STRUCTURAL CHANGE LIKELY INCREASES INEQUALITY IN INDIA MORE THAN CLIMATE POLICY

Marian Leimbach, Michael Hübler, Hendrik Mahlkow, Lorenzo Montrone, Eduard Bukin, Gabriel Felbermayr, Matthias Kalkuhl, Johannes Koch, Marcos Marcolino, Frank Pothen, Jan Christoph Steckel

ABSTRACT

The decarbonization of India's economy will affect economic actors differently. Here we study the distributional effects of climate policy in India, taking the specific role of structural economic change into account. We contrast distributional effects from climate policy with distributional effects from structural change and quantify how far carbon pricing supports structural change and economic development. We develop and apply a comprehensive model framework that combines long-term growth and medium-term trade dynamics related to structural change with detailed household income and expenditure data for India. Our results emphasize that distributional effects from structural change are stronger than from carbon pricing. Consequently, governments should not focus solely on the distributional effects of climate policy, but also consider the larger context of economic transformation processes when designing and implementing social policies.

INTRODUCTION

Given that India is projected to have the largest population in the world by mid-century, a global effort to tackle climate change depends crucially on its ability to decarbonize its economy. However, the changes in energy prices and employment opportunities implied by decarbonization policies may be socially contentious, as they impact households differently. Additionally, they may slow poverty reduction due to potentially adverse effects on economic growth and economic structural change[1,2]. The willingness of political decision-makers in India to implement ambitious climate policies in line with the Paris climate targets will largely depend on these expected distributional effects, and how they can be managed, e.g. through international burden-sharing efforts and technology transfer. This study analyses the distributional effects (e.g. the distribution of wage income and consumption incidences) of climate policies at the household level, accounting for general equilibrium and structural change effects along the low-carbon transition.

Independent of climate policy, India is undergoing a transformation from an agriculture-based economy towards an industry- and service-based economy. How - and how fast - this economic transformation, also called structural change, unfolds will have distributional consequences. While economic structural change is embedded in a broader concept of economic development, in this study we adopt the definition of structural change from the traditional economic literature. It is understood as the reallocation of economic activity across broad sectors such as agriculture, manufacturing, and services[3] and quantified as sectoral shares of total value added or labour. The literature on economic structural change strives to explain macroeconomic growth based on changes in the sectoral decomposition of economies and sector-specific productivity growth[4,5,6]. Empirical studies also investigate distributional effects, such as the relationship between industrial employment and income inequality[7]. The literature does not consider policy instruments that affect and control structural change as explicitly as those that tackle climate change (e.g. carbon pricing). However, several policy measures have been identified that have a potential effect on the sectoral allocation of economic activities; those measures include smart industry policies to prevent premature deindustrialization[8,9].

A number of recent studies analyse the distributional effects of climate policy, and carbon pricing in particular.[14,15,16,17,18,19] The specific role of structural change is not the focus of global climate change mitigation assessment studies. However, the distributional impacts of structural change can be substantial. In this study, we ask two key questions: (i) What are the distributional effects of structural change on poor households in India compared with the distributional effects of climate policy? and (ii) will climate policy accelerate or delay structural change and economic development? Distributional effects are usually measured at the micro level (i.e. for households and income groups), while drivers of climate policy and structural change are best represented at the macro level (i.e. for national economies). To run a meaningful quantitative assessment, it is necessary to bridge these two scales. This study is one of the first to do this by bringing together information from the macro level (carbon taxes, socio-economic and structural change pathways), meso level (production sectors and subnational regions, structural change and factor income) and the micro level (the distribution of income and expenditures at the household level) in a consistent way by coupling several models and methods.

The results of this integrated model-based approach emphasize dominant regressive distributional effects from structural change. Concomitant socially sensitive policies supporting the process of structural transformation appear to be more important for poor households than downsizing climate policy ambitions will be. Policies should be designed in a way that supporting the poor and tackling climate change become congruent policy goals.

RESULTS

Our study is based on scenario analysis performed along three dimensions: (i) climate policy, (ii) structural change, and (iii) socio-economic uncertainty. For the climate policy dimension, we distinguish between a baseline and 2°C climate stabilization scenario. Within the latter scenario, climate stabilization is achieved due to carbon pricing. The baseline scenario covers climate policies that are already implemented today[10]. We further distinguish between scenarios with and without structural change. In the first case, we consider sectoral value-added shares to evolve according to selected projections that we computed for the macro level based on a regression model[11]. In the second case, we keep sectoral shares constant to the base year level. Simultaneously, we use the scenario approach to represent uncertainty of development and structural change. By applying existing shared socio-economic pathways (SSPs)[12,13] we run variations of the baseline, climate policy and structural change scenarios along SSP1 ("Sustainability"), SSP2 ("Middle of the road") and SSP5 ("Fossil fuelled development"). More detailed information on the scenario design is provided in the Methods section.

In the distributional analysis at the household level, we distinguish five income percentiles and compute changes in their income and expenditures between the base year 2015 and the target year 2030. Comparing these differences across baseline and climate policy scenarios indicates how much different households gain (or lose) from climate policy. We proceed in a similar way to quantify the effects of structural change, while a comparison across different SSPs allows us to evaluate the robustness of the results.

We start with the key macro-level output from the climate policy and structural change scenarios. We then discuss the development and intertemporal effects and compare the related effects of climate policy and structural change. This comparison is mainly based on output (price and income changes) from the meso level. Finally, we present the results from the micro level that highlight and compare the distributional effects of structural change and climate policy.

Climate policy and structural change

In this study, climate policy is represented by carbon pricing. The future carbon price is computed by the Regional Model of Investments and Development (REMIND) model. The underlying assumption is a staged accession climate policy regime, a similar form of which was used in a study on climate policies and poverty eradication by Soergel et al.[20]. A global uniform carbon price will become effective in 2050. Until then, differentiated carbon prices exist depending on the differentiated responsibilities and capacities of countries and regions. Consequently, in the short run, India faces much lower carbon prices than advanced economies such as the USA or Europe. Nevertheless, as in all other countries, the highest carbon prices have to be enforced under SSP5 and the lowest are applied under SSP1, with SSP2 in between. The computed CO_2 prices under SSP1, SSP2, and SSP5 for India amount to 20, 25, and 50 US dollars per tonne, respectively, in 2030, and 150, 190, and 380 US dollars per tonne, respectively, in 2050 (see Appendix, Figure A.1). In Europe, by comparison, the respective CO_2 prices in 2030 are between 75 and 190 US dollars per tonne.

The major properties of structural change in each SSP are shown in Figures 1 and 2. Structural transformation is quantified as the change in the relative sector shares of total labour and value added (defined as the sum of labour and capital income). The general pattern of decreasing (increasing) shares of agriculture (services) is associated with initially increasing labour shares and nearly constant value-added shares in the manufacturing sector. While the stagnation of value-added shares in this sector can be observed in other countries as well, compared to other major emerging economies in Asia (e.g. China, South Korea, Indonesia), India exhibits relatively small shares. This phenomenon is addressed in an empirical study by Choudhry[21]. Within our projections, fast structural change towards manufacturing and services is projected for India under SSP1. A peak of the manufacturing labour share can be expected between 2035 and 2040. The structural transition is even faster under SSP5 where this peak in labour share is likely to appear between 2030 and 2035, while the value-added share in manufacturing starts to decline already before 2030. The transformation process will be slower under SSP2, with the peak in manufacturing value-added and labour shares not occurring before 2040.

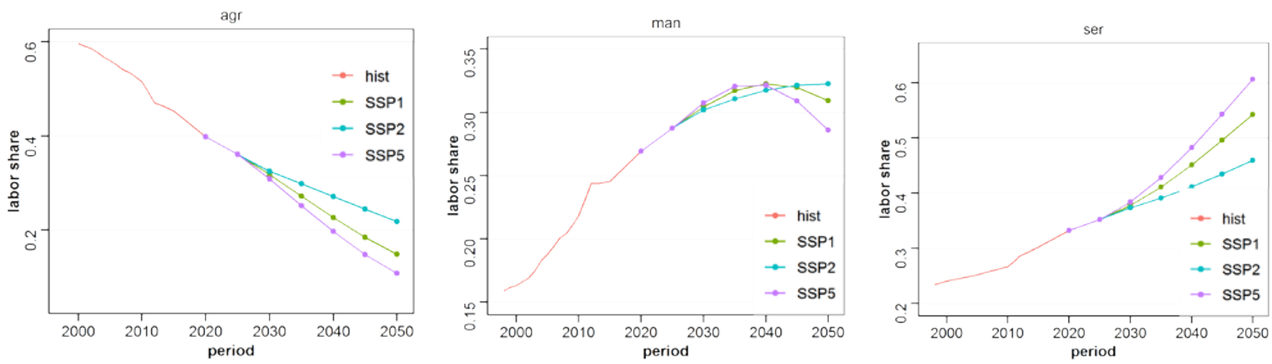

Fig.1: Structural change under different SSPs; labour shares of agricultural (agr), manufacturing (man) and service (ser) sectors.

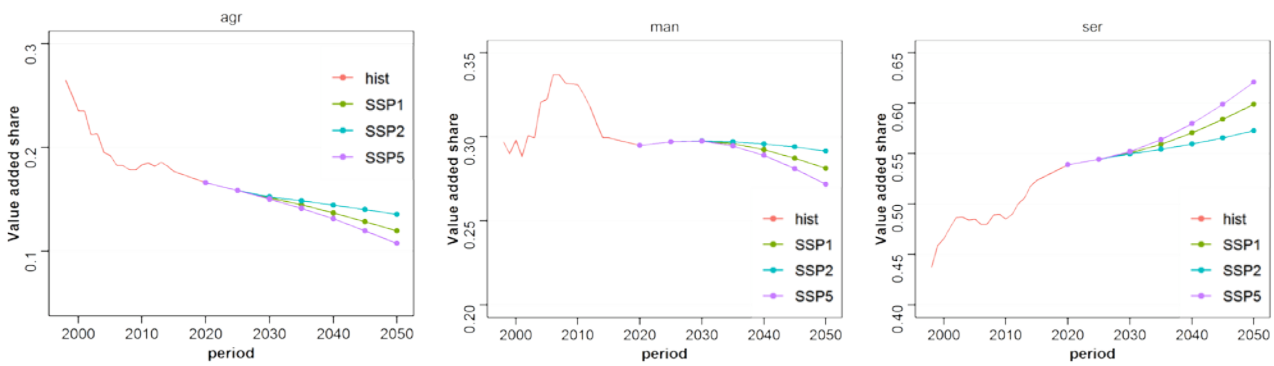

Fig.2: Structural change under different SSPs; value-added shares of agricultural (agr), manufacturing (man) and service (ser) sectors.

Development Effects

To put the magnitude of the distributional effects (discussed in the next section) into perspective, we first analyse changes in prices and income between the base year 2015 and the target year 2030. Figure 3 shows the related changes for SSP2 as computed by the Justus (Liebig) University Sustainable Transition (JUST) trade model and the Kiel Institute Trade Policy Evaluation (KITE) trade models. Overall, we observe decreasing prices (up to 40%) in most sectors with moderate variation across SSPs (see Appendix, Figure A.2). This implies less expenditure in 2030 for the same consumption basket as in 2015 for all household groups. The possibility of increasing consumption in all groups is further extended by income changes. The income effect is larger (changes between 100% and 300%) than the price effect, and is even more substantial under SSP1 and SSP5 than under SSP2 (see Appendix, Figure A.3).

Figure 3 also presents the incremental effects of structural change and climate policy. Without accounting for avoided climate change damages, climate policies in general have a negative impact on consumption due to increasing prices. The income-reducing effect of climate policy in the energy sector is most substantial. While the effects of structural change and climate policy on income and price changes are significant, they are much smaller than the aggregate effects on the overall economic development of India. Even energy prices are subject to a much larger intertemporal effect (10-50%) than climate policy effect (less than 5%). To some extent, this relationship is due to the comparatively small CO_2 price, which would change if India faced a higher carbon price.

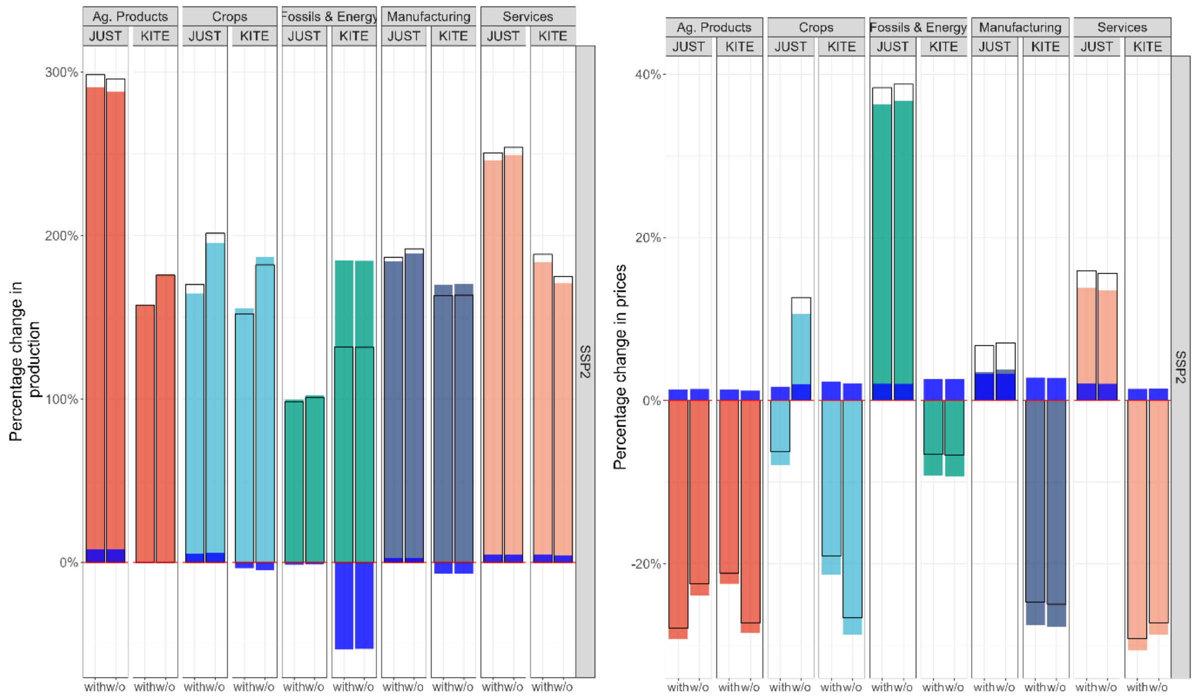

Fig. 3: Left panel: Sectoral income changes computed by KITE and JUST models. Right panel: Sectoral price changes computed by KITE and JUST models. Each bar shows the relative difference between 2015 and 2030 (i.e. representing the intertemporal effect). The differential impact of climate policy is represented by the embedded dark blue bar. The differential impact of structural change is the difference between the left bar (with structural change) and the right bar (without structural change) in each subpanel. Sectoral output from KITE and JUST is aggregated to five sectors with Agricultural Products and Crops representing the agricultural sector, and Fossils & Energy and Manufacturing representing the manufacturing sector.

From a development perspective, a major question is to what extent climate policies accelerate or hinder structural change. This study finds mixed results. While structural change manifests in decreasing value-added shares of the agricultural sector and increasing value-added shares of the service sector, climate policy induces increasing shares in both sectors (see Figure 4). The decline in value added in the manufacturing sector due to climate policy (KITE model) is substantial and can be interpreted as a risk for development. While India has undergone a transformation process that – in contrast to that of China – is characterized by a smaller share of the manufacturing sector, it is not a fully developed country for which declining manufacturing shares are already part of the usual transformation process. Due to its high share of investment goods, the manufacturing sector is crucial for India's development. Climate policy tends to slow down economic structural change.

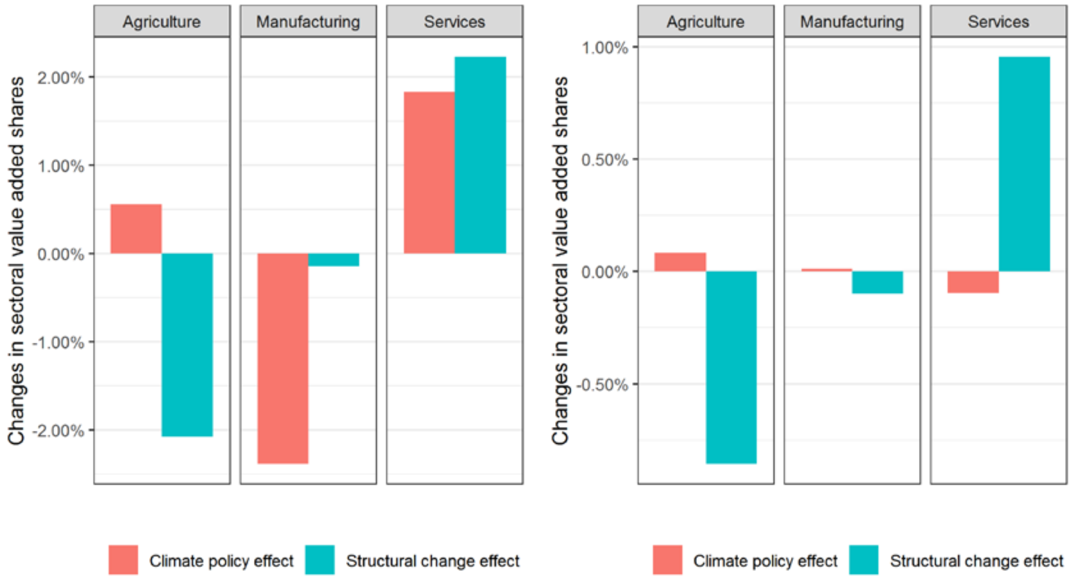

Fig. 4: Change in sectoral value-added shares (in 2030) caused by structural change (red bar) and climate policy (blue bar). The former represents the difference between scenarios with and without structural change (no climate policy); the latter represents the difference between scenarios with and without climate policy (no structural change); left panel: KITE model output, right panel: JUST model output.

Distributional effects

In this section, we use results from the KITE model as an input to the household model to estimate distributional effects. Corresponding results based on the JUST model are presented in the Appendix (Figure A.6). As Figure 5 shows, both climate policy and structural change have negative average consumption and income effects across income groups. The consumption incidence* is 1% and 3.5% lower than without climate policy and structural change, respectively; the income effect is up to 16% lower. Yet, the changes induced by structural change alone are on average twice as high as those from climate policy alone. There is an even larger difference in the distributional effects of climate policy and structural change. While both tend to have regressive effects (i.e. poor households are more adversely affected than rich households), the spread between household groups is very different. Climate policy causes more evenly distributed losses of consumption and income, whereas structural change places a severe burden on the poor. Under SSP2, the income of poor households is 15% lower with structural change than without it, whereas rich households even gain on the order of 5%.

* See Equation (3) in the Methods section for a definition of consumption incidence.

Why does structural change make the poor worse off in relative terms? This question can be answered by looking at household characteristics (see the Methods section). Poor households are mainly employed in the agricultural sector (see Figure 7). Structural change shifts more income to the service sector and reduces the increase of income in the agricultural sector (see Figure 3). Consequently, poor households become worse off if they are not able to switch to other sectors. The assumption of immobility is reasonable because our time horizon is only 15 years. Current workers, who work throughout the period, tend to find it difficult to move to another sector, while it is easier for the next generation to choose a different sector. Furthermore, price changes in the scenario with structural change disproportionately favour rich households. In contrast to poor households, which spent relatively more on agricultural products (food), rich households spend more on services (see Figure 6). Therefore, they benefit more from a more substantial drop in prices for services and are less affected by a less substantial reduction of prices for crops (see Figure 3, KITE model).

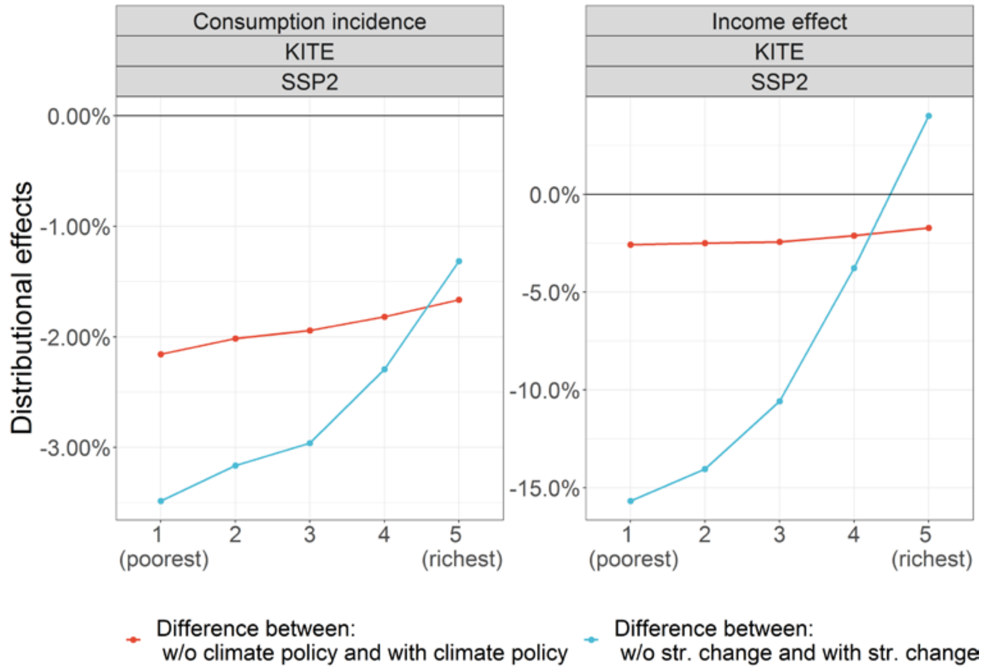

Fig. 5: Consumption incidence and changes in income across income groups due to climate policy and structural change under SSP2. The red lines represent the differences in consumption incidence (left panel) and income (right panel) in a scenario with climate policy and a scenario without climate policy. The blue lines represent the respective differences between scenarios with and without structural change. Negative values indicate that consumption incidence/income values are lower in scenarios with climate policy and structural change, respectively.

The pattern of distributional effects is surprisingly robust across all three SSPs (see Appendix, Figures A.6 and A.7), although there are a few small differences. Under SSP5, all income groups are slightly more adversely affected by climate policy, which hinges on the higher CO_2 price required to stabilize climate change in a fossil-fuel-abundant world. The consumption incidence of poor households is less adversely affected under SSP1 than under SSP2 and SSP5.

DISCUSSION

Economic development induces price and income changes that affect household groups in different ways. We disentangle the distributional effects of structural change and determine how these effects compare to those associated with climate policy. The results for India emphasize the dominance of the distributional effects of structural change. The structural transformation that India is facing – with or without climate policy – may substantially reduce wages in sectors where mostly poor people are working. Climate policy in the form of a carbon price alters wages and prices to a lesser extent, relative to the impacts of structural change.

By changing the relative competitiveness of Indian sectors over time climate policy can delay the structural transition process. Changes in output shares can be expected to be large on a disaggregated sector level (see Figures A.4 and A.5 in the Appendix). The change in sectoral composition is somewhat smaller, but still significant at the aggregate level (see Figure 4). Carbon pricing results in a decline in the manufacturing sector share due to the sector's high share of energy and emission intensive production, and because India is able to import manufactured goods to meet its demand from countries with a more competitive and greener production.[†] Output shares of the agricultural and service sectors consequently increase. While climate policy strongly supports structural transformation within the energy sector[22] through the intrasectoral reallocation of labour, it partially undermines the reallocation effects driven by structural change.

Our results show that climate policy imply a larger agricultural sector at the expense of activities in the manufacturing sector. While this can be beneficial for the large share of poor households employed in agriculture (where labour mobility is low) in the short term, it may also delay industrialization and the transition to an advanced technology based economy with the creation of better-paid jobs in the manufacturing and service sectors.

Reducing inequality and poverty therefore requires a socially sensitive policy approach that targets households that are worse off due to structural change. Such policies can also aim to reduce the adverse effects of carbon pricing[20,23]. While, according to our results, climate policy

[†] We explicitly allow for import substitution in our framework.

turns out to have a rather small distributional effect across household groups, structural change has more pronounced distributional effects with stronger income and consumption losses for poor households than for rich households. Consequently, supporting the poor and tackling climate change are congruent policy goals. While the literature argues that climate change damages tend to hit poor households hardest[24] and climate policy is able to avoid this, we identify an additional mechanism supporting the poor. In the short term, adverse effects on the poor can be alleviated by transfers. The most relevant policy to support the poor is a policy portfolio that stimulates (rural) economic development and structural transformation in line with SSP1, enabling high value-added jobs in the manufacturing and service sectors. Such a policy portfolio includes employment programmes[25], education, digitalization and trade openness; and it supports labour mobility because distributional effects of long-term structural adjustments will be more severe if mobility is constrained.

While the robustness of our results is confirmed by applying various SSP scenarios, and supported by the application of two trade models, the results are still subject to certain assumptions and limitations, including the following:

- the applied SSP scenarios do not take the COVID shock into account,
- the impact of land use competition on food prices is not taken into account,
- climate change damages are not taken into account,
- sectoral wage changes are approximated by sectoral output or labour income changes,
- households do not switch the sector of employment.

Future research is needed to deal with these aspects as well as with the sensitivity of the distributional effects with respect to the specification of the scenario elements (e.g. the climate policy target, structural change projections, or the time horizon).

METHODS

OVERVIEW OF THE METHODOLOGY

This study is based on a large numerical scenario analysis using a cascade of models and methods. A newly developed model-coupling framework exchanges information and connects models at the macro, meso, and micro levels. At the macro level, we use input from existing socioeconomic scenarios (SSPs) and apply a large-scale Integrated Assessment Model (IAM) and a reduced-form structural change model. At the meso level, we apply two advanced trade models. Whereas the macroeconomic models provide complementary output, we use two trade models to test the robustness of the results. Finally, we apply a household model that splits Indian households into five income quintiles on the micro level.

Models

INTEGRATED ASSESSMENT MODEL

The Regional Model of Investments and Development (REMIND) is an IAM that provides a holistic view of the global energy–economy–emissions system and explores self-consistent transformation pathways. It investigates a broad range of possible futures and their relation to technical and socioeconomic developments, as well as policy choices. REMIND is a multi-regional model incorporating the economy of each region with a detailed representation of the energy sector[26]. In each region, a representative household maximizes utility according to per capita consumption. Each region generates macroeconomic output (GDP) based on a nested constant elasticity of substitution (CES) production function using the production factors of labour, capital, and final energy as inputs. Using non-linear optimization, REMIND solves for an intertemporal Pareto optimum in capital and energy investments in the model regions for the time horizon 2005 to 2100, fully accounting for interregional trade in a composite good, and different energy carriers. REMIND thereby enables analyses of technology options and policy proposals for climate change mitigation, with the distinct capability of representing the scale-up of new technologies and the integration of renewable energies in power markets. The spatial resolution of REMIND is flexible. The applied version distinguishes 12 world regions with India modelled as a single region.

REMIND is calibrated to a wide range of data to ensure the consistency of the scenarios with historical developments and realistic future projections. To align with SSP GDP, population, and final energy trajectories, REMIND calibrates its production function, thereby fixing labour productivities. Historical data for the year 2005 is used to calibrate most of the free variables (e.g. primary energy mixes, secondary energy mixes, standing energy conversion capacities, trade in all traded goods). Technology parameters are projected into the future, in general assuming a convergence across regions in the very long term.

STRUCTURAL CHANGE SCENARIO MODEL

The structural change scenarios are constructed on the basis of a regression model which combines country-level data from different sources. Based on given initial shares of labour, value added, and energy for 2015, and using estimated regression coefficients, projections are computed with updated SSP GDP and population scenarios[27] as independent variables. A detailed description of the regression approach can be found in Leimbach et al.[11]. The structural change scenarios represent projections of sectoral shares that are independent of units and can therefore, in contrast to absolute level values, directly be adopted by other models. The shares of the agriculture, manufacturing, and service sectors in economy-wide employment, value added, and final energy use are projected until 2050. The development of these key variables of economic activity is provided for each of the five SSP scenarios.

NEW QUANTITATIVE TRADE MODELS

The scenario simulation results produced by the two macro models are fed into two advanced numerical trade models based on the theoretical Ricardian trade model introduced by Eaton and Kortum[28]. In the Eaton and Kortum model, international trade is driven by Ricardian specialization in lowest-cost varieties of each good without assuming regional preferences for goods. The implementations use a computable general equilibrium (CGE) framework that is commonly described as a new quantitative trade (NQT) model. They are similar to the model originally developed by Caliendo and Parro[29]. They represent a multi-sector version of the Eaton and Kortum model, where countries/regions produce and sell domestically as well as internationally according to their relative comparative advantage. Both models incorporate domestic and international input–output linkages, such that trade includes final and intermediate goods and services. Trade policy analyses can be conducted by tightening or easing trade barriers in the form of tariffs or non-tariff barriers.

The first advanced global trade model is called Justus (Liebig) University Sustainable Transition (JUST). The static version of the model, focusing on German climate and energy policy, has been introduced by Pothen and Hübler[30]. This model uses Global Trade Analysis Project[‡] (GTAP) data version 9 with the benchmark year 2011. The recursive dynamic version presented by Pothen and Hübler[31] adds scenarios of economic growth, energy use, and CO_2 emissions until 2050. Hübler and Pothen's[32]version of the model expresses relative changes between two scenarios and focuses on the sand sector. The new model under scrutiny builds on these previous model versions, but focuses on the Indian economy and uses new SSP scenarios.

The JUST model encompasses 19 countries and aggregated world regions, including India, China, Brazil, the United States, Canada, the former Soviet Union, and the biggest European economies. Each country/region has one representative consumer and a representative producer in each sector. The model covers 17 production sectors and goods (see Appendix, Table A.1). For each time period, the model solution presents a global general equilibrium with market clearance, zero profits, and balanced (private and public) budgets. This equilibrium consists of the market-clearing prices of goods and factors and the corresponding quantities.

The second advanced trade model, the Kiel Institute Trade Policy Evaluation (KITE), provides a novel tool for simulating various types of trade and climate policy effects[33]. The KITE model extends the framework of Caliendo and Parro[29] by incorporating carbon emissions and climate

---

[‡] https://www.gtap.agecon.purdue.edu/.

policies[34], and allowing for subnational input–output linkages across Indian states. In contrast to JUST, KITE uses version 10 of the GTAP database with the benchmark year 2014[25]. The model provides a very rich geographical and sectoral resolution. It features 65 production sectors (see Appendix, Table A.1) as well as 141 countries and aggregated world regions. India is further disaggregated into 33 states, which reveals the spatial heterogeneity of distributional effects. Each state exhibits different production, trade, and comparative advantage patterns.

HOUSEHOLD MODEL

In the household model, we perform a micro simulation based on a) the results obtained from the macro and meso models for India, and b) the distribution of employment, income, and expenditures in India observed in the 2012 Household Consumer Expenditure (NSS 68th Round) survey. Using the household survey data, we calculate the income of each Indian household based on total expenditures per capita. We assign each household to one of five income quintiles based on its income. We furthermore classify each household based on the head’s sector of employment. Finally, we compute the households’ expenditure shares on goods and services from each production sector defined by the trade models (see Appendix, Table A.1 for the matching between consumption items and GTAP sectors).

We analyse the distributional effects of changes in household expenditures (consumption incidence) and income (income effect). We calculate an upper bound estimate of the distributional incidence by assuming that there will be no substitution between consumption goods as a result of price changes. Consequently, the composition of the consumption basket of each income quintile does not change between the base and the target year. We also assume that employment distribution does not change. Figure 6 shows the 2012 expenditure shares for commodities and services from five aggregated sectors. On average, all households spend most for agricultural products (including crops), with substantial expenditures on manufactured goods and services. Notably, the differences in expenditure shares across income groups are significant. While poor households spend comparatively more on agricultural products, rich households spend comparatively more on services. Expenditure shares of goods that are expected to be sensitive to climate policies, such as coal, gas, petroleum, electricity, or transport, are comparatively small.

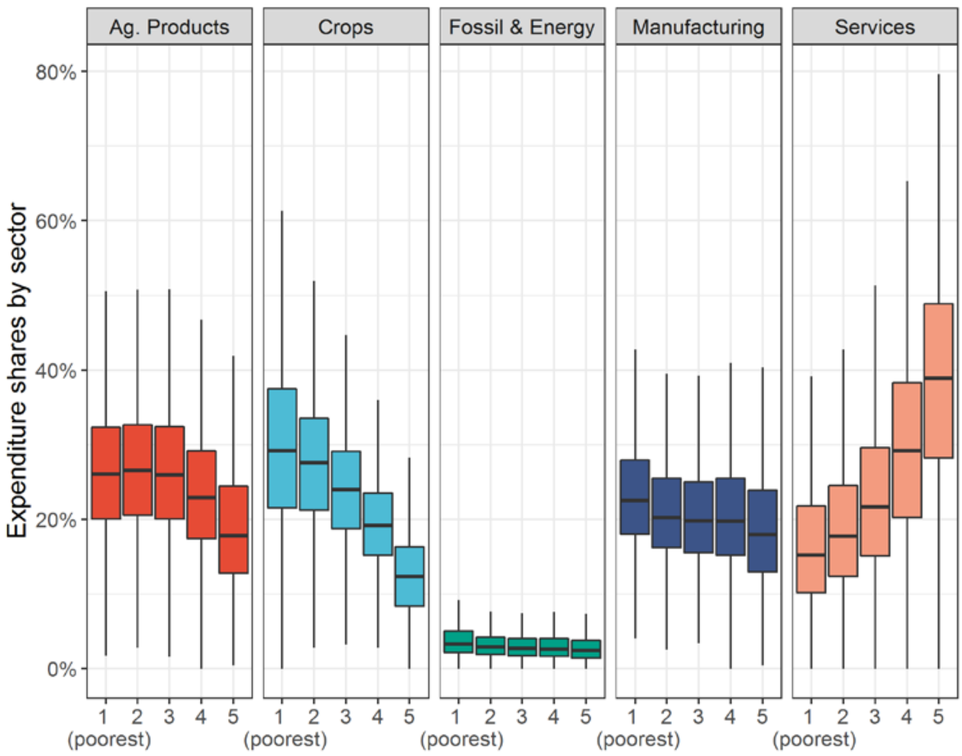

Fig. 6: Expenditure shares by income quintile and sector

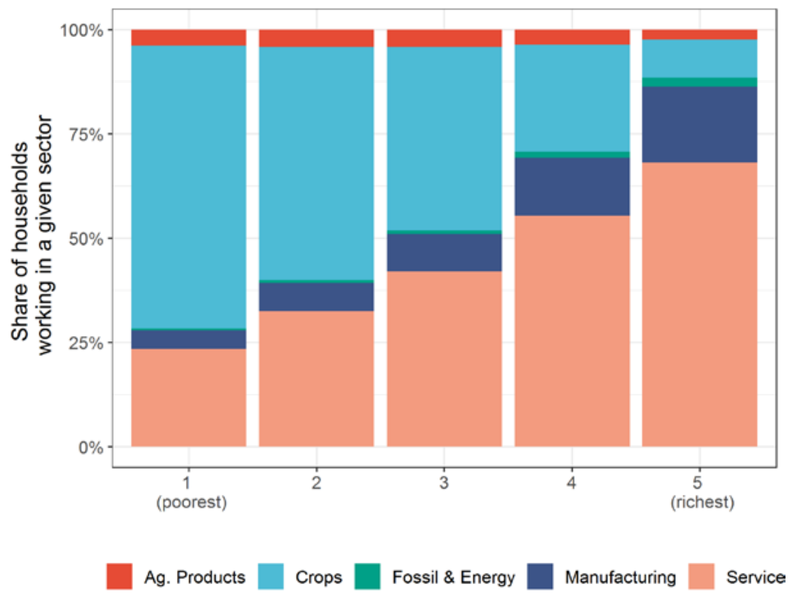

Fig. 7: Employment shares by sector and income quintile

To capture the income effects of climate policy and structural change, we refer to the head of household's sector of employment to approximate the changes in income that the household will experience as a result of development, structural change, and climate policy. Figure 6 shows the distribution of sectoral employment across income quintiles. According to the survey data, poor households tend to have comparatively high employment shares in the agricultural and construction sectors, whereas rich households have high employment shares in the services and manufacturing sectors. When estimating changes in income over time, we make the simplifying assumption that each household is employed in the same sector as in the benchmark year 2012. Income changes arise from labour income changes, which in this study are approximated by changes in sectoral labour income or total output, respectively, computed by the trade models. The two trade models assume perfect mobility of labour across all sectors within each country/region and therefore result in a uniform wage across all sectors in each country/region. Changes in labour income resemble wage changes under imperfect mobility of labour across sectors.

To calculate the distributional effects of structural change and climate policy across income quintiles, we first calculate the new income of households as:

$$HHIncome_{i,s,t+1} = HHIncome_{i,s,t} * \left(1 + \Delta wage_{i,s}\right) \qquad t \in \{1,2\} \qquad (1),$$

where $HHIncome_{i,s,t}$ is the income of household *i* in sector *s* and period *t*, covering the base year 2015 (period 1) and the target year 2030 (period 2). $\Delta wage_{i,s}$ is calculated as the percentage change in labour income (JUST) or the production value (KITE) in the sector of employment of household *i* between the periods *t* and *t+1*. For the base year, income is approximated by total expenditures per capita. The income effect (see Figure 5) is calculated as the difference in $HHIncome_{i,s,t+1}$ between two specified scenarios.

Based on the computation of the income of each household in $t+1$, we calculate the new total expenditures of each household ($HHconsumption_{i,s,t+1}$) as a result of the price changes in consumption goods computed by the trade models (Δp_s), assuming that the composition of the household's consumption basket ($expshare_{i,s}$) remains unchanged:

$$HHconsumption_{i,t+1} = \sum_s (1 + \Delta p_s) * \left(expshare_{i,s} * HHIncome_{i,s,t+1}\right) \qquad (2).$$

We then compare the new total expenditures with the new income of the household to calculate the consumption incidence:

$$incidence_{i,t+1} = (HHIncome_{i,t+1} - HHconsumption_{i,t+1}) / HHconsumption_{i,t+1} \quad (3).$$

Model coupling

The models and methods scrutinized in our model cascade are soft-linked via the exchange of parameter values and solution results. Figure 8 shows the main data flows. The relevant scenario data, which are derived from REMIND and the structural change model and used as inputs for the JUST and KITE model, are: GDP, value-added shares of agriculture, manufacturing, and services, a uniform CO_2 price (imposed on all Indian production sectors and private and public consumption) and the prices of global energy carriers (coal, crude oil, and natural gas). The output variables generated by the trade models as inputs for the household model are: sectoral labour income, sectoral output, and output prices.

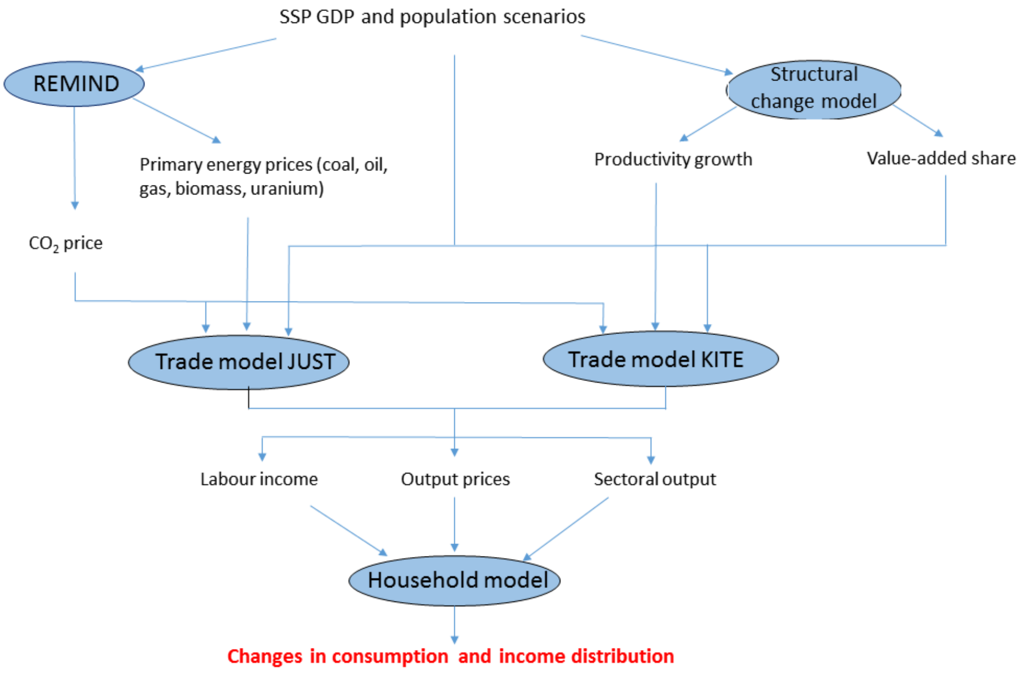

Fig. 8: Data flow between models

Scenario design

Our scenario analysis is performed along three dimensions: (i) climate policy, (ii) structural change, and (iii) socioeconomic uncertainty. Table 1 classifies the 12 underlying scenarios. The properties of the climate policy and structural change scenarios are discussed in the Introduction and Results sections. The pattern of structural change, as displayed in Figure 1 for the baseline scenario, also largely applies under different climate policy scenarios, implying that climate policies will not substantially change the macroeconomic structural transformation[36].

The dimension of socioeconomic uncertainty is covered by three SSP scenarios which can be further specified as follows:

- **SSP1**: medium/high GDP per capita growth based on fast technological progress; less energy intensive; high share of renewable energies already in the baseline scenario; comparatively high energy prices in the short term, and lower energy prices (apart from oil) in the long term; fast structural change towards manufacturing and services; India exhibits peaks of value-added and labour income shares in the manufacturing sector around the years 2035 and 2040, respectively.
- **SSP2**: continuation of long-term trends (e.g. population growth, technological progress, energy, and land use); medium GDP per capita growth; comparatively high energy intensity (similar to SSP5); medium energy prices; moderate structural change towards manufacturing and services; India exhibits peaks of value-added and labour income shares in the manufacturing sector around 2040 and 2050, respectively.
- **SSP5**: high GDP growth based on fast technological progress; energy intensive; abundant fossil resources; energy prices are low in the short term but high in the long term as energy demand is substantial; fast structural change towards services; India exhibits peaks of value-added and labour income shares in the manufacturing sector about 2030 and 2035, respectively.

Table 1: Scenario classification

Climate policy scenario	Socioeconomic/structural change scenario	
	With structural change	Without structural change

	SSP1	SSP2	SSP5	SSP1	SSP2	SSP5
Reference (implemented policies)	SSP1-Base-SC	SSP2-Base-SC	SSP5-Base-SC	SSP1-Base	SSP2-Base	SSP5-Base
Climate policy (2°C)	SSP1-CP-SC	SSP2-CP-SC	SSP5-CP-SC	SSP1-CP	SSP2-CP	SSP5-CP

ACKNOWLEDGEMENT

Funding from the German Federal Ministry of Education and Research (BMBF) in the Funding Priority "Economics of Climate Change" (ROCHADE: 01LA1828A) is greatfully acknowledged.

REFERENCES

1. Kalkuhl, M. et al. Successful coal phase-out requires new models of development. *Nat. Energy* **4**, 897–900 (2019). https://doi.org/10.1038/s41560-019-0500-5
2. Montrone, L., Steckel, J., & Kalkuhl, M. The type of power capacity matters for economic development – Evidence from a global panel. *Resource and Energy Economics* **69**, 101313 (2022). https://doi.org/10.1016/j.reseneeco.2022.101313.
3. Herrendorf, B., Rogerson, R., & Valentinyi, A. Growth and Structural Transformation. *Handbook of Economic Growth* **2**, 855–941 (2014).
4. Kongsamut, P., Rebelo, S. & Xie, D. Beyond Balanced Growth. *The Review of Economic Studies* **68**(4), 869–882. https://doi.org/10.1111/1467-937X.00193 (2001).
5. Acemoglu, D., & Guerrieri, V. Capital Deepening and Non-balanced Economic Growth. *Journal of Political Economy*, **116**(3), 467–498 (2008).
6. McMillan, M., & Rodrik, D. Globalization, structural change and productivity growth. In *Making Globalization Socially Sustainable*, edited by Bachetta, M. & Jansen, M. (eds), 49–84. International Labor Organization, Geneva (2011).
7. Mehic, A. Industrial employment and income inequality: Evidence from panel data. *Structural Change and Economic Dynamics* **45,** 84–93 (2018). https://doi.org/10.1016/j.strueco.2018.02.006.

8. Hartmann, D., Zagato, L., Gala, P., & Pinheiro, F.L. Why did some countries catch-up, while others got stuck in the middle? Stages of productive sophistication and smart industrial policies. *Structural Change and Economic Dynamics* **58**, 1–13 (2021). https://doi.org/10.1016/j.strueco.2021.04.007.
9. Rekha R., & Suresh Babu, M. Premature deindustrialisation and growth slowdowns in middle-income countries. *Structural Change and Economic Dynamics* **62**, 377–389 (2022). https://doi.org/10.1016/j.strueco.2022.04.001.
10. Chaturvedi, V., Koti, P. N., & Chordia, A. R. Pathways towards India's nationally determined contribution and mid-century strategy. *Energy and Climate Change* **2**, 100031 (2021). https://doi.org/10.1016/j.egycc.2021.100031.
11. Leimbach, M., Marcolino, M., & Koch, J. Structural change scenarios within the SSP framework. *Futures* (under review) (2022).
12. O'Neill, B. C. et al. A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change* **122**, 387–400 (2014).
13. Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change* **42**, 153–168 (2017).
14. da Silva Freitas, L.F., de Santana Ribeiro, L.C., de Souza, K.B., & Hewings, G.J.D. The distributional effects of emissions taxation in Brazil and their implications for climate policy. *Energy Economics* **59**, 37–44 (2016). https://doi.org/10.1016/j.eneco.2016.07.021.
15. Dorband, I.I., Jakob, M., Kalkuhl, M., & Steckel, J.C. Poverty and distributional effects of carbon pricing in low- and middle-income countries – A global comparative analysis. *World Development* **115**, 246–257 (2019). https://doi.org/10.1016/j.worlddev.2018.11.015.
16. Chepeliev, M., Osorio-Rodarte, I. & van der Mensbrugghe, D. Distributional impacts of carbon pricing policies under the Paris Agreement: Inter and intra-regional perspectives, *Energy Economics* **102** (2021). https://doi.org/10.1016/j.eneco.2021.105530.
17. Steckel, J.C. et al. Distributional impacts of carbon pricing in developing Asia. *Nat. Sustain.* **4**, 1005–1014 (2021). https://doi.org/10.1038/s41893-021-00758-8
18. Ohlendorf, N., Jakob, M., Minx, J.C., Schröder, C., & Steckel, J. C. Distributional impacts of carbon pricing: A meta-analysis. *Environ. Resource Econ.* **78**, 1–42 (2021). https://doi.org/10.1007/s10640-020-00521-1.
19. Känzig, D.R. The unequal economic consequences of carbon pricing (February 15, 2021). Available at SSRN: https://ssrn.com/abstract=3786030 or http://dx.doi.org/10.2139/ssrn.3786030

20. Soergel, B. et al. Combining ambitious climate policies with efforts to eradicate poverty. *Nat. Commun.* **12**, 2342 (2021). https://doi.org/10.1038/s41467-021-22315-9
21. Choudhry, S. Is India's formal manufacturing sector 'hollowing out'- importance of intermediate input. *Structural Change and Economic Dynamics* **59**, 533–547 (2021). https://doi.org/10.1016/j.strueco.2021.09.014.
22. Malik, A., Bertram, C., Kriegler, E., & Luderer, G. Climate policy accelerates structural changes in energy employment. *Energy Policy* **159**, 112642 (2021). https://doi.org/10.1016/j.enpol.2021.112642.
23. Budolfson, M. et al. Climate action with revenue recycling has benefits for poverty, inequality and well-being. *Nat. Clim. Chang.* **11**, 1111–1116 (2021). https://doi.org/10.1038/s41558-021-01217-0
24. Sedova, B., & Kalkuhl, M. Who are the climate migrants and where do they go? Evidence from rural India. *World Development* **129**, 104848, (2020). https://doi.org/10.1016/j.worlddev.2019.104848.
25. Klonner, S., & Oldiges, C. The welfare effects of India's rural employment guarantee. *Journal of Development Economics* **157**, 102848 (2022). https://doi.org/10.1016/j.jdeveco.2022.102848
26. Baumstark, L. et al. REMIND2.1: transformation and innovation dynamics of the energy-economic system within climate and sustainability limits. *Geoscientific Model Development* **14**, 6571–6603 (2021). https://doi.org/10.5194/gmd-14-6571-2021
27. Koch, J. & Leimbach, M. SSP economic growth projections: major changes of key drivers in environmental assessment studies. *Ecological Economics* (under review) (2022).
28. Eaton, J. & Kortum, S. Technology, geography, and trade. *Econometrica*, **70**(5). 1741–1779 (2002).
29. Caliendo, L. & Parro, F. Estimates of the trade and welfare effects of NAFTA. *The Review of Economic Studies* **82**(1), 1–44 (2015).
30. Pothen, F. & Hübler, M. The interaction of climate and trade policy. *European Economic Review* **107**, 1–26 (2018).
31. Pothen, F. & Hübler, M. A forward calibration method for analyzing energy policy in new quantitative trade models. *Energy Economics* **100**, 105352 (2021).
32. Hübler, M. & Pothen, F. Can smart policies solve the sand mining problem? *PLOS ONE* **16**(4), e0248882 (2021).
33. Felbermayr, G.J., Mahlkow, H., & Sandkamp, A.N. Cutting through the value chain: The long-run effects of decoupling the east from the west. *Empirica* (under review) (2022).
34. Mahlkow, H. & Wanner, J. The carbon footprint of global trade imbalances. Working Paper (2022).

35. Aguiar, A., Chepeliev, M., Corong, E.L., McDougall, R., & Van Der Mensbrugghe, D. The GTAP data base: version 10. *Journal of Global Economic Analysis* **4**(1), 1–27 (2019).
36. Lefevre J. et al. Global socio-economic and climate change mitigation scenarios through the lens of structural change. *Global Environmental Change* **74**, 102510 (2022). https://doi.org/10.1016/j.gloenvcha.2022.102510

APPENDIX

1. Climate policy scenario characteristics

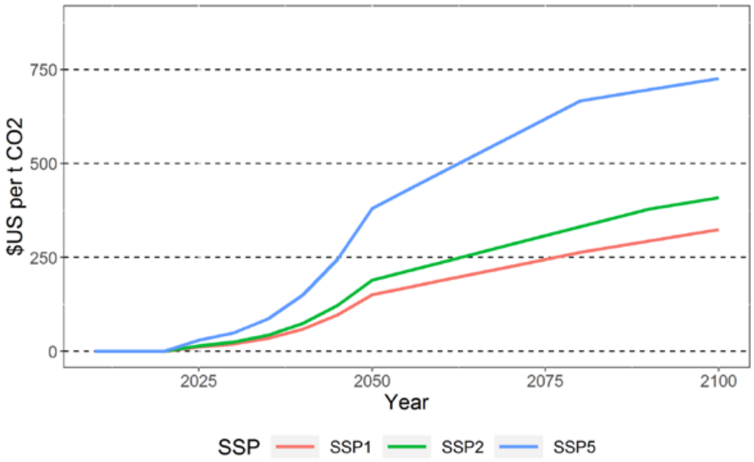

Fig. A.1: Carbon prices for 2°C climate stabilization under SSP1, SSP2, and SSP5.

2. Income and price changes across SSPs

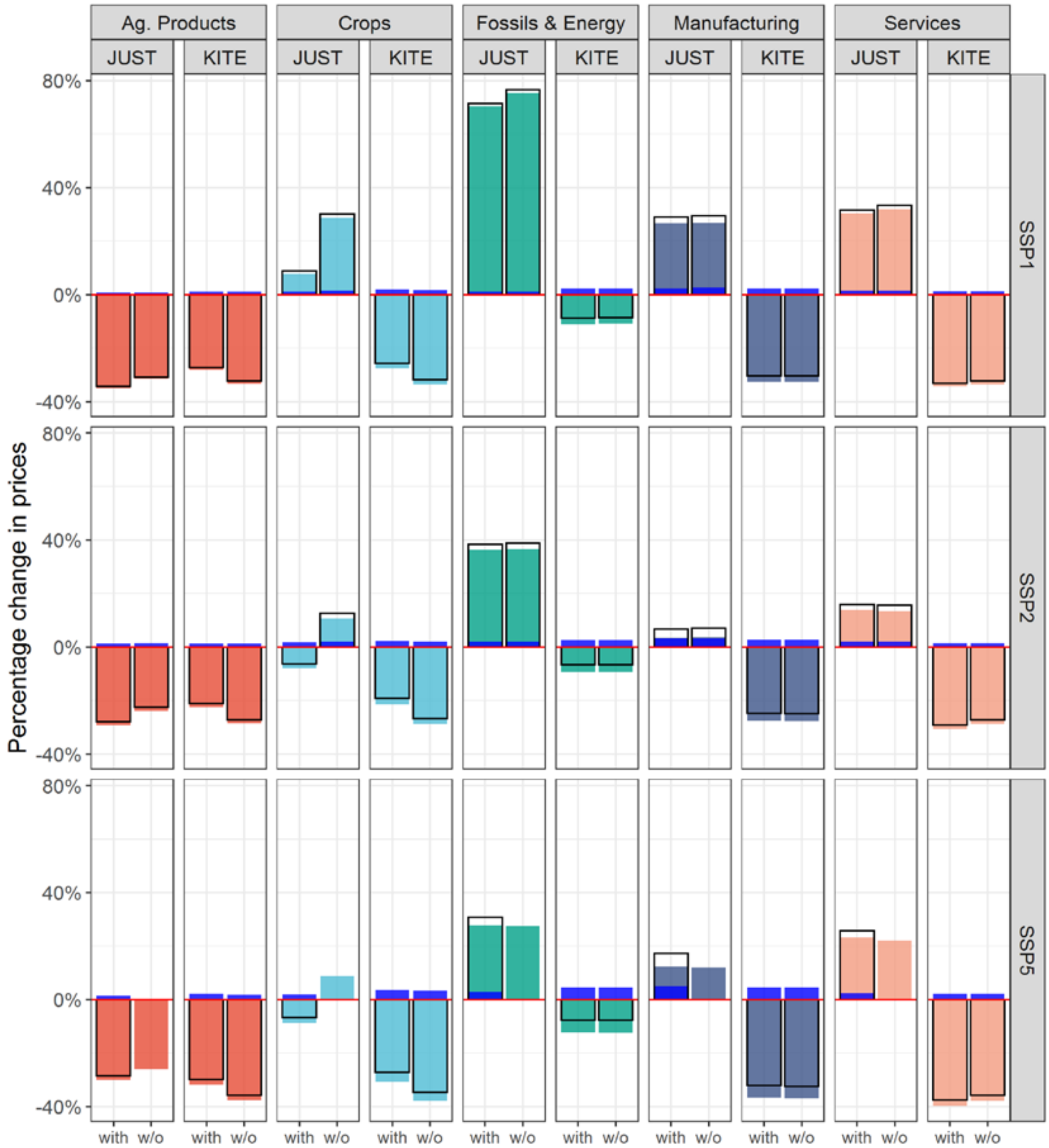

Fig. A.2: Sectoral price changes computed by KITE and JUST models. Each bar shows the relative difference between 2015 and 2030. The differential impact of climate policy is represented by the embedded dark blue bar. The differential impact of structural change is the difference between the left bar (with structural change) and the right bar (without structural change) in each subpanel. Sectoral output from KITE and JUST is aggregated to five sectors with Agricultural Products and Crops representing the agricultural sector, and Fossil & Energy and Manufacturing representing the manufacturing sector.

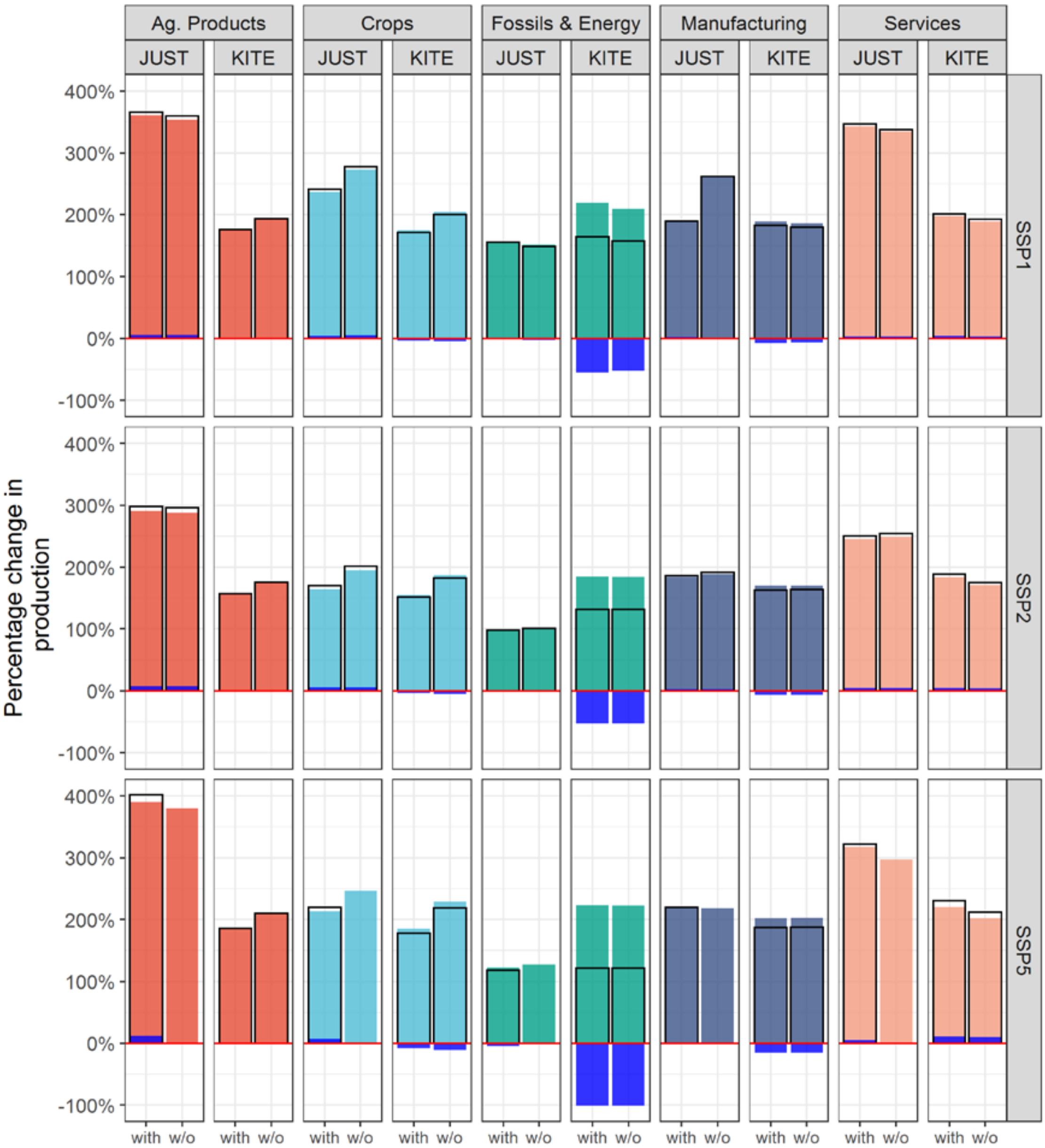

Fig. A.3: Sectoral income changes computed by KITE and JUST models. Each bar shows the relative difference between 2015 and 2030. The differential impact of climate policy is represented by the embedded dark blue bar. The differential impact of structural change is the difference between the left bar (with structural change) and the right bar (without structural change) in each subpanel. Sectoral output from KITE and JUST is aggregated to five sectors with Agricultural Products and Crops representing the agricultural sector, and Fossil & Energy and Manufacturing representing the manufacturing sector.

3. Impact of climate policy on structural change (disaggregated at the sectoral level)

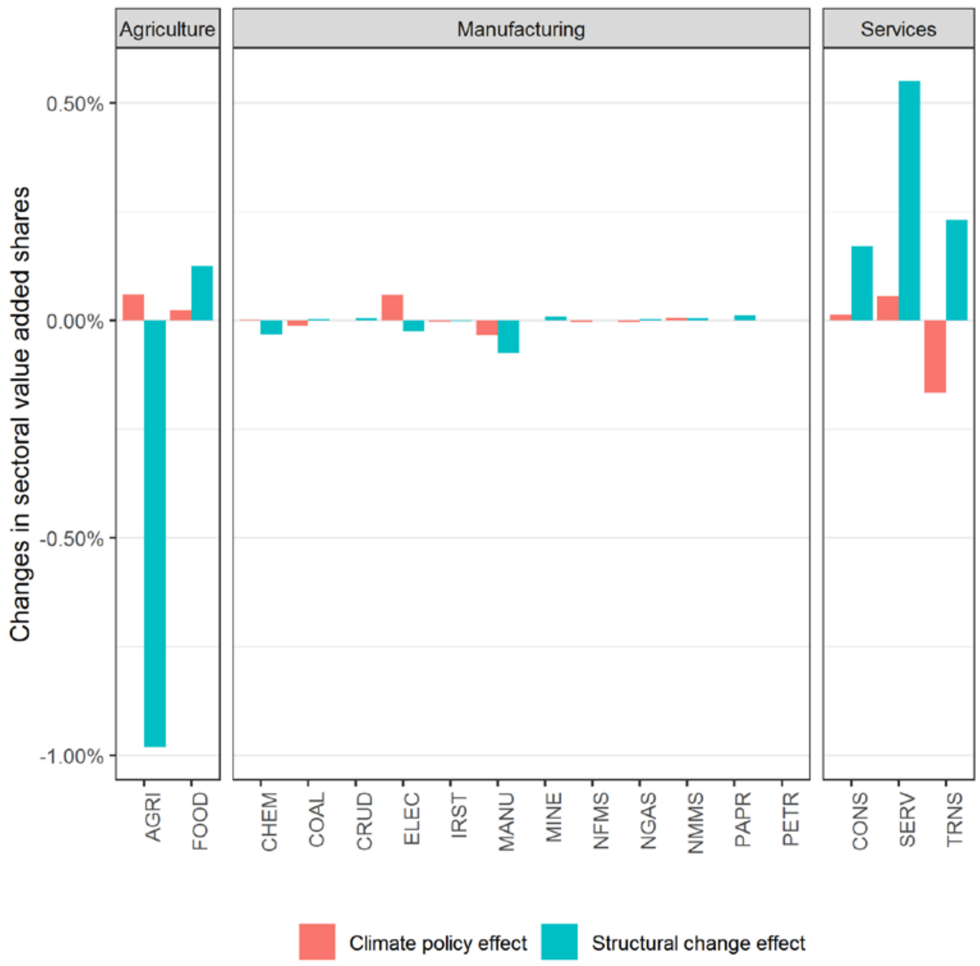

Fig. A.4: Changes in sectoral value-added shares (JUST model).

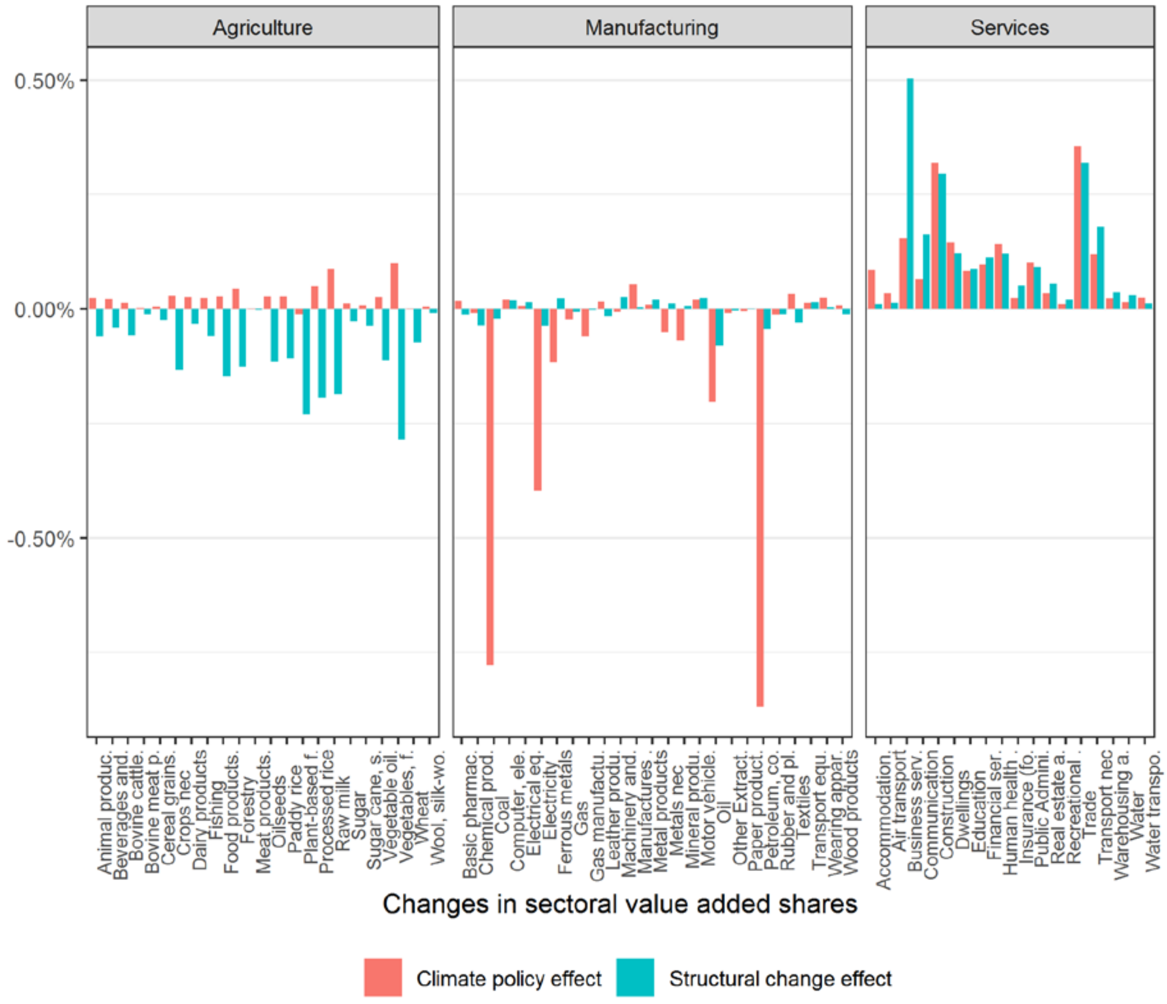

Fig. A.5: Changes in sectoral value-added shares (KITE model).

4. Sector mapping

Both advanced trade models use GTAP data. While the default setting in KITE is the sectoral resolution given by GTAP (column 1 in Table A.1), the JUST model uses the sectoral aggregation as shown in column 3 of Table A.1. To provide consistent and comparable sectoral results, KITE und JUST results are aggregated to five sectors (column 4). These sectors are finally mapped onto the three sectors (agriculture, manufacturing and services) used at the macro level of this study.

Table A.1: Sector mapping related to the JUST and KITE trade models

GTAP (KITE)	Explanation	JUST sectors	KITE+JUST aggregation	Macro aggregation
Pdr	Rice: seed	AGRI	Crops	Agriculture
wht	Wheat: seed	AGRI	Crops	Agriculture
gro	Other Grains: maize (corn)	AGRI	Crops	Agriculture
v_f	Veg & Fruit: vegetables	AGRI	Crops	Agriculture
osd	Oil Seeds: oil seeds and oleaginous fruit	AGRI	Crops	Agriculture
c_b	Cane & Beet: sugar crops	AGRI	Crops	Agriculture
pfb	Fibre crops	AGRI	Crops	Agriculture
ocr	Other Crops: stimulant; spice and aromatic crops; forage products; plants and parts of plants used primarily in perfumery	AGRI	Crops	Agriculture
ctl	Cattle: bovine animals	AGRI	Ag. Products	Agriculture
oap	Other Animal Products: swine; poultry; other live animals; eggs of hens or other birds in shell	AGRI	Ag. Products	Agriculture
rmk	Raw milk	AGRI	Ag. Products	Agriculture
wol	Wool: wool	AGRI	Ag. Products	Agriculture
frs	Forestry: forestry	AGRI	Ag. Products	Agriculture
fsh	Fishing: hunting	AGRI	Ag. Products	Agriculture
coa	Coal: mining and agglomeration of hard coal	COAL	Fossil & Energy	Manufacturing
oil	Oil: extraction of crude petroleum	CRUD	Fossil & Energy	Manufacturing

gas	Gas: extraction of natural gas	NGAS	Fossil & Energy	Manufacturing
oxt	Other Mining Extraction (formerly omn): mining of metal ores; other mining and quarrying	MINE	Fossil & Energy	Manufacturing
cmt	Cattle Meat: fresh or chilled; meat of buffalo	FOOD	Ag. Products	Agriculture
omt	Other Meat: meat of pigs	FOOD	Ag. Products	Agriculture
vol	Vegetable Oils: margarine and similar preparations; cotton linters; oil-cake and other residues resulting from the extraction of vegetable fats or oils; flours and meals of oil seeds or oleaginous fruits	FOOD	Ag. Products	Agriculture
mil	Milk: dairy products	FOOD	Ag. Products	Agriculture
pcr	Processed Rice: semi- or wholly milled	FOOD	Ag. Products	Agriculture
sgr	Sugar and molasses	FOOD	Ag. Products	Agriculture
ofd	Other Food: prepared and preserved fish	FOOD	Ag. Products	Agriculture
b_t	Beverages and Tobacco products	FOOD	Ag. Products	Agriculture
tex	Manufacture of textiles	MANU	Manufacturing	Manufacturing
wap	Manufacture of wearing apparel	MANU	Manufacturing	Manufacturing
lea	Manufacture of leather and related products	MANU	Manufacturing	Manufacturing
lum	Lumber: manufacture of wood and of products of wood and cork	MANU	Manufacturing	Manufacturing
ppp	Paper & Paper Products: includes printing and reproduction of recorded media	PAPR	Manufacturing	Manufacturing
p_c	Petroleum & Coke: manufacture of coke and refined petroleum products	PETR	Manufacturing	Manufacturing
chm	Manufacture of chemicals and chemical products	CHEM	Manufacturing	Manufacturing
bph	Manufacture of pharmaceuticals	CHEM	Manufacturing	Manufacturing
rpp	Manufacture of rubber and plastics products	CHEM	Manufacturing	Manufacturing
nmm	Manufacture of other non-metallic mineral products		Manufacturing	Manufacturing
i_s	Iron & Steel: basic production and casting	IRST	Manufacturing	Manufacturing
nfm	Non-Ferrous Metals: production and casting of copper	NFMS	Manufacturing	Manufacturing
fmp	Manufacture of fabricated metal products	MANU	Manufacturing	Manufacturing
ele	Manufacture of computer	MANU	Manufacturing	Manufacturing
eeq	Manufacture of electrical equipment	MANU	Manufacturing	Manufacturing
ome	Manufacture of machinery and equipment n.e.c.	MANU	Manufacturing	Manufacturing
mvh	Manufacture of motor vehicles	MANU	Manufacturing	Manufacturing

otn	Manufacture of other transport equipment	MANU	Manufacturing	Manufacturing
omf	Other Manufacturing: includes furniture	MANU	Manufacturing	Manufacturing
ely	Electricity; steam and air conditioning supply	ELEC	Fossil & Energy	Manufacturing
gdt	Gas manufacture	NGAS	Fossil & Energy	Manufacturing
wtr	Water supply; sewerage	SERV	Services	Services
cns	Construction: building houses factories offices and roads	CONS	Services	Services
trd	Wholesale and retail trade; repair of motor vehicles and motorcycles	SERV	Services	Services
afs	Accommodation	SERV	Services	Services
otp	Land transport and transport via pipelines	TRNS	Services	Services
wtp	Water transport	TRNS	Services	Services
atp	Air transport	TRNS	Services	Services
whs	Warehousing and support activities	SERV	Services	Services
cmn	Information and communication	SERV	Services	Services
ofi	Other Financial Intermediation: includes auxiliary activities but not insurance and pension funding	SERV	Services	Services
ins	Insurance (formerly isr): includes pension funding	SERV	Services	Services
rsa	Real estate activities	SERV	Services	Services
obs	Other Business Services n.e.c	SERV	Services	Services
ros	Recreation & Other Services: recreational	SERV	Services	Services
osg	Other Services (Government): public administration and defence; compulsory social security	SERV	Services	Services
edu	Education	SERV	Services	Services
hht	Human health and social work	SERV	Services	Services
dwe	Dwellings: ownership of dwellings (imputed rents of houses occupied by owners)	SERV	Services	Services

5. Robustness of distributional effects

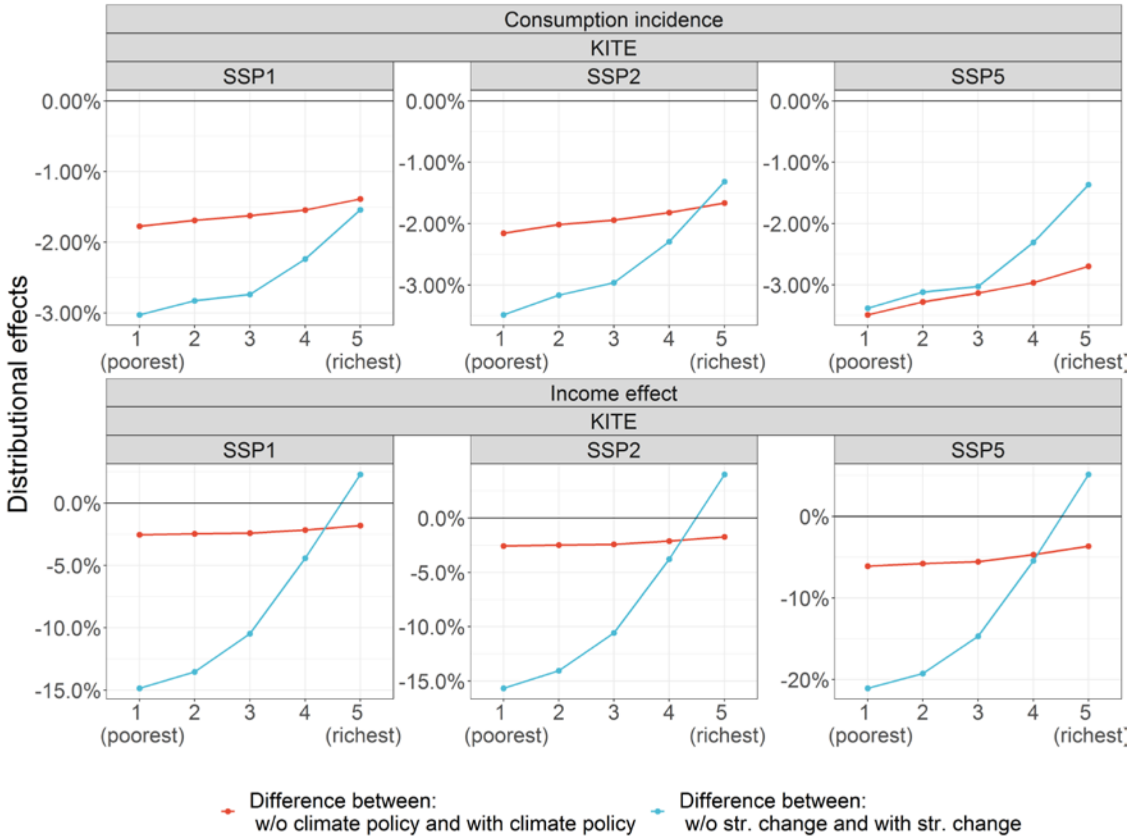

Fig. A.6: Consumption incidence and changes in income across income groups due to climate policy and structural change under SSP2 (based on KITE model output). The red lines represent the differences in consumption incidence (left panel) and income (right panel) in a scenario with climate policy and a scenario without climate policy. The blue lines represent the respective differences between scenarios with and without structural change. Negative values indicate that consumption incidence/income values are lower in scenarios with climate policy and structural change, respectively.

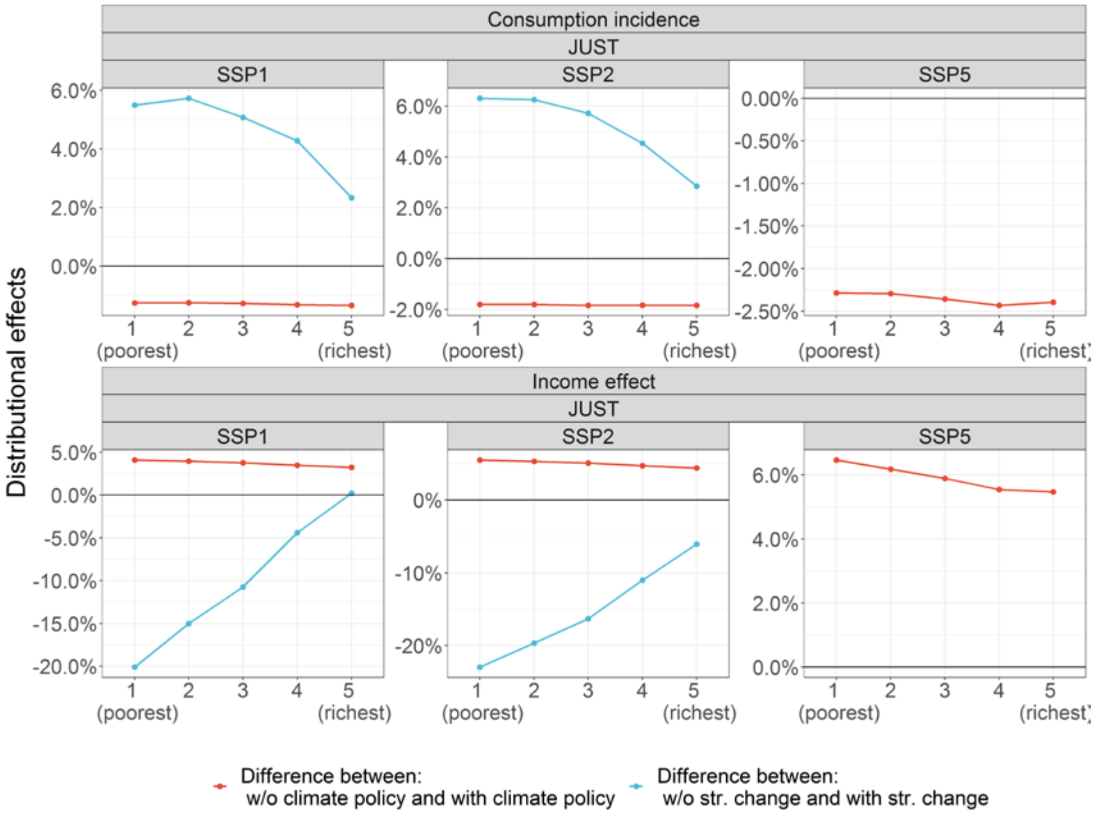

Fig. A.7: Consumption incidence and changes in income across income groups due to climate policy and structural change under SSP2 (based on JUST model output). The red lines represent the differences in consumption incidence (left panel) and income (right panel) in a scenario with climate policy and a scenario without climate policy. The blue lines represent the respective differences between scenarios with and without structural change. Negative values indicate that consumption incidence/income values are lower in scenarios with climate policy and structural change, respectively.