11,371.27

Note: Dependent variable = 1, if the individual changed their country of residence during the year prior to the survey. The reference category for the Foreign-born EU and Foreign-born non-EU dummies is 'Native'. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Our results are presented in Tables 5 and 6. We find that non-EU-born immigrants are less likely to migrate internationally compared to EU-born immigrants, which is in line with our baseline results in Table 4. Furthermore, immigrant share at the region of residence as well as tertiary education are found

to have positive effects on both types of mobility. The effect of immigrant share is in line with Røed and Schöne (2012), who find for Norway that ethnic concentration has a large positive effect on immigrants' probability of settling in a given region, suggesting that they tend to move to areas where their

TABLE 5 | 1.5- versus first-generation interregional mobility.

Variable	2011		2014	
	(1)	(2)	(3)	(4)
1.5 generation	-0.1139 (0.0939)	-0.3048*** (0.1025)	0.0951 (0.0766)	-0.3864*** (0.1367)
Foreign-born non-EU	-0.3285*** (0.0675)	0.041 (0.0751)	-0.0487 (0.0670)	-0.0048 (0.0955)
Immigrant share		4.6752*** (0.3105)		6.6461*** (0.3739)
Unemployed		0.4503*** (0.0902)		0.3206*** (0.1168)
Age				
20–24		0.4570*** (0.1732)		0.4283* (0.2224)
25–29		0.5556*** (0.1679)		0.3860* (0.2182)
30–34		0.0120 (0.1772)		0.1664 (0.2222)
35–39		-0.3494* (0.1833)		-0.1997 (0.2304)
40–44		-0.3120* (0.1828)		-0.3230 (0.2317)
45–49		-1.1747*** (0.2191)		-0.7233*** (0.2517)
50–54		-1.1728*** (0.2286)		-1.3115*** (0.2992)
55–59		-0.9967*** (0.2305)		-1.0580*** (0.2951)
60–64		-0.6888*** (0.2278)		-1.4661*** (0.3614)
Married		-0.5038*** (0.0761)		-0.5551*** (0.0990)
Secondary education		-0.2715** (0.1074)		-0.4317*** (0.1412)
Tertiary education		0.7166*** (0.1138)		0.2296 (0.1510)
Female		0.1483** (0.0687)		-0.1236 (0.0888)
N	142,369	122,616	165,162	102,128
Log-likelihood	-5638.725	-4789.848	-7059.852	-2983.485

Note: Dependent variable = 1, if the individual changed their region of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is 'First-generation immigrant'. The reference category for the Foreign-born EU dummy is 'Foreign-born non-EU'. Standard errors in parentheses.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

compatriots are already living. On the other hand, this finding stands in contrast to spatial assimilation theory, which holds that immigrants tend to disperse from areas of high ethnic concentration as they assimilate (e.g., Hall 2009). Unfortunately, the EU-LFS data does not allow us to observe immigrants' country of origin beyond whether they were in or

outside the EU, preventing us from conducting a more fine-grained analysis of network effects.

Gender is found to have no statistically significant effect on both types of mobility with the exception of interregional mobility for 2011. Unemployment is only found to have a

TABLE 6 | 1.5- versus first-generation international mobility.

Variable	2011		2014	
	(1)	(2)	(3)	(4)
1.5 generation	-3.100*** (0.2142)	-3.4829*** (0.2524)	-2.4405*** (0.1360)	-2.4636*** (0.1694)
Foreign-born non-EU	-0.5888*** (0.0394)	-0.4101*** (0.0500)	-0.2196*** (0.0385)	-0.4721*** (0.0561)
Immigrant share		2.3928*** (0.2367)		2.9531*** (0.2697)
Unemployed		0.0372 (0.0699)		-0.0610 (0.0783)
Age				
20-24		-0.1967** (0.0946)		-0.0759 (0.1120)
25-29		-0.7401*** (0.0970)		-0.5582*** (0.1127)
30-34		-1.3937*** (0.1040)		-1.3582*** (0.1232)
35-39		-1.8458*** (0.1122)		-1.8018*** (0.1306)
40-44		-2.0096*** (0.1157)		-1.8908*** (0.1327)
45-49		-2.5489*** (0.1362)		-2.0310*** (0.1394)
50-54		-2.5855*** (0.1450)		-2.3530*** (0.1576)
55-59		-2.9240*** (0.1746)		-2.7826*** (0.1926)
60-64		-2.6962*** (0.1719)		-2.9170*** (0.2188)
Married		-0.0711 (0.0545)		-0.0701 (0.0618)
Secondary education		-0.3383*** (0.0739)		-0.1094 (0.1008)
Tertiary education		0.8210*** (0.0796)		0.9374*** (0.1058)
Female		0.0014 (0.0482)		0.0004 (0.0542)
N	158,860	125,934	180,513	105,071
Log-likelihood	-13,101.34	-8477.463	-16,158.08	-6798.823

Note: Dependent variable = 1 if the individual changed their country of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is 'First-generation immigrant'. The reference category for the Foreign-born EU dummy is 'Foreign-born non-EU'. Standard errors in parentheses. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

positive effect on interregional mobility. Similar to our baseline results, in Table 5 we find an inverted U-shaped relationship between age and mobility as well as a negative effect of marital status for interregional mobility. On the other hand, we observe no effect of being married on international mobility, which is in contrast to previous research suggesting that married

immigrants are less likely to leave their host country than their non-married counterparts (Bijwaard and Van Doeselaar 2014; Monti 2020).

The results show for both types of mobility that 1.5-generation immigrants are less likely to migrate than first-generation

immigrants: Evaluated at the mean of the explanatory variables, 1.5-generation immigrants have a 0.1 (between 1.0 and 1.2) percentage points lower probability of migrating interregionally (internationally) over 1-year period than first-generation immigrants. This finding is in line with previous literature (Ellis and Goodwin-White 2006; Goodwin-White 2018). We argue that the lower mobility of the 1.5 generation can be explained by our hypothesis that as immigrants assimilate, the first generation's characteristics associated with higher responsiveness to labour market differences are not completely passed on across generations. The fact that the difference in mobility is larger for international mobility underlines this hypothesis since international mobility is associated with higher costs of migration.

4.3 | Mobility of 1.5-Generation Immigrants and Natives

Tables 7 and 8 compare the interregional and international mobility, respectively, of 1.5-generation immigrants and natives. For both types of mobility the immigrant share at the region of residence as well as tertiary education and unemployment are found to have positive effects. Gender is now negatively associated with international mobility, indicating that women are less likely to migrate across Euro Area member states than men. Additionally, we find an inverted U-shaped relationship between age and mobility as well as a negative effect of marital status for both types of mobility, which is consistent with our baseline results.

The findings indicate that the 1.5 generation is more likely to migrate interregionally than EU natives. More specifically, 1.5-generation immigrants have a 0.1 percentage points higher probability of migrating between regions compared to natives. This is interesting insofar as the findings in Section 4.2 suggest that the 1.5 generation is less likely to migrate than immigrants who arrived later in life. With respect to international mobility, we only find a significant but small positive difference between 1.5-generation immigrants and natives for 2014 but no effect for 2011.

Our results differ from Ellis and Goodwin-White (2006) in this respect as the authors find no difference between mobility patterns of the 1.5 generation and natives. They interpret their findings as evidence that the parents of the 1.5 generation selected themselves for the regions offering the best labour market prospects. Thus, without labour market shocks the 1.5 generation assimilates to the natives' labour mobility patterns. However, our results show that in the context of labour market shocks the 1.5 generation nevertheless exhibits higher responsiveness to regional labour market differences. These findings are consistent with our hypothesis that the characteristics that contribute to first-generation immigrants' higher responsiveness to labour market shocks are to some extent passed on to their children.

5 | Robustness Checks

We conduct a number of robustness checks, which are presented in the Appendix. First, we follow Basso, D'Amuri and Peri (2019)

and consider individuals aged 15 to 64. However, many other studies (e.g., Schoeni 1997; Friedberg 2001; Aydemir, Chen, and Corak 2009; Green and Worswick 2012) define 25 years as the age of entering the labour market to abstract from differing ages for leaving school. Therefore, we re-estimate our baseline results excluding individuals younger than 25 years at the time of the survey. The results are presented in Tables A2 and A3 in the Appendix. Some of the coefficients of interest slightly decrease in magnitude, but overall the findings are very similar to our baseline results presented in Tables 3 and 4. Interestingly, however, the coefficient for 'Female' is now negative and significant for interregional mobility, whereas no effect was observed in our baseline results.

Second, due to lack of information on individuals' parents' country of birth in the EU-LFS, we follow Ellis and Goodwin-White (2006) and Goodwin-White (2018) and proxy for second-generation immigrants as those born outside their host country but who arrived before they were 10 years old (Section 3). To address concerns that our results are driven by this arbitrary age threshold, we re-estimate our models in Eqs. (2) and (3) using alternative age thresholds of 7 and 13 years of age for the 1.5 generation.

Tables A4 and A5 present results for interregional and international mobility differences between 1.5- and first-generation immigrants. The results are consistent with our previous findings in Section 4.2, with coefficients for the 1.5 generation remaining negative and statistically significant for both types of mobility and both years. With respect to mobility differences between 1.5-generation immigrants and natives, we find that the results in Tables A6 and A7 are generally robust to using alternative thresholds.

Third, to check whether mobility responses of immigrants are in fact driven by differences in regional economic conditions, we include the growth rate of real gross value added (RGVA) on NUTS-2 region level. In addition, we follow Schündeln (2014) and include individuals' income decile as an additional individual-level characteristic. Tables A8 and A9 compare interregional and international mobility of 1.5- and first-generation immigrants. With respect to international mobility differences, our results are consistent with our findings in section 4.2. However, when including RGVA growth and income deciles in Table A8, differences in interregional mobility are no longer significant. This may be explained in part by a reduction in sample size due to missing observations for income decile. With the exception of interregional mobility for 2011, we find large positive and statistically significant effects of RGVA growth on interregional and international mobility. This result suggests that individuals are more likely to migrate to regions that experience economic growth and thereby potentially offer positive labour market conditions.

As for mobility differences between 1.5-generation immigrants and natives, coefficients in Tables A10 and A11 remain positive and significant for interregional mobility in 2011 and international mobility in 2014. However, coefficients for interregional (international) mobility in 2014 (2011) are no longer significant, which again may be attributed to the reduced sample size. Regarding RGVA

TABLE 7 | 1.5 Generation versus natives interregional mobility.

Variable	2011		2014	
	(1)	(2)	(3)	(4)
1.5 generation	0.5733*** (0.1035)	0.4488*** (0.1106)	0.5098*** (0.0774)	0.3864** (0.1537)
Foreign-born EU	-0.1495 (0.1941)	-0.2095 (0.1989)	-0.4196** (0.1838)	-0.0869 (0.2494)
Immigrant share		3.2103*** (0.2280)		5.5596*** (0.2534)
Unemployed		0.3678*** (0.0464)		0.3324*** (0.0600)
Age				
20–24		0.8915*** (0.0677)		0.7061*** (0.1080)
25–29		0.7044*** (0.0712)		1.1405*** (0.1052)
30–34		0.4365*** (0.0761)		0.8691*** (0.1107)
35–39		0.0530 (0.0821)		0.5070*** (0.1170)
40–44		-0.4832*** (0.0932)		0.0492 (0.1261)
45–49		-0.5220*** (0.0947)		-0.2519* (0.1340)
50–54		-0.6402*** (0.1006)		-0.2447* (0.1350)
55–59		-0.6756*** (0.1060)		-0.2928** (0.1396)
60–64		-0.5801*** (0.1047)		-0.3885*** (0.1462)
Married		-0.6463*** (0.0459)		-0.6164*** (0.0602)
Secondary education		0.0441 (0.0738)		-0.5188*** (0.0849)
Tertiary education		0.9767*** (0.0765)		0.1625* (0.0894)
Female		0.0116 (0.0336)		-0.0072 (0.0463)
N	1,212,278	957,657	1,277,255	728,075
Log-likelihood	-28,794.9	-22,201.4	-41,510.34	-12,411.42

Note: Dependent variable = 1, if the individual changed their region of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is 'Native'. The reference category for the Foreign-born EU dummy is 'Native'. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

growth and income deciles, we find similar results as in Tables A8 and A9.

Finally, throughout our analysis, we separately estimated mobility responses for interregional and international

mobility. However, these two forms of mobility could be viewed as part of the same decision problem in the sense that individuals are faced with three alternatives (Røed and Schöne 2012; Røed and Schöne 2015): (i) remain in the current region of residence, (ii) move to another region in

TABLE 8 | 1.5 Generation versus natives international mobility.

Variable	2011		2014	
	(1)	(2)	(3)	(4)
1.5 generation	-0.2028 (0.2903)	-0.1208 (0.3041)	0.3434** (0.1736)	0.6346*** (0.2407)
Foreign-born EU	0.6581 (0.4284)	-0.1183 (0.5407)	0.6679** (0.2779)	0.5931* (0.331)
Immigrant share		2.7320*** (0.4975)		4.7161*** (0.4863)
Unemployed		0.5365*** (0.0933)		0.3990*** (0.1055)
Age				
20–24		0.8690*** (0.1444)		0.8908*** (0.1755)
25–29		0.5062*** (0.1531)		0.8087*** (0.1825)
30–34		0.1469 (0.1641)		0.6288*** (0.1909)
35–39		-0.6201*** (0.1897)		0.0291 (0.2114)
40–44		-0.5573*** (0.1857)		-0.1091 (0.2137)
45–49		-0.9147*** (0.2019)		-0.6345*** (0.2398)
50–54		-0.9801*** (0.2086)		-0.4078* (0.2282)
55–59		-1.0886*** (0.2202)		-0.9897*** (0.2718)
60–64		-1.2827*** (0.2335)		-1.3466*** (0.3101)
Married		-0.0765 (0.0938)		-0.3364*** (0.1108)
Secondary education		-0.5973*** (0.1284)		-0.8117*** (0.1422)
Tertiary education		0.6696*** (0.1325)		-0.0993 (0.1518)
Female		-0.2286*** (0.0703)		-0.1669** (0.0836)
<i>N</i>	1,310,702	97,299	1,368,920	744,436
Log-likelihood	-9108.803	-6269.835	-11,938.71	-4508.862

Note: Dependent variable = 1, if the individual changed their country of residence during the year prior to the survey. The reference category for the 1.5 generation dummy is 'Native'. The reference category for the Foreign-born EU dummy is 'Native'. Standard errors in parentheses.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

the current country of residence or (iii) move to a different country. To address this hierarchical nature of our mobility data, we follow Røed and Schøne (2012) and Røed and Schøne (2015) and re-estimate our main results using multinomial logistic regression models.

The results are presented in Table A12. Overall, we continue to find that immigrants are more mobile than natives both inter-regionally and internationally. Likewise, coefficients for age dummies suggest an inverted U-shaped relationship between age and mobility, and tertiary education always has a positive

effect on mobility. Some of the effects of the control variables differ from our baseline results, however, with ambiguous effects of unemployment, secondary education and gender. Even so, the findings are generally in line with our baseline results.

6 | Conclusion

Immigrants' higher responsiveness to regional differences in labour market conditions has long been recognised as a potentially important adjustment mechanism to labour market shocks. In this paper, we investigate how labour mobility patterns are passed on across immigrant generations and differ between immigrants and natives. For this purpose, we consider the context of the European debt crisis from 2010 onwards and use household-level data for the Euro Area from 2007 to 2014.

Consistent with our expectations, we find that 1.5-generation immigrants are interregionally and internationally less mobile than the first generation. More specifically, we observe that 1.5-generation immigrants have a 0.1 (between 1.0 and 1.2) percentage points lower probability of interregional (international) migration over a 1-year period compared to first-generation immigrants. Thus, our findings are in line with the work of Ellis and Goodwin-White (2006) and Goodwin-White (2007) and Goodwin-White (2018). When compared to natives, 1.5-generation immigrants are found to be 0.1 percentage points more likely to migrate interregionally, but we cannot find conclusive evidence that this difference holds with respect to international mobility.

In addition, we observe for both types of mobility that EU-born and non-EU-born immigrants are more mobile than natives. However, the differences in international mobility are somewhat smaller for non-EU-born immigrants. These findings are consistent with previous research (e.g., Schündeln 2014; Røed and Schöne 2015; Basso, D'Amuri, and Peri 2019) on mobility differences between immigrants and natives.

In summary, our findings are in line with the idea that immigrants constitute a self-selected group that differs systematically from natives regarding characteristics such as risk aversion (e.g., Chiswick 2000). In particular, the results support our hypothesis that these characteristics associated with higher responsiveness to labour market differences are to some extent passed on to the following generation. Thus, our paper suggests that not only first-generation immigrants but also their descendants contribute to labour market flexibility, which provides additional support to the notion that immigration is 'greasing the wheels' of the labour market (e.g., Borjas 2001).

A number of policy implications emerge from our findings. First, policymakers should focus on reducing immigration restrictions for immigrants trying to enter currency areas such as the Euro Area, as this group plays an important role in adjusting to labour market shocks. Second, policies should facilitate immigrants' labour mobility to reduce the costs of migration in times of labour market shocks, for example, by measures such as language courses. Third, to increase natives' contribution to labour market flexibility, policies should focus on fostering cultural exchange within the Euro Area to reduce the cultural costs of migration.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from Eurostat. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from <https://ec.europa.eu/eurostat/web/microdata/european-union-labour-force-survey> with the permission of Eurostat.

Endnotes

¹For Austria and Germany, information on region of residence in the year of the survey is only available on the NUTS-1 level.

²Primary, secondary and tertiary education correspond to ISCED levels 0 to 1, 2 to 4 and 5 and higher, respectively.

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Appendix A

TABLE A1 | Descriptive statistics for natives, first-generation and 1.5-generation immigrants.

Variables	2011		
	Natives	First generation	1.5 generation
Female (share)	0.509	0.543	0.504
Married (share)	0.520	0.642	0.440
Unemployed (share)	0.093	0.138	0.114
Secondary education (share)	0.668	0.620	0.719
Tertiary education (share)	0.212	0.222	0.195
Mean migration rates			
National	0.001	0.0197	0.001
Regional	0.063	0.009	0.010
<i>N</i>	1578982	170958	32692

2014			
Female (share)	0.507	0.549	0.508
Married (share)	0.497	0.641	0.424
Unemployed (share)	0.114	0.164	0.136
Secondary education (share)	0.670	0.617	0.716
Tertiary education (share)	0.238	0.242	0.206
National	0.001	0.022	0.002
Regional	0.005	0.007	0.008
<i>N</i>	1,722,477	199,233	40,208

TABLE A2 | Interregional mobility: excluding individuals younger than 25.

Variable	2007		2011		2014	
	(1)	(2)	(3)	(4)	(5)	(6)
Foreign-born EU	0.615*** (0.081)	0.350*** (0.087)	-1.524*** (0.043)	0.605*** (0.066)	0.496*** (0.064)	0.418*** (0.084)
Foreign-born non-EU	0.578*** (0.057)	0.555*** (0.062)	-2.289*** (0.042)	0.536*** (0.055)	0.370*** (0.041)	0.326*** (0.077)
Immigrant share		1.944*** (0.253)		3.304*** (0.222)		6.344*** (0.246)
Unemployed		0.496*** (0.055)		0.574*** (0.048)		0.270*** (0.067)
Age						
30-34		-0.272*** (0.053)		-0.303*** (0.053)		-0.304*** (0.071)
35-39		-0.704*** (0.062)		-0.681*** (0.060)		-0.766*** (0.081)
40-44		-1.031*** (0.070)		-1.041*** (0.068)		-1.098*** (0.091)
45-49		-1.212*** (0.078)		-1.291*** (0.076)		-1.568*** (0.109)

(Continues)

TABLE A2 | (Continued)

Variable	2007		2011		2014	
	(1)	(2)	(3)	(4)	(5)	(6)
50–54		–1.366*** (0.087)		–1.366*** (0.082)		–1.579*** (0.113)
55–59		–1.271*** (0.087)		–1.388*** (0.088)		–1.582*** (0.119)
60–64		–1.370*** (0.097)		–1.240*** (0.086)		–1.731*** (0.133)
Married		–0.6158*** (0.042)		–0.593*** (0.041)		–0.707*** (0.058)
Secondary education		0.103 (0.066)		0.062 (0.071)		–0.263*** (0.097)
Tertiary education		1.034*** (0.068)		0.905*** (0.073)		0.437*** (0.099)
Female		–0.122*** (0.037)		–0.105*** (0.037)		–0.093* (0.050)
N	1,087,378	886,562	1,109,264	829,972	1,185,902	670,969
Log-likelihood	–23,084.18	–18,558.79	–234,682.8	–18,714.24	–34,616.3	–10,356.51

Note: Dependent variable = 1 if the individual changed their region of residence during the year prior to the survey. The reference category for the ‘Foreign-born EU’ and ‘Foreign-born non-EU’ dummies is ‘Native’. Standard errors in parentheses.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE A3 | International mobility: excluding individuals younger than 25.

Variable	2007		2011		2014	
	(1)	(2)	(3)	(4)	(5)	(6)
Foreign-born EU	3.028*** (0.050)	2.845*** (0.066)	3.359*** (0.051)	3.051*** (0.069)	3.046*** (0.050)	3.095*** (0.074)
Foreign-born non-EU	2.372*** (0.047)	2.239*** (0.063)	2.772*** (0.048)	2.681*** (0.066)	2.788*** (0.041)	2.620*** (0.074)
Immigrant share		0.527* (0.299)		3.927*** (0.226)		3.614*** (0.248)
Unemployed		0.551*** (0.075)		0.313*** (0.070)		0.275*** (0.072)
Age						
30–34		–0.467*** (0.072)		–0.525*** (0.071)		–0.568*** (0.080)
35–39		–0.869*** (0.080)		–1.048*** (0.080)		–1.051*** (0.089)
40–44		–1.338*** (0.095)		–1.159*** (0.083)		–1.211*** (0.093)
45–49		–1.523*** (0.106)		–1.660*** (0.103)		–1.390*** (0.102)
50–54		–1.564*** (0.115)		–1.669*** (0.111)		–1.574*** (0.115)
55–59		–2.267***		–1.966***		–1.927***

(Continues)

TABLE A3 | (Continued)

Variable	2007		2011		2014	
	(1)	(2)	(3)	(4)	(5)	(6)
		(0.161)		(0.133)		(0.144)
60–64		–1.633***		–1.806***		–2.054***
		(0.131)		(0.133)		(0.166)
Married		0.021		–0.074		–0.195***
		(0.056)		(0.053)		(0.058)
Secondary education		–0.339***		–0.506***		–0.433***
		(0.076)		(0.078)		(0.095)
Tertiary education		0.598***		0.618***		0.582***
		(0.080)		(0.078)		(0.095)
Female		–0.090*		–0.114**		–0.131**
		(0.051)		(0.049)		(0.054)
N	1,187,844	889,451	1,199,129	831,737	1,270,782	672,373
Log-likelihood	–16,025.47	–9860.564	–16,057.96	–9621.664	–19,908.6	–8008.355

Note: Dependent variable = 1 if individual changed their country of residence during the year prior to the survey. The reference category for the Foreign-born EU and Foreign-born non-EU dummies is 'Native'. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE A4 | 1.5- versus first-generation immigrants interregional mobility: varying age threshold.

Variable	2011		2014	
	Age 7	Age 13	Age 7	Age 13
1.5 generation	–0.407***	–0.501***	–0.706***	–0.493***
	(0.146)	(0.096)	(0.217)	(0.126)
Foreign-born non-EU	0.035	0.057	–0.015	0.008
	(0.075)	(0.075)	(0.095)	(0.096)
Immigrant share	4.678***	4.661***	6.654***	6.620***
	(0.310)	(0.311)	(0.374)	(0.374)
Unemployed	0.452***	0.451***	0.316***	0.322***
	(0.090)	(0.090)	(0.117)	(0.117)
Age				
20–24	0.507***	0.356**	0.461**	0.363
	(0.172)	(0.175)	(0.221)	(0.224)
25–29	0.612***	0.380**	0.435**	0.255
	(0.166)	(0.173)	(0.215)	(0.224)
30–34	0.078	–0.181	0.218	0.014
	(0.174)	(0.183)	(0.218)	(0.230)
35–39	–0.286	–0.543***	–0.142	–0.355
	(0.181)	(0.189)	(0.226)	(0.238)
40–44	–0.250	–0.503***	–0.266	–0.478**
	(0.181)	(0.188)	(0.228)	(0.239)
45–49	–1.113***	–1.363***	–0.672***	–0.875***
	(0.217)	(0.223)	(0.248)	(0.258)
50–54	–1.108***	–1.361***	–1.255***	–1.460***
	(0.227)	(0.233)	(0.296)	(0.305)

(Continues)

TABLE A4 | (Continued)

Variable	2011		2014	
	Age 7	Age 13	Age 7	Age 13
55–59	–0.942*** (0.229)	–1.183*** (0.234)	–1.002*** (0.292)	–1.211*** (0.301)
60–64	–0.629*** (0.226)	–0.869*** (0.232)	–1.411*** (0.359)	–1.621*** (0.366)
Married	–0.496*** (0.076)	–0.527*** (0.076)	–0.547*** (0.099)	–0.571*** (0.099)
Secondary education	–0.281*** (0.107)	–0.252** (0.107)	–0.437*** (0.141)	–0.416*** (0.141)
Tertiary education	0.711*** (0.114)	0.730*** (0.114)	0.223 (0.151)	0.233 (0.151)
Female	–0.146** (0.069)	–0.154** (0.069)	–0.117 (0.089)	–0.129 (0.089)
N	122,616	122,616	102,128	102,128
Log-likelihood	–4790.177	–4779.696	–2981.299	–2979.507

Note: Dependent variable = 1 if the individual changed their region of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is 'First-generation immigrant'. The reference category for the Foreign-born EU dummy is 'Foreign-born non-EU'. Standard errors in parentheses.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE A5 | 1.5- versus first-generation immigrants international mobility: varying age threshold.

Variable	2011		2014	
	Age 7	Age 13	Age 7	Age 13
1.5 generation	–3.483*** (0.409)	–3.541*** (0.167)	–2.182*** (0.239)	–2.888*** (0.141)
Foreign-born non-EU	–0.442*** (0.050)	–0.364*** (0.050)	–0.519*** (0.056)	–0.415*** (0.056)
Immigrant share	2.343*** (0.235)	2.375*** (0.239)	2.957*** (0.268)	2.8574*** (0.273)
Unemployed	0.059 (0.070)	0.050 (0.070)	–0.072 (0.078)	–0.041 (0.079)
Age				
20–24	0.118 (0.094)	–0.771*** (0.098)	0.192* (0.111)	–0.560*** (0.116)
25–29	–0.375*** (0.096)	–1.502*** (0.100)	–0.197* (0.111)	–1.261*** (0.118)
30–34	–0.995*** (0.104)	–2.171*** (0.107)	–0.977*** (0.122)	–2.094*** (0.127)
35–39	–1.471*** (0.112)	–2.636*** (0.115)	–1.413*** (0.130)	–2.540*** (0.134)
40–44	–1.636*** (0.115)	–2.790*** (0.118)	–1.518*** (0.132)	–2.628*** (0.136)
45–49	–2.175*** (0.136)	–3.318*** (0.138)	–1.665*** (0.139)	–2.763*** (0.143)
50–54	–2.204***	–3.360***	–1.968***	–3.077***

(Continues)

TABLE A5 | (Continued)

Variable	2011		2014	
	Age 7	Age 13	Age 7	Age 13
	(0.145)	(0.147)	(0.157)	(0.161)
55–59	–2.578***	–3.696***	–2.395***	–3.517***
	(0.174)	(0.176)	(0.192)	(0.195)
60–64	–2.326***	–3.443***	–2.528***	–3.652***
	(0.172)	(0.174)	(0.218)	(0.221)
Married	–0.014	–0.138**	–0.012	–0.135**
	(0.055)	(0.054)	(0.062)	(0.061)
Secondary education	–0.397***	–0.326***	–0.170*	–0.071
	(0.074)	(0.074)	(0.101)	(0.101)
Tertiary education	0.775***	0.812***	0.873***	0.937***
	(0.079)	(0.080)	(0.105)	(0.106)
Female	0.013	–0.026	0.025	–0.010
	(0.048)	(0.048)	(0.054)	(0.054)
N	125,934	125,934	105,071	105,071
Log-likelihood	–8673.121	–8223.066	–6934.143	–6617.536

Note: Dependent variable = 1 if the individual changed their country of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is ‘First-generation immigrant’. The reference category for the Foreign-born EU dummy is ‘Foreign-born non-EU’. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE A6 | 1.5-generation immigrants versus natives interregional mobility: varying age threshold.

Variable	2011		2014	
	Age 7	Age 13	Age 7	Age 13
1.5 generation	0.318*	0.359***	–0.0737	0.365***
	(0.171)	(0.093)	(0.291)	(0.126)
Foreign-born EU	–0.231	–0.222	0.1603	–0.066
	(0.298)	(0.173)	(0.420)	(0.209)
Immigrant share	3.251***	3.218***	5.636***	5.546***
	(0.231)	(0.226)	(0.255)	(0.251)
Unemployed	0.374***	0.375***	0.318***	0.338***
	(0.047)	(0.046)	(0.061)	(0.059)
Age				
20–24	0.887***	0.889***	0.713***	0.712***
	(0.069)	(0.067)	(0.111)	(0.106)
25–29	0.687***	0.703***	1.144***	1.129***
	(0.072)	(0.071)	(0.108)	(0.104)
30–34	0.423***	0.433***	0.883***	0.858***
	(0.077)	(0.076)	(0.113)	(0.109)
35–39	0.046	0.050	0.533***	0.505***
	(0.083)	(0.082)	(0.119)	(0.115)
40–44	–0.484***	–0.477***	0.055	0.044
	(0.094)	(0.092)	(0.129)	(0.125)
45–49	–0.520***	–0.527***	–0.285**	–0.248*

(Continues)

TABLE A6 | (Continued)

Variable	2011		2014	
	Age 7	Age 13	Age 7	Age 13
	(0.096)	(0.094)	(0.138)	(0.132)
50–54	–0.629***	–0.642***	–0.259*	–0.259*
	(0.101)	(0.100)	(0.138)	(0.134)
55–59	–0.701***	–0.655***	–0.274*	–0.292**
	(0.108)	(0.105)	(0.141)	(0.138)
60–64	–0.576***	–0.577***	–0.373**	–0.383***
	(0.105)	(0.104)	(0.148)	(0.145)
Married	–0.658***	–0.641***	–0.626***	–0.620***
	(0.046)	(0.046)	(0.061)	(0.060)
Secondary education	0.056	0.046	–0.524***	–0.511***
	(0.075)	(0.073)	(0.086)	(0.084)
Tertiary education	0.997***	0.982***	0.1603*	0.170*
	(0.078)	(0.076)	(0.090)	(0.089)
Female	0.014	0.019	0.0031	–0.004
	(0.034)	(0.033)	(0.047)	(0.046)
<i>N</i>	947,584	966,918	719,708	735,639
Log-likelihood	–21,797.18	–22,483.11	–12,122.11	–12,610.92

Note: Dependent variable = 1 if the individual changed their region of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is 'Native'. The reference category for the Foreign-born EU dummy is 'Native'. Standard errors in parentheses.
 * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE A7 | 1.5-generation immigrants versus natives international mobility: varying age threshold.

Variable	2011		2014	
	Age 7	Age 13	Age 7	Age 13
1.5 generation	–0.382	0.232	0.686*	0.695***
	(0.502)	(0.204)	(0.357)	(0.189)
Foreign-born EU	–0.151	0.199	0.549	0.604**
	(0.867)	(0.335)	(0.477)	(0.263)
Immigrant share	2.813***	2.628***	4.932***	4.626***
	(0.500)	(0.487)	(0.491)	(0.476)
Unemployed	0.557***	0.509***	0.420***	0.408***
	(0.093)	(0.093)	(0.107)	(0.104)
Age				
20–24	0.861***	0.686***	1.012***	0.714***
	(0.145)	(0.133)	(0.186)	(0.162)
25–29	0.471***	0.314**	0.885***	0.616***
	(0.155)	(0.143)	(0.194)	(0.170)
30–34	0.131	–0.042	0.754***	0.432**
	(0.165)	(0.155)	(0.201)	(0.179)
35–39	–0.649***	–0.792***	0.148	–0.168
	(0.191)	(0.181)	(0.221)	(0.201)
40–44	–0.585***	–0.745***	0.036	–0.286
	(0.187)	(0.178)	(0.222)	(0.203)

(Continues)

TABLE A7 | (Continued)

Variable	2011		2014	
	Age 7	Age 13	Age 7	Age 13
45–49	–0.973*** (0.205)	–1.103*** (0.194)	–0.520** (0.249)	–0.833*** (0.231)
50–54	–0.996*** (0.209)	–1.170*** (0.201)	–0.273 (0.236)	–0.561*** (0.216)
55–59	–1.102*** (0.221)	–1.282*** (0.213)	–0.860*** (0.278)	–1.143*** (0.260)
60–64	–1.299*** (0.234)	–1.451*** (0.224)	–1.289*** (0.323)	–1.545*** (0.303)
Married	–0.062 (0.094)	–0.091 (0.093)	–0.370*** (0.112)	–0.323*** (0.109)
Secondary education	–0.598*** (0.129)	–0.674*** (0.122)	–0.839*** (0.144)	–0.864*** (0.136)
Tertiary education	0.681*** (0.133)	0.614*** (0.127)	–0.126 (0.153)	–0.132 (0.146)
Female	–0.232*** (0.071)	–0.228*** (0.069)	–0.206** (0.085)	–0.141* (0.082)
<i>N</i>	962,774	982,419	735,862	752,117
Log-likelihood	–6189.31	–6433.989	–4371.886	–4657.853

Note: Dependent variable = 1 if an individual changed their country of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is 'Native'. The reference category for the Foreign-born EU dummy is 'Native'. Standard errors in parentheses.
 * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE A8 | 1.5- versus first-generation immigrants interregional mobility: additional control variables.

Variable	2011	2014
1.5 generation	-0.0602 (0.1732)	-0.3033 (0.2093)
Foreign-born non-EU	-0.2432* (0.1258)	-0.0323 (0.1475)
Immigrant share	4.8516*** (0.4694)	4.1805*** (0.5887)
Unemployed	0.6769 (0.5184)	0.2820 (0.7239)
Age		
20–24	1.4911 (1.0236)	1.0915 (1.0360)
25–29	1.9753* (1.0129)	1.1604 (1.0232)
30–34	1.3033 (1.0171)	0.8577 (1.0256)
35–39	0.7046 (1.0213)	0.3623 (1.0317)
40–44	0.6876 (1.0217)	0.3748 (1.0305)
45–49	-0.1812 (1.0415)	-0.3538 (1.0465)
50–54	0.0760 (1.0434)	-0.9104 (1.0783)
55–59	-0.2980 (1.0799)	-0.4379 (1.0717)
60–64	-0.6702 (1.2355)	-1.8298 (1.4270)
Married	-0.3916*** (0.1228)	-0.4909*** (0.1456)
Secondary education	-0.5066** (0.1974)	-0.2576 (0.2915)
Tertiary education	0.3590* (0.2154)	0.4368 (0.3045)
Female	-0.2152* (0.1225)	-0.1743 (0.1451)
RGVA	-7.7605** (3.5887)	51.1241*** (6.7230)
Income category indicators (10)	Yes	Yes
<i>N</i>	51,997	48,760
Log-likelihood	-1712.787	-1.250.915

Note: Dependent variable = 1 if the individual changed their region of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is 'First-generation immigrant'. The reference category for the Foreign-born EU dummy is 'Foreign-born non-EU'. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE A9 | 1.5- versus first-generation immigrants international mobility: additional control variables.

Variable	2011	2014
1.5 generation	-2.7308*** (0.3820)	-2.2604*** (0.2740)
Foreign-born non-EU	-0.8136*** (0.0914)	-0.8228*** (0.0960)
Immigrant share	3.2874*** (0.3626)	0.7849* (0.4362)
Unemployed	0.7155** (0.3515)	-0.3875 (0.5926)
Age		
20–24	0.3888 (0.3442)	-0.4049 (0.2856)
25–29	0.0386 (0.3416)	-0.7650*** (0.2802)
30–34	-0.6170* (0.3465)	-1.6994*** (0.2917)
35–39	-1.0948** (0.3527)	-2.0820*** (0.2988)
40–44	-1.3190*** (0.3567)	-2.3066*** (0.3040)
45–49	-1.7951*** (0.3731)	-2.3219*** (0.3078)
50–54	-1.7097*** (0.3791)	-2.6455*** (0.3286)
55–59	-2.0123*** (0.4156)	-3.3407*** (0.4008)
60–64	-1.8715*** (0.4760)	-4.0536*** (0.6412)
Married	-0.4817*** (0.0903)	-0.3496*** (0.0960)
Secondary education	-0.4677*** (0.1539)	0.3522 (0.2478)
Tertiary education	0.5623*** (0.1666)	1.2528*** (0.2540)
Female	-0.3438*** (0.0895)	-0.3763*** (0.0927)
RGVA	11.6452*** (2.5201)	42.9619*** (4.1418)
Income category indicators (10)	Yes	Yes
<i>N</i>	53,409	50,250
Log-likelihood	-2891.292	-2641.027

Note: Dependent variable = 1 if the individual changed their country of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is 'First-generation immigrant'. The reference category for the Foreign-born EU dummy is 'Foreign-born non-EU'. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE A10 | 1.5-generation immigrants versus natives inter-regional mobility: additional control variables.

Variable	2011	2014
1.5 generation	0.4866** (0.2174)	0.4185 (0.2548)
Foreign-born EU	0.2919 (0.3177)	-0.1038 (0.3863)
Immigrant share	3.2378*** (0.3845)	2.0281*** (0.4147)
Unemployed	(0.0551)	0.3965 (0.4558)
Age		
20–24	1.5197*** (0.3452)	0.3876 (0.2808)
25–29	1.5011*** (0.3447)	0.7998*** (0.2745)
30–34	1.0193*** (0.3492)	0.3373 (0.2809)
35–39	0.5694 (0.3538)	-0.3592 (0.2918)
40–44	-0.0718 (0.3643)	-0.6090** (0.2967)
45–49	-0.0176 (0.3640)	-1.3325*** (0.3201)
50–54	-0.4930 (0.3816)	-1.2799*** (0.3221)
55–59	-0.2081 (0.3845)	-1.3333*** (0.3402)
60–64	-0.8972* (0.5351)	-1.9853*** (0.5257)
Married	-0.6764*** (0.0830)	-0.7716*** (0.0943)
Secondary education	-0.5202*** (0.1552)	-0.5094** (0.2049)
Tertiary education	0.5384*** (0.1610)	0.2824 (0.2103)
Female	0.0026 (0.0675)	-0.0598 (0.0765)
RGVA	-4.5646** (1.7742)	56.1344*** (3.0804)
Income category indicators (10)	Yes	Yes
<i>N</i>	332,560	312,167
Log-likelihood	-6127.455	-4775.577

Note: Dependent variable = 1 if the individual changed their region of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is 'Native'. The reference category for the Foreign-born EU dummy is 'Native'. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE A11 | 1.5-generation immigrants versus natives international mobility: additional control variables.

Variable	2011	2014
1.5 generation	0.5023 (0.5073)	0.7910** (0.3859)
Foreign-born EU	0.2593 (0.7676)	0.3199 (0.5385)
Immigrant share	2.8263*** (0.9966)	2.7506*** (0.7911)
Unemployed	0.1305 (1.0115)	-14.2511 (652.6887)
Age		
20–24	1.0711* (0.6136)	0.3161 (0.3959)
25–29	0.8341 (0.6168)	0.2032 (0.3979)
30–34	0.3093 (0.6300)	-0.0887 (0.4101)
35–39	-0.2831 (0.6455)	-0.7745* (0.4330)
40–44	-0.3129 (0.6453)	-1.0721** (0.4419)
45–49	-1.7498** (0.7370)	-1.6989*** (0.4799)
50–54	-1.5203** (0.7229)	-1.1255** (0.4477)
55–59	-1.3882* (0.7408)	-2.3846*** (0.5969)
60–64	-2.1553* (1.1745)	-14.9679 (228.3442)
Married	-0.4843** (0.1883)	-0.5686*** (0.1677)
Secondary education	-1.7095*** (0.2994)	-0.8957*** (0.3122)
Tertiary education	-0.6898** (0.3147)	-0.5819* (0.3299)
Female	-0.1727 (0.1620)	-0.1222 (0.1441)
RGVA	16.0615*** (3.5003)	47.6265*** (5.7147)
Income category indicators (10)	Yes	Yes
<i>N</i>	340,322	321,970
Log-likelihood	-1393.901	-1692.225

Note: Dependent variable = 1 if the individual changed their country of residence during the year prior to the survey. The reference category for the 1.5 Generation dummy is 'Native'. The reference category for the Foreign-born EU dummy is 'Native'. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

TABLE A12 | Baseline results: multinomial logit model.

	2007		2011		2014	
	Interregional mobility	International mobility	Interregional mobility	International mobility	Interregional mobility	International mobility
Foreign-born EU	1.306*** (0.0615)	2.186*** (0.069)	0.135* (0.072)	3.514*** (0.053)	0.063 (0.093)	3.291*** (0.063)
Foreign-born non-EU	0.418*** (0.062)	1.670*** (0.071)	0.315*** (0.052)	3.134*** (0.051)	0.432*** (0.069)	2.762*** (0.063)
Immigrant share	-16.095*** (0.409)	7.039*** (0.220)	1.946*** (0.211)	4.626*** (0.163)	5.636*** (0.235)	3.611*** (0.215)
Unemployed	0.315*** (0.043)	-1.692*** (0.185)	0.099** (0.046)	0.087 (0.056)	0.231*** (0.060)	0.135** (0.064)
Age						
20-24	0.855*** (0.067)	1.398*** (0.155)	0.788*** (0.071)	0.729*** (0.081)	0.987*** (0.112)	0.446*** (0.096)
25-29	-0.110 (0.078)	1.758*** (0.154)	1.106*** (0.069)	-0.139 (0.088)	1.299*** (0.110)	0.119 (0.098)
30-34	0.810*** (0.070)	-0.071 (0.170)	0.716*** (0.073)	-1.092*** (0.099)	0.982*** (0.115)	-0.500*** (0.106)
35-39	-0.790*** (0.102)	-2.669*** (0.297)	-0.115 (0.084)	-1.265*** (0.100)	0.497*** (0.123)	-1.001*** (0.114)
40-44	-1.412*** (0.131)	-3.795*** (0.483)	0.163* (0.080)	-0.815*** (0.093)	0.1534 (0.129)	-1.168*** (0.117)
45-49	1.734*** (0.067)	-0.103 (0.176)	-0.384*** (0.091)	-1.021*** (0.098)	-0.349** (0.144)	-1.345*** (0.124)
50-54	0.248*** (0.082)	-2.921*** (0.388)	-0.520*** (0.098)	-0.622*** (0.095)	-0.275* (0.145)	-1.522*** (0.135)
55-59	-2.002*** (0.174)	-3.575*** (0.550)	-0.490*** (0.100)	-1.546*** (0.120)	-0.288* (0.150)	-1.870*** (0.159)
60-64	-0.318*** (0.095)	-3.288*** (0.533)	-0.444*** (0.101)	-1.133*** (0.114)	-0.431** (0.160)	-2.001*** (0.179)
Married	-1.269*** (0.036)	-0.211*** (0.065)	-0.666*** (0.040)	0.413*** (0.043)	-0.736*** (0.059)	-0.052 (0.055)
Secondary education	-0.843*** (0.041)	0.204 (0.142)	0.041 (0.065)	0.294*** (0.067)	-0.325*** (0.089)	-0.390*** (0.083)
Tertiary education	0.608*** (0.043)	2.375*** (0.140)	1.018*** (0.067)	1.177*** (0.070)	0.384*** (0.092)	0.628*** (0.086)
Female	0.638*** (0.031)	0.252*** (0.053)	-0.264*** (0.031)	0.357*** (0.037)	0.007 (0.046)	0.011 (0.046)
N	1,070,014		995,732		800,460	
Log-likelihood	-47,908.4		-38,982.48		-23,363.89	

Note: The reference outcome is staying in the current region of residence. The reference category for the 'Foreign-born EU' and 'Foreign-born non-EU' dummies is 'Native'. Standard errors in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Eidesstattliche Erklärung

Ich erkläre hiermit, dass ich die vorgelegten und nachfolgend aufgelisteten Aufsätze selbstständig und nur mit den Hilfen angefertigt habe, die im jeweiligen Aufsatz angegeben oder zusätzlich in der nachfolgenden Liste aufgeführt sind. In der Zusammenarbeit mit den angeführten Koautoren war ich mindestens anteilig beteiligt. Bei den von mir durchgeführten und in den Aufsätzen erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in der Satzung der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis niedergelegt sind, eingehalten.

Marius Braun
Gießen, den 19. Mai 2025

Submitted Papers:

1. Braun, M. (2023), A Real-Options Analysis of Climate Change and International Migration, *Environment and Development Economics* 28, 429–448.
2. Braun, M. and J. Görts (2025), Climate-Related Natural Disasters and Regional Migration in Europe: A Spatial Econometric Analysis, *Working Paper*.
3. Hübler, M., M. Wiese, M. Braun and J. Damster (2024), The Distributional Effects of CO2 Pricing at Home and at the Border on German Income Groups, *Resource and Energy Economics* 77, 101435.
4. Hübler, M., M. Braun and N. Keimes (2025), Regional Climate Policy Analysis in the EU Member Country Germany, *Working Paper*.
5. Braun, M. and J. Görts (2025), Differences in Labour Mobility Between Immigrant Generations: Evidence From the European Debt Crisis, *Population, Space and Place* 31, e2884.