



Distributional Aspects of Climate Policies

Marie Young-Brun

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UNIVERSITÉ PARIS 1 PANTHÉON-SORBONNE – PARIS SCHOOL OF ECONOMICS

ÉCOLE DOCTORALE 465 – Économie Panthéon Sorbonne
Centre d'économie de la Sorbonne

THÈSE

Pour l'obtention du titre de Docteur en Économie
Présentée et soutenue publiquement le 18 septembre 2023 par

Marie YOUNG-BRUN

ASPECTS DISTRIBUTIFS
DES POLITIQUES CLIMATIQUES

Sous la direction de:
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THESIS

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Marie YOUNG-BRUN

DISTRIBUTIONAL ASPECTS OF CLIMATE POLICIES

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Résumé de la thèse

L'atténuation du changement climatique et la gestion des dommages nécessitent la conception de mesures climatiques socialement acceptables et équitables. Les trois chapitres de cette thèse étudient les effets distributifs des politiques climatiques.

Le premier chapitre, co-écrit avec Simon Feindt, analyse comment les dommages climatiques sur les facteurs de production et leur incidence sur les ménages affectent le coût social du carbone. Dans un modèle mondial d'évaluation intégrée à l'échelle mondiale avec une désagrégation régionale, nous décomposons l'inégalité des revenus et les dommages climatiques en une composante travail et une composante capital. Nous montrons que la consommation des plus pauvres et l'inégalité sont plus affectées par les dommages liés au travail que par ceux liés au capital, mais que l'inverse est vrai pour le coût social du carbone. Nous démêlons les effets distributifs et de croissance sur le coût social du carbone et montrons que si les dommages sont peu régressifs, les effets de croissance des dommages touchant le stock de capital dominant.

Le deuxième chapitre, co-écrit avec Aurélie Méjean et Stéphane Zuber, porte sur la conception de politiques équitables de taxation du carbone au niveau mondial. Nous développons un modèle d'évaluation intégré à l'échelle mondiale avec une désagrégation au niveau des pays et des inégalités au sein des pays. Nous proposons des profils de taxes carbone uniformes et différenciés compatibles avec une limitation de la hausse de la température mondiale à 2°C. Nous évaluons l'efficacité, les effets distributifs et les effets sur le bien-être de plusieurs options de recyclage des revenus. Nos résultats montrent qu'une taxe carbone uniforme avec un recyclage forfaitaire global est la meilleure en termes d'amélioration du bien-être et de réduction des inégalités. Une telle politique pourrait cependant être confrontée à des problèmes de faisabilité en raison des importants transferts internationaux qu'elle implique. Le recyclage d'un pourcentage limité des recettes d'une taxe carbone peut apporter des bénéfices en termes d'inégalité et de bien-être lorsque les transferts sont ciblés vers les pays à faible revenu et particulièrement vulnérables aux effets du changement climatique.

Le troisième chapitre explore la manière dont les effets distributifs d'une taxe carbone peuvent affecter son acceptabilité politique au niveau national. Je pose la question de savoir si les effets distributifs horizontaux, c'est-à-dire les effets au sein d'une même classe de revenu, limitent le soutien politique à la taxe carbone. Je développe

un modèle du soutien politique à la taxe carbone qui comprend inégalité de revenus et inégalité entre urbains et ruraux. Cette dernière correspond à une différence du niveau de consommation de biens de première nécessité à forte intensité carbone, tel que le carburant en fonction de la localisation (rural ou urbain). Je montre que l'hétérogénéité horizontale entraîne un écart de soutien politique entre les ménages urbains et ruraux. Le soutien politique peut être sous-optimal dans un groupe concentré de la population, alors que l'électeur médian soutient une taxe carbone proche du niveau de taxe pigouvien. Une calibration avec des données européennes permet de mieux comprendre les conséquences en termes d'équité et d'acceptabilité des différentes options de recyclage des recettes de la taxe carbone.

DISCIPLINE: Sciences Économiques

MOTS-CLÉS: Politiques climatiques; Effets distributifs; Économie du climat

Thesis summary

Mitigating greenhouse gas emissions and managing climate change impacts requires designing socially acceptable and equitable climate policies. The three chapters of this dissertation examine the distributional impacts of climate policies.

The first chapter, joint with Simon Feindt, analyzes how the social cost of carbon emissions is affected by climate damages on factors of production and how they are distributed across households. We address this question using a global integrated assessment model with regional disaggregation in which we decompose income inequality and climate damages into labor and capital components. We show that inequality and consumption at the lower end of the distribution are more affected by labor damages than capital damages, but that the reverse is true for the social cost of carbon. We disentangle the distributional and growth channels of effects on the social cost of carbon, and show that if damages are not very regressive, the growth effects of damages hitting the capital stock tend to dominate.

The second chapter, written with Aurélie Méjean and Stéphane Zuber, focuses on the design of equitable carbon taxation policies at the global level. We develop a global integrated assessment model with country level disaggregation and within-country inequality. We find global uniform and differentiated carbon tax schemes compatible with a 2°C scenario, and assess the efficiency, distributional and wellbeing outcomes of several revenue recycling options. Our results show that a uniform carbon tax with global lump-sum recycling performs best in terms of welfare and equality improvements, but could face feasibility issues because of the large international transfers it entails. Recycling only a smaller percentage of revenues can bring inequality and welfare benefits when transfers are targeted to lower income countries which are vulnerable to climate change impacts.

The third chapter explores how the distributive impacts of carbon taxation may affect its political acceptability at a national level. I examine whether horizontal distributional effects, i.e., effects within income groups, limit political support for carbon taxation. I develop a model of political support for carbon taxation with income and urban-rural inequality. The latter corresponds to a difference in the level of carbon-intensive necessity consumption, such as heterogeneous needs for transport fuel depending on location (rural vs. urban). The results demonstrate that horizontal het-

erogeneity leads to a gap in political support between urban and rural households. Political support can be inefficiently low in a concentrated section of the population, while the median voter supports a carbon tax close to the Pigouvian level. A calibration with European data provides insights into the equity and acceptability consequences of different carbon tax revenue-recycling options.

DISCIPLINE: Economics

KEYWORDS: Climate policies; Distributional effects; Climate economics

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Introduction générale

Le changement climatique est un problème de plus en plus épineux, car les émissions de gaz à effet de serre continuent d'augmenter au niveau mondial, tandis que les conséquences du changement climatique en cours se font déjà sentir dans le monde entier. L'augmentation actuelle de la température mondiale d'au moins 1,1 °C par rapport au niveau préindustriel a entraîné une augmentation de la fréquence des phénomènes extrêmes tels que les vagues de chaleur, les fortes précipitations, les sécheresses et les cyclones tropicaux, et a eu des répercussions sur la santé humaine, la productivité agricole, les infrastructures et les revenus (IPCC, 2023).

Le sixième rapport d'évaluation du Groupe d'experts intergouvernemental sur l'évolution du climat des Nations Unies indique que "la vulnérabilité aux extrêmes climatiques actuels et la contribution historique au changement climatique sont très hétérogènes, beaucoup de ceux qui ont le moins contribué au changement climatique jusqu'à présent étant les plus vulnérables à ses impacts" (IPCC, 2023). Les régions et pays les plus pauvres sont ceux qui subissent le plus les effets du changement climatique, notamment en raison de leur situation géographique (Mendelsohn et al., 2006; Stern, 2006; Tol, 2018; Diffenbaugh and Burke, 2019). Au sein des pays, des études de plus en plus nombreuses montrent que les ménages les plus défavorisés seront touchés de manière disproportionnée, en raison d'une exposition et d'une vulnérabilité accrues aux risques climatiques, et d'une capacité plus faible à faire face aux chocs. (Islam and Winkel, 2017; Hallegatte and Rozenberg, 2017; Hsiang et al., 2019). Les ménages les plus pauvres sont plus susceptibles de travailler dans des secteurs plus exposés aux phénomènes météorologiques extrêmes (Hallegatte et al., 2020) et au stress thermique (Park et al., 2018).

Les politiques d'atténuation des émissions de gaz à effet de serre ont également des effets distributifs. Historiquement, les pays développés ont contribué à la majorité des émissions mondiales (Wei et al., 2012). Toutefois, le coût de la réduction des émissions actuelles et futures pourrait être plus élevé pour les pays les plus pauvres (Taconet et al., 2020). Au sein des pays, la répartition des coûts et des bénéfices de l'atténuation dépend du type d'instrument, des émissions couvertes et des potentielles politiques de compensation (Vona, 2021; Drupp et al., 2021). Dans le cas de la tarification carbone, un effet progressif est plus probable dans les pays à faible revenu et pour les politiques

de transport (Ohlendorf et al., 2021).

La décarbonisation des économies et la gestion des conséquences actuelles du changement climatique nécessitent la conception de mesures climatiques équitables et socialement acceptables. Au niveau international, les négociations sur les instruments de coopération en matière climatique achoppent souvent sur des questions de partage des efforts. Dans le contexte de l'accord de Paris, les engagements volontaires nationaux et la rapidité de leur mise en œuvre déterminent les trajectoires de réduction des émissions mondiales et leur équité (Van den Berg et al., 2020). Le niveau des efforts décidé par les dirigeants au sein des pays reflète également les pressions internes exercées par les électeurs et les groupes d'intérêt auxquels les gouvernements doivent faire face, qui peuvent résulter de conflits distributifs (Aklin and Mildenberger, 2020). En outre, les politiques climatiques peuvent entraîner des co-bénéfices qui accroissent l'équité, tels que le double dividende provenant du recyclage des recettes d'une tarification carbone (Karlsson et al., 2020). Elles interagissent également avec d'autres objectifs politiques mondiaux, tels que la réduction de la pauvreté ou les objectifs de développement durable (Fujimori et al., 2020; Soergel et al., 2021).

La représentation des effets distributifs est donc essentielle pour éclairer les politiques climatiques mondiales et leur mise en œuvre au niveau national. Les modèles d'évaluation intégrée (MEI), qui relient les modèles climatiques et économiques, constituent un outil important pour formuler des recommandations politiques mondiales. Les MEI sont notamment utilisés pour calculer le coût social du carbone, un indicateur qui agrège les coûts de l'émission d'une tonne supplémentaire de carbone, exprimé en termes monétaires. Toutefois, les MEI reposent encore souvent sur la modélisation d'un agent représentatif et manquent d'hétérogénéité spatiale et socio-économique (Keppo et al., 2021; Emmerling and Tavoni, 2021). En outre, la conception de politiques politiquement viables nécessite une analyse adéquate des impacts distributifs des politiques d'atténuation de l'effet de serre au sein des pays (Markkanen and Anger-Kraavi, 2019). Bien que l'acceptabilité politique soit souvent utilisée comme motivation dans l'étude des compromis équité-efficacité, la modélisation explicite des contraintes politiques dans les modèles économiques reste difficile (Peng et al., 2021). Enfin, pour mieux comprendre les mécanismes des impacts distributifs, plusieurs dimensions de l'hétérogénéité socio-économique des ménages doivent être représentées, en plus des inégalités de revenu ou de consommation (Rao et al., 2017).

Cette thèse

Cette thèse s'articule autour de trois chapitres qui se concentrent sur les effets distributifs des politiques climatiques, sous l'angle des impacts du changement climatique (chapitre 1) et des politiques d'atténuation (chapitres 2 et 3). L'objectif est d'évaluer les conséquences des inégalités sur la conception des politiques climatiques, selon

trois perspectives. La thèse explore le rôle des effets distributifs dans la quantification des bénéfices des dommages climatiques évités (chapitre 1), la conception d'une politique d'atténuation globale équitable et compatible avec l'Accord de Paris (chapitre 2), et l'acceptabilité sociale de la taxation du carbone (chapitre 3). Dans le reste de cette section, je résume les contributions de chaque chapitre et détaille les approches méthodologiques.

Contributions

Le premier chapitre, *Climate change damages on labor and capital, inequality, and the social cost of carbon*, est un travail conjoint avec Simon Feindt. Nous examinons les impacts distributifs des dommages causés par le changement climatique sur les facteurs de production dans un modèle global d'évaluation intégrée. Notre principale contribution est d'intégrer une nouvelle source d'hétérogénéité sociale qui détermine la distribution des impacts climatiques au sein des régions. Nous modélisons la distribution conjointe des revenus du capital et du travail au niveau intra-régional et la relierons à des dommages affectant les stocks de capital et de travail productif. Une deuxième contribution consiste à évaluer les effets de persistance et d'inégalité pour différentes combinaisons de dommages affectant le capital et le travail. Nous constatons que les dommages sur le capital et le travail ont des effets de niveau et de croissance sur le revenu, avec de l'hétérogénéité entre régions. Nous montrons que les dommages sur le travail et leur distribution ont un impact négatif plus important sur la part dans le revenu et la consommation du bas de la distribution, que les dommages affectant le capital. Nos résultats mettent en évidence trois mécanismes déterminant la distribution des dommages spécifiques aux facteurs : la composition des revenus et l'ampleur de l'inégalité pré-existante, le type de dommages, et la régressivité de chaque type de dommages. Nous contribuons également à la littérature sur le coût social du carbone en évaluant comment il est affecté par les dommages sur le capital et le travail et leur distribution au niveau intra-régional. Nous distinguons les mécanismes de persistance et distributifs. Nous montrons que les effets via la réduction de la croissance dominent lorsque la régressivité des dommages est faible, tandis que des niveaux plus élevés de régressivité entraînent des pertes de consommation au bas de la distribution dans les régions les plus touchées, ce qui soulève des questions normatives plus larges.

Le second chapitre, *Different taxes or redistribution: How to shape a just global climate policy?*, est un travail conjoint avec Aurélie Méjean et Stéphane Zuber. Nous évaluons le potentiel des taxes carbone différenciées par rapport aux taxes carbone globales avec recyclage des revenus afin d'assurer une transition plus équitable dans un scénario de limitation du réchauffement global à 2°C. La principale contribution est le développement d'un modèle d'évaluation intégré mondial qui présente une granularité par pays et représente les inégalités au sein des pays. Nous incluons les effets dis-

tributifs des dommages et de l'atténuation au niveau national. Cela permet d'évaluer les effets des politiques climatiques mondiales en tenant compte des impacts sur le bien-être à l'intérieur des pays. Nous constatons qu'en cas de recyclage au sein des pays, des taxes différenciées se traduisent par des gains plus importants au début du siècle pour les pays riches, et à plus lointaine échéance pour les pays pauvres, tandis qu'une taxe uniforme profite aux pays pauvres à plus court terme. Une deuxième contribution est l'étude d'une variété de politiques, comprenant des transferts internationaux et le recyclage national des revenus de la taxation du carbone. Nous montrons qu'une taxation uniforme du carbone avec un recyclage forfaitaire à l'échelle mondiale entraînerait le gain de bien-être et la réduction des inégalités au niveau mondial le plus important dans la première moitié du siècle, mais impliquerait d'importants transferts intergouvernementaux. La troisième contribution consiste à tester une politique inspirée des propositions de création d'un fonds pour les pertes et dommages, pour lequel une petite partie des recettes fiscales mondiales est destinée aux pays à faible revenu vulnérables au changement climatique. Nous montrons que cette politique pourrait apporter des améliorations significatives du bien-être avec des transferts internationaux limités.

Le troisième chapitre, *Public acceptability of carbon taxation : a model of political support with income and urban-rural inequality*, évalue comment les effets distributifs de la taxation du carbone peuvent limiter son acceptabilité sociale. Ce chapitre contribue à la littérature théorique sur l'économie politique de la taxation du carbone. La principale nouveauté est l'introduction de l'hétérogénéité urbains-ruraux dans un modèle de vote majoritaire avec inégalité des revenus. L'hétérogénéité du coût du carbone au sein des groupes de revenus est obtenue en modélisant des ménages qui diffèrent par l'ampleur de leur consommation contrainte à forte intensité de carbone, reflétant leurs besoins énergétiques plus élevés en matière de transport et de logement. Je montre que l'inégalité entre les urbains et les ruraux se traduit par un soutien politique à la taxe carbone plus faible chez les ménages ruraux que chez les ménages urbains à niveau de revenu égal. Une deuxième contribution consiste à caractériser le niveau de la taxe carbone qui recueille le soutien de l'opinion publique. Je dérive des conditions analytiques sous lesquelles cette taxe carbone acceptable est inférieure à la taxe optimale, fixée par un planificateur social prenant en compte les questions d'équité verticale et horizontale. L'exercice numérique montre que la taxe votée à la majorité est inférieure à la taxe optimale dans tous les pays inclus, même dans l'hypothèse où le planificateur social et les ménages partagent la même préférence environnementale. La troisième contribution consiste à évaluer le rôle du recyclage des recettes de la taxe carbone dans l'amélioration de ses résultats distributifs et de son acceptabilité publique. Je montre que le recyclage des recettes de la taxe sous la forme d'un montant forfaitaire ou d'un transfert sous condition de ressources rend le dispositif progressif,

mais entraîne des effets horizontaux, les ménages ruraux en bénéficiant moins que les ménages urbains. Mes résultats montrent que l'absence de prise en compte des effets distributifs horizontaux peut atténuer l'impact de la redistribution sur le soutien politique à la taxation du carbone.

Approches méthodologiques

Cette thèse se concentre principalement sur les impacts distributifs des politiques climatiques au niveau intra-pays ou intra-région. L'hypothèse fondamentale des trois chapitres est qu'une représentation adéquate de l'hétérogénéité des ménages est essentielle pour modéliser les aspects normatifs pertinents et l'acceptabilité sociale des politiques climatiques. Les chapitres 1 et 2 se concentrent sur les résultats des politiques climatiques mondiales avec l'hétérogénéité entre et au sein des pays (ou régions), et mobilisent des modèles d'évaluation intégrée. Le chapitre 3 se concentre sur les questions d'acceptabilité sociale intra-pays et développe un modèle de soutien public national à la taxation du carbone.

Chapitres 1 et 2

Les premier et second chapitres de cette thèse sont basés sur un modèle d'évaluation intégrée (MEI) économie-climat, le NICE (Nested Inequalities Climate Economy, [Denning et al., 2015](#)). Les MEI combinent un modèle économique avec une série de modules représentant les émissions de l'activité économique, la dynamique du climat et les conséquences du changement climatique sur l'économie. Les MEI ont récemment progressé dans l'intégration de l'hétérogénéité sociale, mais sont encore limités à cet égard ([Rao et al., 2017](#); [Emmerling and Tavoni, 2021](#)). La modélisation des inégalités au sein d'un MEI au niveau mondial, dans le cadre de cette thèse, pose un certain nombre de problèmes méthodologiques.

Premièrement, les inégalités pré-existantes présentes et futures, qui sont un déterminant important des effets distributifs des politiques climatiques, doivent être représentées de manière adéquate. L'ajustement du modèle avec des données sur les inégalités présentes pose des problèmes de couverture et de décalage micro-macro. Dans le chapitre 1, nous modélisons la distribution conjointe des revenus du capital et du travail. La représentation précise d'autres dimensions des inégalités en dehors de la consommation ou des revenus nets, telles que les inégalités patrimoine, présente des défis encore plus importants ([Flores, 2021](#)). Dans le chapitre 2, nous combinons les données macro-ajustées sur le revenu du travail de l'Organisation Internationale du Travail et les données sur l'inégalité de la richesse du Global Wealth Databook avec une approche de comptabilité nationale distributive. Dans les chapitres 1 et 2, nous utilisons des hypothèses sur la distribution du revenu pour transformer les variables d'inégalité agrégée en quantiles à intra-pays ou régions, en particulier

avec l'hypothèse d'un revenu distribué de façon log-normale. En outre, la nature prospective de la modélisation exige de prévoir l'évolution de l'hétérogénéité sociale de référence. Dans les chapitres 1 et 2, nous projetons les inégalités futures et les taux de croissance des pays sur la base d'un scénario de "trajectoires socio-économiques partagées" (*shared socioeconomic pathways*, SSP) (Rao et al., 2019). Les SSP sont des récits décrivant un panel de trajectoires socio-économiques (Riahi et al., 2017), permettant aux modélisateurs d'adopter une vision plus large des possibles futurs dans lesquels l'atténuation devra avoir lieu et d'accroître la transparence des hypothèses socio-économiques de référence. Dans le chapitre 2, nous décomposons les inégalités projetées à partir du scénario SSP choisi en une composante capital et une composante travail à l'aide d'une méthode de décomposition de l'indice de Gini.

Deuxièmement, le bilan distributif des politiques climatiques est déterminé par la distribution jointe des coûts d'atténuation des émissions et des dommages climatiques évités, à la fois entre et à l'intérieur des pays ou des régions. Les MEI utilisés dans les chapitres 1 et 2 intègrent ces distributions avec une approche de forme réduite, c'est-à-dire en réduisant la relation entre une variable socio-économique de référence et la distribution d'intérêt à un seul paramètre, à partir des données empiriques existantes. Le chapitre 1 est davantage axé sur les dommages climatiques et le chapitre 2 sur les politiques d'atténuation. Les dommages climatiques sont répartis entre les pays ou les régions à l'aide d'une fonction de dommage désagrégée, établissant un lien entre la température mondiale et les impacts climatiques locaux. Dans le chapitre 1, l'introduction de dommages affectant les facteurs de production ajoute des dommages persistants, qui induisent des impacts sur la croissance et sont hétérogènes d'une région à l'autre. Au sein des régions ou des pays, l'élasticité-revenu des dommages détermine la propension des ménages les plus pauvres à subir des dommages disproportionnés. En ce qui concerne l'atténuation, le chapitre 2 explore une série de scénarios de taxation carbone avec recyclage des recettes, qui se traduisent par une répartition différente des efforts de réduction des émissions et des transferts internationaux entre les pays. Les effets distributifs au sein des pays des politiques de taxation carbone avec recyclage des recettes sont également pris en compte, grâce à une élasticité endogène des coûts d'atténuation par rapport à la consommation et à la modélisation des effets distributifs des transferts forfaitaires.

Troisièmement, la prise en compte des effets distributifs soulève des questions normatives liées à l'évaluation du bilan des politiques climatiques. Dans une analyse coût-bénéfice, l'évaluation de politiques aux effets hétérogènes dans la population soulève la question de l'agrégation de gains et de pertes subis par différents groupes. Les premières applications de l'analyse coûts-avantages au changement climatique utilisaient le critère conventionnel de compensation (supposant implicitement que les perdants sont indemnisés). Cependant, cette méthode donne des résultats moralement contre-intuitifs en raison de la nature mondiale du problème climatique et des inégalités entre

les régions du monde, ce qui rend flagrante la nécessité d'une pondération basée sur des critères d'équité (Dennig, 2018). Dans le chapitre 1, nous calculons le coût social du carbone, qui est une agrégation des coûts et bénéfices de la politique climatique. Nous nous appuyons sur une fonction de bien-être social, qui rend explicites les jugements normatifs sur les compromis entre les groupes. À la suite d'Anthoff and Emmerling (2019), nous mettons en œuvre une fonction de bien-être social qui permet de démêler l'aversion pour l'inégalité au sein et entre les générations. En outre, dans l'évaluation du coût social du carbone, les bénéfices présents dus à l'émission d'une unité additionnelle d'émissions servent de normalisation, en permettant de convertir les unités de bien-être en unités monétaires. Ces bénéfices reflètent les gains liés au fait de ne pas encourir les coûts d'atténuation de cette unité émissions additionnelle. Nous développons une normalisation qui prend en compte la distribution des bénéfices au sein et entre toutes les régions¹ et qui est donc cohérente avec une évaluation impartiale des politiques climatiques au niveau mondial. Dans le chapitre 2, nous évaluons le bilan des politiques à l'aide d'une mesure du bien-être qui intègre l'aversion à l'inégalité au sein des générations, l'équivalent d'égalité de la répartition de la consommation (Atkinson, 1970).

Chapitre 3

Le troisième chapitre fait appel aux méthodes de théorie appliquée, c'est-à-dire qu'il utilise des outils développés dans le cadre de la théorie économique pour mettre en évidence des mécanismes analytiques dans un contexte particulier et délimité. L'élément central est un modèle de taxation optimale du carbone avec des ménages, qui est augmenté pour permettre de relier le soutien du public à la taxe carbone à ses effets redistributifs.

Le premier choix majeur en matière de modélisation est d'inclure l'hétérogénéité des ménages dans deux dimensions, en croisant les inégalités de revenus et les inégalités horizontales (urbains-ruraux). À l'instar du chapitre 2, la répartition des coûts d'atténuation au sein des pays est prise en compte par la modélisation de la régressivité de la taxation du carbone. Le chapitre 3 endogénéise davantage l'élasticité consommation de la charge fiscale de la taxe carbone présentée au chapitre 2, en faisant de l'élasticité une fonction du revenu des ménages et de la dépendance à l'égard de la consommation à forte intensité de carbone. L'existence de multiples sources d'hétérogénéité peut poser des problèmes pour l'obtention de résultats analytiques. Le choix des formes fonctionnelles et le degré de finesse de l'hétérogénéité incorporée sont donc déterminés par l'objectif de représenter de manière adéquate l'hétérogénéité pertinente tout en maintenant la tractabilité du modèle, c'est-à-dire sa facilité de manipulation et de résolution (Cherrier, 2023).

¹L'approche classique consiste à utiliser le bien-être marginal de la consommation moyenne mondiale ou celle d'une région en particulier (Fankhauser et al., 1997 ; Anthoff et al., 2019).

Deuxièmement, le modèle de taxation optimale du carbone est complété par une approche d'économie politique. L'objectif est de contraster les résultats normatifs sur la taxation optimale du carbone et les considérations sur son équité avec sa faisabilité politique. L'absence de soutien public suffisant en faveur de la taxation du carbone est un facteur clé expliquant l'échec de la mise en œuvre de la taxe carbone ou de son augmentation (Levi et al., 2020). J'utilise un modèle de vote à la majorité pour représenter le soutien public national à un niveau donné de taxation du carbone. L'objectif de l'utilisation de ce cadre n'est pas de modéliser un processus législatif spécifique, mais plutôt l'opinion publique à l'égard de la taxation du carbone. Par hypothèse, les moteurs du soutien public dans le modèle sont limités à a) un motif d'intérêt personnel déterminé par les coûts de la taxe carbone auxquels chaque ménage est confronté, et b) une préférence générale pour l'environnement (ou un soutien général à l'atténuation des émissions). Le modèle est construit de manière à reproduire deux corrélations mises en évidence dans les enquêtes d'opinions, à savoir que les ménages plus riches ont tendance à soutenir davantage la taxation du carbone tandis que les ménages vivant dans des zones moins densément peuplées ont tendance à moins la soutenir (Umit and Schaffer, 2020).

Enfin, je procède à une calibration du modèle à l'aide de données micro-économiques. Une calibration est une procédure permettant de donner un contenu à la théorie, dans laquelle le modèle théorique est utilisé comme base de lecture des données (Cooley, 1997). Le modèle que je développe produit un ensemble de paramètres qui peuvent être estimés à l'aide de données micro-économiques, et un paramètre qui ne peut pas l'être. La forme fonctionnelle de la fonction d'utilité, l'utilité de Stone-Geary, produit un système de demande qui peut être estimé, le système linéaire de dépenses (Linear Expenditure System). J'utilise la dernière enquête européenne sur le budget des ménages (HBS 2015) pour estimer les paramètres de ce système de demande ainsi que les paramètres socio-démographiques (consommation totale et part des ménages par niveau de densité) pour un ensemble de pays européens. Un dernier paramètre, la préférence pour la qualité de l'environnement, ne peut être directement estimé à partir des données de budgets des ménages et est ajusté à l'aide d'hypothèses sur la politique optimale au niveau national.

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General introduction

Climate change is an increasingly challenging issue, as greenhouse gas emissions are still on the rise globally, while the consequences of ongoing climate change are already being felt all around the world. The current global temperature increase of at least 1.1°C above pre-industrial levels has led to a rise in the frequency of extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and has resulted in impacts on human health, agricultural productivity, infrastructure and income (IPCC, 2023).

The Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change reports that “Both vulnerability to current climate extremes and historical contribution to climate change are highly heterogeneous with many of those who have least contributed to climate change to date being most vulnerable to its impacts.” (IPCC, 2023). Poorer countries and regions have been found and are expected to bear the brunt of climate change, in particular due to their location (Mendelsohn et al., 2006; Stern, 2006; Tol, 2018; Diffenbaugh and Burke, 2019). Within countries, there is growing evidence that the most disadvantaged households will be disproportionately affected, due to higher exposure and vulnerability to climate hazards and lower capacity to cope with shocks (Islam and Winkel, 2017; Hallegatte and Rozenberg, 2017; Hsiang et al., 2019). Poorer households are more likely to work in sectors more exposed to extreme weather events (Hallegatte et al., 2020), and heat stress (Park et al., 2018).

Mitigation policies also result in distributional effects. Historically, developed countries have contributed a majority of global emissions (Wei et al., 2012). However, the cost of reducing current and future emissions could be larger for poorer countries (Taconet et al., 2020). Within countries, the distribution of mitigation costs and benefits depends on the type of instrument, the emissions coverage, and potential compensation policies (Vona, 2021; Drupp et al., 2021). In the case of carbon pricing, progressive outcomes are more likely in lower-income countries and for transport policies (Ohlendorf et al., 2021).

Decarbonizing economies and managing the ongoing consequences of climate change requires designing equitable and socially acceptable climate measures. At the international level, negotiations over climate mitigation cooperation instruments

often falter over burden sharing issues. In the Paris Agreement context, national voluntary pledges and their implementation speed drive global emissions reduction pathways and their fairness (Van den Berg et al., 2020). The level of mitigation efforts chosen by decision-makers within countries also reflects the internal pressures from constituents and interest groups that governments face, which can arise from distributive conflicts (Aklin and Mildenberger, 2020). Furthermore, climate policies can result in equity-improving co-benefits, such as a double dividend from recycling of carbon pricing revenues (Karlsson et al., 2020). They also interact with other global policy goals such as poverty reduction or the Sustainable Development Goals (Fujimori et al., 2020; Soergel et al., 2021).

Hence, representing distributional effects is key to informing global climate policies and implementation at the domestic level. Integrated Assessment Models (IAM), which link climate and economic models, are an important tool for formulating global policy recommendations. In particular, IAMs are used to compute the social cost of carbon, a policy metric that aggregates the costs of emitting an additional ton of carbon, expressed in monetary terms. However, IAMs still often rely on a representative agent and lack spatial and socio-economic heterogeneity (Keppo et al., 2021; Emmerling and Tavoni, 2021). Furthermore, designing politically viable policies requires an adequate analysis of the distributive impacts of greenhouse mitigation policies within countries (Markkanen and Anger-Kraavi, 2019). Although political acceptability is often used as justification for assessing equity-efficiency trade-offs, explicit modeling of political constraints within economic frameworks remains challenging (Peng et al., 2021). Finally, achieving a better understanding of the channels of distributional impacts also requires representing different dimensions of household socio-economic heterogeneity, beyond income or consumption inequality (Rao et al., 2017).

This dissertation

This dissertation is organized around three chapters that focus on the distributional effects of climate policies, from the angle of climate change impacts (chapter 1) and mitigation policies (chapters 2 and 3). The goal is to assess the consequences of inequalities on the design of climate policies, from three perspectives. The thesis explores the role of distributional effects in the quantification of the benefits from avoided climate damages (chapter 1), the conception of an equitable global mitigation policy which is compatible with the Paris Agreement (chapter 2), and the public acceptability of carbon taxation (chapter 3). In the rest of this section, I summarize the contributions of each chapter and detail the methodological approaches.

Main contributions

The first chapter, *Climate change damages on labor and capital, inequality, and the social cost of carbon*, is a joint work with Simon Feindt. We examine the distributional impacts of climate change damages hitting the factors of production in a global integrated assessment model. Our main contribution is to integrate a novel source of social heterogeneity driving the distribution of climate impacts within regions. We model the joint distribution of capital and labor income at the sub-regional level and connect it to damages hitting the stock of capital and productive labor. A second contribution is to assess the persistence and inequality effects for a range of combinations of capital and labor damages. We find that capital and labor damages result in level and growth effects, with heterogeneity across regions. We show that labor damages and their distribution have a stronger negative impact than capital damages on income share and consumption at the bottom of the distribution. Our results highlight three determinants of the distribution of factor-specific damages: the composition of income across the distribution and magnitude of pre-existing inequality, the channel of damage, and the regressivity of each damage channel. We also contribute to the literature on the social cost of carbon by assessing how it is affected by capital and labor damages and their distribution at the sub-regional level. We disentangle the persistence and distributional channels. We show that the growth reduction effects dominate at low levels of regressivity of damages, while higher levels of regressivity trigger total consumption losses at the bottom of the distribution in the most affected regions, raising broader normative issues.

The second chapter, *Different taxes or redistribution: How to shape a just global climate policy?*, is a joint work with Aurélie Méjean and Stéphane Zuber. We assess the potential for differentiated carbon taxes versus global carbon taxes with revenue recycling to bring about a more equitable transition pathway toward a 2°C target. The main contribution is to develop a global integrated assessment model which features country granularity and within-country inequality. We include distributional effects of damages and mitigation at the country level. This enables an evaluation of the effects of global climate policies which takes into account the welfare impacts within countries. We find that with domestic recycling, differentiated taxes result in larger benefits earlier in the century for richer countries, and later for poorer countries, while a uniform tax benefits poorer countries in the nearer term. A second contribution is to study a variety of policy alternatives including international transfers and domestic recycling of the revenues from carbon taxation. We show that uniform global carbon taxation with global lump-sum recycling would bring the most welfare gains and global reductions in inequality in the first half of the century, but would entail important inter-governmental transfers. A third contribution is to test a policy inspired by proposals for a Loss and Damage fund, in which a small portion of global tax revenues

is targeted towards low-income countries vulnerable to climate change. We show that this could bring significant welfare improvements with limited international transfers.

The third chapter, *Public acceptability of carbon taxation: a model of political support with income and urban-rural inequality*, assesses how the distributional effects of carbon taxation can limit its political feasibility. The chapter contributes to the theory literature on the political economy of carbon taxation. The main novelty is the introduction of urban-rural heterogeneity in a majority voting framework with income inequality. Heterogeneity within income groups in the cost of carbon is achieved by modeling households that differ in the magnitude of constrained carbon-intensive consumption, reflecting their higher energy needs for transport and housing. I show that urban-rural inequality results in lower political support for the carbon tax among rural households than among urban households at the same income level. A second contribution is to characterize the level of carbon tax which garners public support. I derive analytical conditions under which this acceptable carbon tax is lower than the optimal tax, set by a social planner taking into account both vertical and horizontal equity issues. The numerical exercise shows that the majority voting tax is lower than the optimal tax in every country included, even under the assumption that the social planner and households share the same environmental preference. A third contribution is to assess the role of recycling the revenues from carbon taxation in improving its distributive outcomes and political feasibility. I find that recycling the proceedings from the tax as a lump-sum or means-tested transfer makes the tax scheme progressive, but results in horizontal effects with rural households benefiting less than urban households. My results highlight how the failure to address horizontal distributive effects can lessen the impact of redistribution on political support for carbon taxation.

Methodological approaches

The main focus of this thesis is on distributional impacts of climate policies at the subnational or subregional level. The core assumption behind all three chapters is that an adequate representation of heterogeneity is key to modeling relevant normative aspects and political acceptability of climate policies. Chapter 1 and chapter 2 focus on the outcomes of global climate policies with heterogeneity between and within countries (or regions), and mobilizes Integrated Assessment Models (IAMs). Chapter 3 concentrates on questions of political acceptability within countries, and develops a model of domestic public support for carbon taxation.

Chapters 1 and 2

The first and second chapters of this thesis are based on an economy-climate IAM, the NICE (Nested Inequalities Climate Economy, [Dennig et al., 2015](#)). IAMs combine an

economic model with a series of modules representing emissions from economic activity, climate dynamics and the consequences of climate change on the economy. IAMs have made recent progress in incorporating social heterogeneity, but are still limited in this regard (Rao et al., 2017; Emmerling and Tavoni, 2021). Modeling inequalities within a global IAM posed a number of methodological issues in the context of this thesis.

First, current and future baseline inequalities, which are an important determinant of the distributional effects of climate policies, need to be adequately represented. Fitting the model with data on current inequalities poses coverage and micro-macro discrepancy issues. In chapter 1, we model the joint distribution of capital and labor income inequality. Accurately representing other dimensions of inequality outside of consumption or net income inequality, such as wealth inequality, presents even greater challenges (Flores, 2021). In chapter 2, we combine macro-adjusted data on labor income from the International Labour Organisation and Wealth inequality data from the Global Wealth Databook with a Distributional National Accounts approach. In both chapters 1 and 2, we use distributional assumptions over income to transform aggregate inequality variables into quantiles within countries or regions, in particular with the assumption of log-normally distributed income. In addition, the forward-looking nature of the modeling requires forecasting the evolution of baseline social heterogeneity. In chapter 1 and 2, we project future inequalities and country growth rates based on a “shared socioeconomic pathways” (SSP) scenario (Rao et al., 2019). SSPs are narratives describing alternative socioeconomic trends (Riahi et al., 2017), enabling modelers to take a broader view on the possible worlds in which mitigation must take place and to increase transparency over baseline socioeconomic assumptions. In chapter 2, we further decompose projected inequalities from the chosen SSP scenario into a capital and labor component with a Gini decomposition method.

Second, the distributional outcomes of climate policies are determined by the combined distributions of mitigation costs and avoided climate damages, both between and within countries or regions. The IAMs used in chapters 1 and 2 incorporate these distributions with a reduced form approach, i.e. reducing the relationship between a baseline socioeconomic variable and the particular distribution to a single parameter based on existing empirical evidence. Chapter 1 has a stronger focus on climate damages and chapter 2 on mitigation policies. Climate damages are distributed across countries or regions with a disaggregated damage function, relating global temperature to local climate impacts. In chapter 1, the introduction of damages affecting the factors of production adds persistent damages resulting in growth impacts that are heterogeneous across regions. Within regions or countries, the income elasticity of damages determines how disproportionately damages fall on the poorest households. On the mitigation side, chapter 2 explores a range of carbon tax and revenue recycling scenarios, resulting in different burden sharing and international transfers across countries.

The distributional effects of tax and revenue recycling schemes within countries is also accounted for, through an endogenous consumption-elasticity of mitigation costs and modeling of the distributive outcomes of lump-sum rebates.

Third, the inclusion of distributional effects raises normative issues related to the evaluation of climate policies outcomes. In a cost-benefit analysis, evaluating policies with heterogeneous outcomes raises the issue of aggregation of gains and loss that fall on different groups. The early applications of cost-benefit analysis to climate change used the conventional compensation criterion (implicitly assuming that losers are compensated). However, this produced morally counter-intuitive results because of the global nature of the climate issue and the inequalities between regions of the world, making the need to use equity weighting more blatant (Dennig, 2018). In chapter 1, we compute the social cost of carbon, an aggregation of the costs and benefits of a climate policy. We rely on a social welfare function, which makes explicit the normative judgments over trade-offs between groups. Following Anthoff and Emmerling (2019), we implement a social welfare function which allows for disentangling of the inequality aversion within and across generations. Furthermore, in the evaluation of the social cost of carbon the current benefits of emitting a marginal unit of emissions serve as a normalization, converting welfare units into monetary units. These benefits capture the gains from not incurring the costs of mitigating the marginal emissions. We develop a normalization which takes into account the distribution of the benefits across and within all regions² and which is therefore consistent with a globally impartial evaluation of climate policies. In chapter 2, we evaluate policy outcomes using a measure of welfare that incorporates within generation inequality aversion, equally distributed equivalent consumption (Atkinson, 1970).

Chapter 3

The third chapter features applied theory, meaning that it uses tools developed within economic theory to highlight analytical mechanisms in a particular and delimited context. The core is a household optimal carbon taxation model, which is augmented to relate public support for carbon taxes to their distributional impacts.

The first key modeling choice is to include household heterogeneity in two dimensions, intersecting income and horizontal (urban-rural) inequalities. As in chapter 2, the distribution of mitigation costs within countries is captured through modeling the regressivity of carbon taxation. Chapter 3 further endogenizes the consumption-elasticity of the tax burden featured in chapter 2, making the elasticity a function of household income and of dependence on carbon-intensive consumption. Having multiple sources of heterogeneity can produce challenges in deriving analytical results. The choice of functional forms and coarseness of the incorporated heterogeneity are

²The classic approach is to use marginal welfare of world average consumption or in one chosen region (Fankhauser et al., 1997; Anthoff and Emmerling, 2019).

thus driven by the objective of adequately representing the relevant heterogeneity while keeping the model tractable, i.e. easier to manipulate and solve (Cherrier, 2023).

Second, the optimal carbon taxation model is augmented with a political economy approach. The objective is to contrast the normative results on optimal carbon taxation and equity considerations with the political feasibility of the policy. Lack of sufficient public support for carbon taxation is a key factor explaining the failure to implement carbon tax or to raise them (Levi et al., 2020). I use a majority voting framework to represent domestic public support for a given level of carbon taxation. The goal of using this framework is not to model a specific legislative process, but rather public attitudes, or domestic support, towards carbon taxation. By assumption, the drivers of public support in the model are restricted to a) a self-interest motive driven by the costs of the carbon taxation faced by each household, and b) general preference for the environment (or general support for mitigating emissions). The model is built to reproduce two correlations highlighted in surveys on public attitudes, that richer households tend to have higher support for carbon taxation, and that households living in less densely populated areas tend to have lower support for carbon taxation (Umit and Schaffer, 2020).

Finally, I perform a calibration of the model with micro data. A calibration is a procedure to give content to the theory, in which the theoretical model is used as a basis to map into the data (Cooley, 1997). The model I develop yields a set of parameters that can be estimated with micro data, and one parameter that cannot. The functional form of the utility function, Stone-Geary utility, yields a demand system that can be estimated, the Linear Expenditure System. I use the latest available European Household Budget Survey (HBS 2015) to estimate the parameters of this demand system as well as the socio-demographic parameters (total consumption and share of households by density level) for a set of European countries. A final parameter, the environmental quality preference parameter, cannot be directly estimated from micro consumption data and is instead fitted using assumptions on the optimal policy path at the country level.

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Chapter 1

Climate change damages on labor and capital, inequality, and the social cost of carbon

Climate change damages on labor and capital, inequality, and the social cost of carbon

Marie Young-Brun¹ and Simon Feindt²

Abstract

Climate change is poised to generate economic damages through many channels, in particular through shocks to the factors of production. We use an integrated assessment model with sub-regional inequality and introduce direct impacts on capital and productive labor stocks, resulting in endogenously persistent damages. We model and calibrate the joint distribution of labor and capital income, to capture the role played by income composition heterogeneity in within-region inequality. When taking the non-proportionality of damages into account, global inequality increases with labor productivity and capital damages. The share of labor damages hitting labor and the regressivity of labor damages are key determinants of outcomes at the bottom of the distribution. Having damages fall on the factors of production rather than on output directly increases the social cost of carbon, through both persistence and distributional effects.

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1 Introduction

The social cost of carbon captures the welfare loss from emitting an additional ton of carbon and is used to guide climate policy. Because of the delay between emissions and climate change, climate policy appears as a primarily inter-generational issue, a trade-off between the wealth of the present and future generations. Heated debates about the appropriate discount rate (with [Stern \(2007\)](#) and [Nordhaus \(2007\)](#) as headliners) reflect the focus on the inter-temporal dimension. Yet, there is also significant spatial and socioeconomic heterogeneity in climate change impacts. For instance, heatwaves are prone to hit warmer and more humid regions, and to reduce the productivity and health of heat-exposed workers (e.g. [Kjellstrom et al. \(2009\)](#)). By and large, vulnerability and exposure are determined by "non-climatic factors and multidimensional inequalities often produced by uneven development processes." (IPCC Working Group II, [Field et al. \(2014\)](#)). Heterogeneity in damages results in impacts of varying durations and interacts with pre-existing social heterogeneity. A proper evaluation of climate policy requires taking these discrepancies into account.

This paper studies the impacts of differential climate damages on incomes, inequality, and the social cost of carbon, using an Integrated Assessment Model (IAM). We disentangle damages on the factors of production and analyze their joint distributional and persistent effects. We improve the representation of social heterogeneity through decomposing economic inequality by income source. To do so, we model the joint distribution of capital and labor income and evaluate how it interacts with damages hitting the stocks of capital and labor productivity directly. We investigate the relative importance of these two impact channels for the distributional outcomes of climate policy, contrasting their effect on the duration of damages with their direct distributive effect.

Our paper is not the first to use an IAM to explore the distributional consequences of climate policy. While IAMs have integrated equity weights ([Anthoff et al., 2009](#)), the representation of spatial and social heterogeneity is still limited, and in particular impacts on the poor ([Rao et al., 2017](#)). Several significant improvements have been made recently. Both process-based and cost-benefit IAMs have introduced sub-regional inequality, either through cross-country inequality ([Anthoff and Emmerling, 2019](#); [Taconet et al., 2020](#); [Gazzotti et al., 2021](#)) or through within-region or within-country distributions ([Dennig et al., 2015](#); [Budolfson et al., 2021](#); [Soergel et al., 2021](#); [Malafray and Brinca, 2022](#)). Climate change is found likely to increase inequality ([Taconet et al., 2020](#); [Gazzotti et al., 2021](#)) and to have significant adverse effects on the poorest ([Dennig et al., 2015](#); [Soergel et al., 2021](#)), albeit possibly alleviated by the redistribution of the proceeds from a carbon tax ([Budolfson et al., 2021](#); [Soergel et al., 2021](#)). Additionally, cost-benefit IAMs show that introducing inequality considerations can lead to more stringent policy recommendations, captured by an increase in the SCC ([Dennig et al., 2015](#); [Anthoff and Emmerling, 2019](#)).

In this paper, we build on the Nested Inequalities Climate Economy (NICE) model developed by [Dennig et al. \(2015\)](#) based on the RICE¹ model ([Nordhaus, 2010](#)). Previous efforts to capture inequality in IAMs rely on aggregate indices or distributions of net income or consumption, except for [Malafry and Brinca \(2022\)](#) who use information on the global wealth Gini index. Our contribution is to introduce a novel source of social heterogeneity by modeling and calibrating jointly labor and capital gross income distributions, as well as consumption distributions.

Representing these sources of inequality is key to better incorporate the growing evidence on the distributional impacts of climate change, especially on the poor ([Hallegatte and Rozenberg, 2017](#); [Hsiang et al., 2019](#)). More destitute households tend to have a higher reliance on labor earnings with greater exposure to unstable weather conditions ([Park et al., 2018](#); [Hallegatte et al., 2020](#); [Parsons et al., 2021](#)), and on more vulnerable asset portfolios ([Hallegatte et al., 2020](#)). This makes them more prone to suffer from consequential income losses and to fall into poverty traps ([Carter et al., 2007](#)). The high concentration of wealth and assets at the top of the distribution also implies that the poorest often have little leeway to smooth consumption in case of a shock and that they are more dependent upon wages. We incorporate this dependence through income composition inequalities—how the composition of income in two sources, such as capital and labor income, varies across the income distribution ([Ranaldi, 2021](#))—and couple it to damages on the factors of production.

To model channel-specific damages, we build upon a second strand of IAM literature, which introduces climate shocks to different channels at the aggregate level and studies their subsequent persistence and growth effects. [Kopp et al. \(2012\)](#); [Dietz and Stern \(2015\)](#) and [Moore and Diaz \(2015\)](#) investigate the role of impacts on the capital stock or on total factor productivity. [Estrada et al. \(2015\)](#) analyze implicit persistence in IAMs and show that implied impact durations are not consistent with the available evidence on general output shocks. [Piontek et al. \(2019\)](#) study the impact and half-life of damages on a large variety of input channels and discuss possible implications for the labor share. [Kikstra et al. \(2021\)](#) introduce empirically estimated partial damage persistence through direct impacts on GDP growth and find strong effects on future GDP per capita and the social cost of carbon. We build on the insights of this strand of literature and adopt labor and capital damages based on [Kopp et al. \(2012\)](#) and [Piontek et al. \(2019\)](#)’s formulations.

We thereby generate an improved representation of heterogeneous income and damages in an IAM. We find that including labor and capital damages leads to persistent damages and growth effects, with heterogeneity across countries. Our results show that the allocation of the burden of channel-specific damages across the income distribution has strong impacts on inequality and on the livelihoods of the future poor. With slightly regressive income and labor damages, having half of the damages fall on

¹RICE is the Regional Integrated Climate-Economy model.

the labor channel and half on the capital channel results in an increase in the global Gini, compared to the baseline with only direct output damages, of 5% in 2050 and 15% in 2100. We also show that labor damages and their distribution have a stronger negative impact than capital damages on income share and consumption at the bottom of the distribution. The growth and distributional effects of factor-specific damages result in an increased social cost of carbon (SCC). Compared to a baseline in which all damages fall directly on output, having half of the damages fall on capital and half on labor increases the SCC 3.4 times if damages are proportional to income, and at least 4 times if the burden fall disproportionately on the poorest households. We further disentangle the persistence and distributional channels of impacts on the SCC and explore the role of normative parameters.

The rest of this paper is structured as follows. Section 3 details the model and the calibration of factor income and consumption inequalities. In section 4 we present aggregate effects from the introduction of capital and labor damages, before turning to distributional outcomes and the impact on the SCC. We discuss our results in section 4 and conclude in section 5.

2 Methods

In this section, we present the key components of the Integrated Assessment Model we use. We start by introducing the macroeconomic framework, a growth model à la Solow-Swan. We then turn to the breakdown of aggregate income into capital and labor components and detail the distribution of factor-income within regions. Next, we describe our damage specification, including the newly implemented factor-specific damages, as well as their distribution. Lastly, we detail the analytical formulation for the social cost of carbon (SCC).

2.1 Regional output and consumption

As in RICE (Nordhaus, 2014), gross output at time t in region r is modelled through a Cobb-Douglas production function occurs at the regional level

$$Y_{rt}^G = A_{rt} K_{rt}^\alpha L_{rt}^{1-\alpha} \quad (2.1.1)$$

with A exogenous total factor productivity, K the stock of capital, L labor and $\alpha \in [0, 1]$ output elasticity of capital. Capital stock and productive labor are shared at the quintile level, and aggregated for production and accumulation at the regional level. Initial capital and output levels are calibrated using Penn World Table data. The trajectory of total factor productivity is then calibrated to match the "Middle of the road" Shared Socioeconomic Pathways (SSP) scenario. Resulting baseline output per capita and growth are shown in Figure A3.

Damages and abatement costs are subtracted from gross output, resulting in net output

$$Y_{rt}^N = (1 - \Lambda_{rt})(1 - D_{rt}^G)Y_{rt}^G \quad (2.1.2)$$

with D_{rt}^G damages as a share of gross output and Λ_{rt} abatement costs as a share of net-of-damages output. In the rest of the paper, we will focus on inequality outcomes and the SCC along a "Business-as-usual" path, which implies that $\Lambda_{rt} = 0, \forall r$. Net output is either consumed or invested in capital stock with a fixed savings rate s .² Capital accumulates at the regional level, with a yearly depreciation rate of δ

$$K_{r,t+1} = (1 - \delta)K_{r,t} + sY_{r,t}^N. \quad (2.1.3)$$

Regional aggregate consumption is then given by

$$C_{rt} = (1 - s)Y_{rt}^N. \quad (2.1.4)$$

Population $P_{r,t}$ and labor $L_{r,t}$ are equal in the first period but can differ when shocks to the labor stock occur. Population grows according to UN population projections (United Nations, 2019).

2.2 Factor income distribution

Next, we relate total net output to the distribution of income across households, splitting the population of each region into quintiles. To avoid the pitfalls of macro-micro discrepancies that arise when coupling aggregate outcomes to household level evidence, we build on the concepts and methods used in the construction of Distributional National Accounts (DINA)³ (Alvaredo et al., 2016; Piketty et al., 2017).

We equate net output to pretax regional income. In turn, net income is split between a capital income component Y^K and labor income component Y^L . With a Cobb-Douglas production function, output elasticity α also captures factor shares:

$$Y_{rt}^K = \alpha Y_{rt}^N \quad (2.2.1)$$

$$Y_{rt}^L = (1 - \alpha)Y_{rt}^N \quad (2.2.2)$$

Factor income in each region is shared across quintiles. The distribution of factor income reflects an implicit distribution of wealth, returns and wages. Denoting y_{rqt}^K (resp. y_{rqt}^L) capital (labor) income of quintile q and $sh_{rqt}^{Y^K}$ (resp. $sh_{rqt}^{Y^L}$) quintile q 's share in capital income (resp. labor income), pretax income of quintile q writes

$$y_{rqt} = y_{rqt}^K + y_{rqt}^L = sh_{rqt}^{Y^K} Y_{rqt}^K + sh_{rqt}^{Y^L} Y_{rqt}^L \quad (2.2.3)$$

$$= (\alpha sh_{rqt}^{Y^K} + (1 - \alpha)sh_{rqt}^{Y^L}) Y_{rqt}^N \quad (2.2.4)$$

²We discuss this assumption in Section 4.

³In particular, the DINA methodology aims at reconciling inequality measurement and national accounting (Alvaredo et al., 2016).

It follows that quintile q 's share in pretax regional income is

$$sh_{rqt}^Y = \frac{y_{rqt}}{Y_{rqt}^N} = \alpha sh_{rqt}^{Y^K} + (1 - \alpha) sh_{rqt}^{Y^L} \quad (2.2.5)$$

We calibrate capital income distribution using wealth distribution data from the Credit Suisse Global Wealth databooks (Davies et al., 2017). The Gini index is converted into wealth quintiles with log-normal distributions. We assume that capital income and wealth are identically distributed. Given the evidence for higher returns at the top of the wealth distribution (Benhabib and Bisin, 2018; Garbinti et al., 2021), we expect our calibration is a lower bound of capital income inequality. We combine the resulting capital income distribution with data on labor income distribution at the decile level from the International Labour Organization (Gomis, 2019). Under the assumptions of equal ranking between labor and capital income distribution and given the fixed aggregate labor share $(1 - \alpha)$, we retrieve total income distributions for the twelve regions in RICE. We take this approach rather than relying on available factor income micro-data because it is likely that a significant proportion of national income is missing from micro sources (see e.g. Flores (2021)). Figure A1 displays the input data for labor and capital income distribution.

To account for the future evolution of the income distribution, we follow the inequality projection of the "Middle of the road" SSP scenario, SSP2 (Rao et al., 2019). In this scenario, historical trends are continued. Income inequality is assumed to persist or slowly improve, and development trends remain heterogeneous (Fricko et al., 2017).

These trends describe the evolution of total income inequality, so we use the Gini decomposition method introduced by Rao (1969) and Kakwani (1977) to project inequality by income type. With equal ranking between income components and total income, Gini index for total income G_Y is given by the sum of the Gini coefficients for each income component (G_i) weighted with the share of this component in total income (sh_i^Y). With total income being the sum of capital and labor income and the factor share being equal to the respective output elasticity (as in equation 2.2.1 and 2.2.2), the change in the total income Gini is given by

$$\frac{\Delta G_Y}{G_Y(t)} = \frac{\Delta(\sum_{i=1}^n sh_i^Y G_i)}{G_Y(t)} = \frac{\alpha \Delta G_K + (1 - \alpha) \Delta G_L}{G_Y(t)} \quad (2.2.6)$$

The contribution of an income component to the change in the total income Gini is

$$sh_i^{\Delta G_Y} = \frac{\frac{sh_i^Y \Delta G_i}{G_Y(t)}}{\frac{d \log(G_Y)}{dt}} = \frac{sh_i^Y \Delta G_i}{\Delta G_Y} \quad (2.2.7)$$

We decompose changes of the total income Gini by assuming that $sh_i^{\Delta G_Y}$ is equal to its factor income share sh_i^Y . The absolute change of an income channel Gini is then

the absolute change of the total income Gini ($\Delta G_i = \Delta G_Y$). The resulting evolution of capital and labor income shares in each region are depicted in [Figure A2](#). Consistent with evidence on factor income distribution, our calibration features a more unequal distribution of capital income than labor income in most regions.

Income is more unequally distributed than consumption (e.g. [World Bank \(2016\)](#)) because of consumption smoothing, redistribution and consumption of public goods, etc. To capture this expected discrepancy, we estimate below an elasticity of consumption share with respect to income share for each region from our calibrated income shares and World Income Inequality Database consumption shares for 2019.

2.3 Aggregate damages

Damages from climate change on gross output result from a temperature increase above the pre-industrial level. We model the global temperature response with the Finite Amplitude Impulse Response model (FaIR, v2.0.0) developed by [Leach et al. \(2021\)](#). The FaIR model is a simplified climate model estimating radiative forcing and temperature increase from factors such as greenhouse gas emissions (e.g. CO_2 , CH_4), land use, and others. The main advantage of the FaIR model compared to the RICE climate model previously used in the NICE model is the state dependency of the model. The FaIR model represents state dependency through feedback loops in the carbon cycle. Feedback loop implementation is necessary to obtain radiative forcing estimates close to those of more complex Earth system models. We use the Julia implementation from [Errickson et al. \(2022\)](#) based on the default model by [Leach et al. \(2021\)](#). As in [Errickson et al. \(2022\)](#), we assume that non- CO_2 emissions follow the SSP2-45 scenario. Recent assessments of the SCC deploy the FaIR model to estimate the global temperature increase (e.g. [Rennert et al. \(2022\)](#); [Hänsel et al. \(2020\)](#); [Rode et al. \(2021\)](#); [Barrage and Nordhaus \(2023\)](#)).

Damages from the resulting global temperature increase are assumed to follow a quadratic function with temperature

$$D_{rt} = \psi_{1r}(T_t - \bar{T}_{1986-2005}) + \psi_{2r}(T_t - \bar{T}_{1986-2005})^2 \quad (2.3.1)$$

with ψ_{1r} and ψ_{2r} the region-specific damage parameters, T_t the temperature anomaly with respect to pre-industrial levels, and $\bar{T}_{1986-2005}$ the average temperature anomaly of the period 1986 to 2005 to pre-industrial levels. We calibrate ψ_{1r} and ψ_{2r} based on the regional COACCH damage functions and employ the results from the 50th quantile regression of a quadratic fit with optimal adaptation to sea level rise for the REMIND model ([Van Der Wijst et al., 2023](#)). Due to differences in the regional aggregation between the REMIND and the NICE model, we map the regional damage estimates to each country within a REMIND region. We then estimate new regional coefficients for the NICE regions based on a GDP-weighted regression.

2.4 Capital and labor damages

In Nordhaus (2014) and Dennig et al. (2015), damages fall directly on aggregate output. Although this formulation is meant to capture the overall impact of the myriad of ways in which climate change manifests, it misses some of the endogenous economic responses. In the RICE and the NICE model, production is modeled with a Cobb-Douglas function taking labor and capital inputs. We introduce impacts hitting directly these factors of production. We then use a National Distributional Accounts type framework to relate the aggregate damages to their impacts on earnings.

First, we consider that the productivity of labor and the number of hours worked are adversely affected by climate change. Increases in temperatures and heat stress can lead to a reduction in productivity in exposed sectors and an overall increase in absenteeism, resulting in decreased output (Heal and Park, 2020; Dasgupta et al., 2021; Parsons et al., 2021; Somanathan et al., 2021; Acevedo et al., 2020). Impacts on labor productivity can be long-lasting, for instance through reductions in educational outcomes (Park et al., 2021) and health (Hallegatte et al., 2020).

Second, climate change also impacts the capital stock. The increased frequency and magnitude of extreme events, such as, for instance cyclones, floods, landslides, or fires, leads to more damages on physical capital such as plants or infrastructure (?). Productive assets owned by households such as plantations, livestock, or land can also be damaged by extreme events (e.g. Carter et al. (2007)) or by slow onset changes such as sea level rise (Islam and Winkel, 2017).

We capture the aggregate effect of damages on labor and capital by splitting up output damages. Following Kopp et al. (2012) and Piontek et al. (2019), we model capital, labor, and output damages to ensure the overall impact on output at time t matches the output damages in the absence of factor-specific damages. We add damages to productive labor, leaving population unchanged, to the formulation used in Kopp et al. (2012). In this way, output net of damages

$$(1 - D_{rt}^G) A_{rt} L_{rt}^{1-\alpha} K_{rt}^\alpha \quad (2.4.1)$$

can be rewritten as

$$(1 - D_{rt}^G)^{f_Y} A_{rt} \left((1 - D_{rt}^G)^{\frac{f_L}{1-\alpha}} L_{rt} \right)^{1-\alpha} \left((1 - D_{rt}^G)^{\frac{f_K}{\alpha}} K_{rt} \right)^\alpha \quad (2.4.2)$$

with f_Y , f_K , and f_L the share of damages falling respectively on output, capital, and labor, and $f_Y + f_L + f_K = 1$. The direct impact on output is captured by $(1 - D_{rt}^G)^{f_Y} Y_{rt}^G$, and post-damage stocks of capital and productive labor write

$$K_{rt}^N = (1 - D_{rt}^G)^{\frac{f_K}{\alpha}} K_{rt} \quad (2.4.3)$$

$$L_{rt}^N = (1 - D_{rt}^G)^{\frac{f_L}{1-\alpha}} L_{rt}. \quad (2.4.4)$$

Damages on capital and labor stocks result in persistent impacts through two channels. First, stock damages produce a direct impact, as output remains diminished while the productive stocks have not recovered their counterfactual level. Full persistence of labor shocks would be an extreme assumption. Instead, we control the dissipative dynamic of the shocks through a persistence parameter λ , between 0 (full and instantaneous dissipation of the shock) and 1 (no dissipation of the shock). This specification is close to that of [Piontek et al. \(2019\)](#) for a one-time shock and exogenous labor productivity growth, adapted to our specification with repeated shocks. Given that labor grows at the same rate as population, we get:

$$L_{rt} = (1 - \lambda)P_{rt} + \lambda \frac{P_{rt}}{P_{r,t-1}} L_{r,t-1}^N. \quad (2.4.5)$$

When $\lambda = 0$, all labor damages from the previous period dissipate, and labor is equal to population in the region. When $\lambda = 1$, the shock fully persists and the rate of population increase is applied to the region's net-of-damage labor from the previous period.

The persistence of capital damages depends on the rate of depreciation, which determines how fast new investment replaces the capital stock. With a depreciation rate of 100% over a decade, capital damages have no direct persistent impact in a model with ten-year time-steps, as the next period capital stock is entirely replaced by investment. In a neo-classical growth framework, labor damages tend to be more persistent than capital damages ([Piontek et al., 2019](#)).

Second, lower output begets lower investment in capital stock which causes an indirect persistent impact. Indirect persistence increases with the depreciation rate—contrary to direct persistence—and with the output elasticity of capital ([Estrada et al., 2015](#)). This indirect impact occurs even in the absence of any channel-specific damage. It plays a role in compounding the direct output impacts, albeit limited.

We recover persistent damages as a share of gross output, $D_{rt}^{G,P}$, by comparing gross output and a counterfactual with no channel-specific impacts, or "unpersistent" output. This counterfactual, $Y_{rt}^{G,cf}$, corresponds to gross output in the case where all damages fall directly on output, all other parameters in the model being equal, i.e. $Y_{rt|f_Y=1}^G$. In turn, persistent damage is

$$D_{rt}^{G,P} = \frac{Y_{rt}^{G,cf} - Y_{rt}^G}{Y_{rt}^{G,cf}} \quad (2.4.6)$$

This metric of persistent damages captures direct persistence and indirect persistence from capital and labor damages, but not persistence from damages that fall directly on output. As a result, this metric captures the additional persistence resulting from channel-specific damages.

2.5 Distribution of damages

Damages are allocated between labor productivity, capital stock, and direct output impacts according to damages shares f_i , $i \in \{L, K, Y\}$. These damages are then distributed according to labor income, capital income, and total income respectively, with an income elasticity parameter ξ reflecting how proportional damages are with respect to the specific income distribution. ξ_i equivalently captures the income elasticity of damages in absolute terms, and the elasticity between the quintile's share in income of type i , $sh_q^{Y_i}$ and the quintile's share in damages of type i , $sh_q^{D_i}$, i.e.

$$\xi_i = \frac{\partial \ln d_q^i}{\partial \ln y_q^i} = \frac{\partial \ln sh_q^{D_i}}{\partial \ln sh_q^{Y_i}}, \quad (2.5.1)$$

with $i \in \{L, K, Y\}$ and d_q^i the damages of type i hitting quintile q . An income elasticity ξ of 1 implies that damages fall proportionally to income shares. $\xi = 0$ means that each quintile bears a fifth of the damages, i.e. that damages are independent of the income share.

In turn, a quintile's share in total damages, adding up damages from labor, capital, and directly on output, is

$$sh_q^D = \sum_{i \in \{Y, K, L\}} f_i sh_q^{D_i} \quad (2.5.2)$$

$$= \sum_{i \in \{Y, K, L\}} f_i \frac{(sh_q^{Y_i})^{\xi_i}}{\sum_{j=1}^5 (sh_j^{Y_i})^{\xi_i}}. \quad (2.5.3)$$

The progressivity (or regressivity) of damages overall will stem from the pre-damage income distributions, the composition of damages across channels (f_L , f_K , f_Y) and the income elasticity of each damage type.

The literature on the distribution of climate impacts cannot provide a central estimate of the income elasticities of labor and capital damages, but it can help outline a plausible range of values. Disadvantaged groups are found to suffer *disproportionately* from climate change because of i) higher exposure to climate hazards, ii) higher vulnerability, and iii) lower ability to cope with adverse impacts (Islam and Winkel, 2017; Hallegatte and Rozenberg, 2017).

Evidence for damage disproportionality indicates that the income elasticity of climate damages is likely below 1, but a more detailed description of the distribution of damages is needed to pinpoint its value more precisely. In particular, whether the poorest bear a larger damage share in *absolute value* is key to restricting the range of plausible values for the income elasticities of damages.

The poorest, in particular in hot countries, are more likely to work in sectors with higher exposure to heat stress (Park et al., 2018) and in which the hours worked and

productivity losses are largest (Graff Zivin and Neidell, 2014). They are also less likely to have access to a variety of income sources, making them more vulnerable to natural disasters (Hallegatte et al., 2020). However, significant losses from the perspective of the poorest households do not necessarily translate into the largest share at the national and regional scale, because the income of the poor makes up only a small fraction of aggregate income (Hallegatte et al., 2020). For example, a case study of heat stress-related income losses in Australia showed that the most expensive productivity loss in absolute value corresponded to the higher-paid occupations, although these were not the most exposed (Zander et al., 2015). It is therefore likely that the income elasticity of labor damages is significantly larger than zero.

Turning to capital (or asset) damages, most of the available evidence concerns physical capital impacts, mainly through studies of natural disasters. To the best of our knowledge, very little is known about how climate change will impact financial assets. Natural disasters are more prone to strike the assets of the poor because of higher exposure and vulnerability. Indeed, asset composition differs across the wealth distribution: the portfolio of the poorer tends to be less diversified and more vulnerable (e.g. housing and livestock rather than financial assets) (Hallegatte et al., 2020). Insurance take-up also tends to be lower (e.g., Kousky, 2019). In the rest of the paper, we use income elasticities between 0.5 and 1.

Finally, we recover the share of quintile q in net regional income, by combining income and damages distributions. We focus on a "Business-as-Usual" case, in which there is no abatement. The share of quintile q in net regional income then writes

$$\text{sh}_{rqt}^{YN} = \frac{y_{rqt}^N}{Y_{rt}^N} \quad (2.5.4)$$

$$= \frac{(\text{sh}_{rqt}^Y - \text{sh}_{rqt}^D D_{rt}^G) Y_{rt}^G}{(1 - D_{rt}^G) Y_{rt}^G} \quad (2.5.5)$$

Put differently, the net income share captures the gap between equally distributed income and damages, and their actual joint distribution.

In turn, re-scaling the net income share sh_{rqt}^{YN} with the income-to-consumption elasticity β_r yields the share of quintile q in regional consumption

$$\text{sh}_{rqt}^C = \frac{(\text{sh}_{rqt}^{YN})^{\beta_r}}{\sum_q (\text{sh}_{rqt}^{YN})^{\beta_r}}. \quad (2.5.6)$$

We estimate the elasticity β_r based on a log-log model with income shares as calculated in eq. (2.2.5) and country-level consumption shares from the latest release of the World Income Inequality Database (WIID) (UNU-WIDER, 2022) aggregated to regional

quintiles.⁴ Climate damages thus impact final consumption in two ways: by reducing the level of aggregate regional consumption, and by affecting the share of each quintile in regional consumption.

2.6 The social cost of carbon

The social cost of carbon (SCC) represents the present loss of consumption that is as costly as the discounted stream of future consumption losses due to the emission of an additional ton of carbon. We do not compute the SCC along the model's optimal emissions pathway, but instead along an emissions trajectory calibrated on the "Middle of the road" Shared Socio-economic Pathway (SSP2). SSP2 continues historical trends in socio-economic variables. This has two consequences. First, it allows us to compare values of the SCC on the same baseline emissions pathway when varying the main parameters of our model. This would not be possible with an emissions trajectory achieved through optimization, because a change in parameters would also lead to a change in the emissions pathways. Second, the SCC values computed along SSP2 trajectories will not be equal to the optimal carbon price⁵. We calibrate the model using a descriptive approach and perform a normative evaluation of damages on labor and capital.

To evaluate consumption losses, we use an utilitarian social welfare function (SWF) in which welfare is derived from consumption. The SWF features two key normative parameters: η captures aversion to inequality (inter- and intra-generational) and ρ is the pure rate of time preference.

We first focus on welfare assuming a global representative consumer. With $c_t = \frac{C_t}{P_t}$ world consumption per capita at time t , the discounted utilitarian global SWF is

$$W^G = \sum_{t=0}^T \frac{P_t}{(1+\rho)^t} \frac{c_t^{1-\eta}}{(1-\eta)} \quad (2.6.1)$$

The global SCC is then the ratio between the marginal impact of one additional ton of carbon on global welfare and the welfare cost of losing one unit of global consumption in the first period (Nordhaus, 2014),

$$SCC_G = \frac{\sum_{t=0}^T \Delta C_t \frac{\partial W^G}{\partial C_t}}{\frac{\partial W^G}{\partial C_0}}, \quad (2.6.2)$$

⁴We use consumption data from 2019 if available, otherwise we use data from the closest year to 2019. In case no consumption data is available, we take net income data (41 out of 190 countries) or income data labelled "net/gross" (12 countries).

⁵The SCC is equal to the optimal carbon price if marginal damages are measured along the optimal emissions trajectory.

with ΔC_t the change in global consumption due to an additional ton of carbon. The global SCC uses aggregate consumption at the world level, and thus cannot reflect inter- and sub-regional impacts of climate change.

As our analysis accounts for the distribution of impacts across regions and quintiles, we turn to a welfare function with regional quintile consumption to compute the SCC. We use a welfare function with disentangled inter-temporal (η) and intra-temporal (γ) inequality aversion (Anthoff and Emmerling, 2019). With $c_{trq} = \frac{C_{rqt}}{P_{rt}/5}$ consumption per capita for quintile q in region r , the social welfare function is

$$W^Q = \sum_{t=0}^T \frac{P_t}{(1+\rho)^t} \frac{1}{1-\eta} \left(\sum_r \sum_q \frac{P_{rqt}}{P_t} c_{rqt}^{1-\gamma} \right)^{\frac{1-\eta}{1-\gamma}} \quad (2.6.3)$$

If not stated otherwise, we assume as in Dennig et al. (2015) that inter- and intra-temporal inequality are equal⁶, i.e. $\eta = \gamma$, which results in the following social welfare function

$$W^Q = \sum_{t=0}^T \sum_r \sum_q \frac{P_{rqt}}{(1+\rho)^t} \frac{c_{rqt}^{1-\eta}}{1-\eta} \quad (2.6.4)$$

The SCC translates the welfare effect of a marginal ton of emissions into an equivalent change in present consumption, in monetary units. This change in consumption represents the present welfare benefit from the marginal emission, or equivalently the present welfare cost of mitigating the additional unit of emission. When consumption is aggregated at the global level with a unique representative agent, the normalization can be based on global average consumption. However, when consumption is disaggregated, a choice becomes necessary over the entity whose present marginal welfare will serve as normalization.

Picking a specific region for this normalization amounts to considering that the costs of mitigation are borne only by that region. In addition, choosing a richer region mechanically results in a higher SCC (e.g., Anthoff and Emmerling, 2019; Adler et al., 2017) because foregoing present consumption has a lower welfare cost for a richer region. Consistent with our normative approach and the assumption of a globally impartial decision-maker, we assume instead that the cost of mitigation is shared globally across all quintiles. We expand the concept of a “World-fair normalization” (Adler et al., 2017) to quintile level consumption. The present cost of a marginal emission reduction is borne by regions in proportion to their share in global consumption, and by quintiles within regions in proportion to their share in regional consumption weighted by the

⁶In the results section we test the sensitivity of the SCC to changes in the inter- and intra-temporal inequality aversion as in Anthoff and Emmerling (2019). We assume that within- and between-region inequality aversion is equal.

consumption-elasticity of mitigation costs ξ_Λ . The quintile level social cost of carbon with quintile world-fair normalization then writes

$$SCC_Q = \frac{\sum_{t=0}^T \sum_r \sum_q \Delta C_{trq} \frac{\partial W^Q}{\partial C_{trq}}}{\sum_r \sum_q \pi_{rq} \frac{\partial W^Q}{\partial C_{0rq}}} \quad (2.6.5)$$

with π_{rq} the weight of quintile q in region r such that

$$\pi_{rq} = \frac{C_{0r}}{C_0} \frac{\left(\frac{C_{0rq}}{C_{0r}}\right)^{\xi_\Lambda}}{\sum_q \left(\frac{C_{0rq}}{C_{0r}}\right)^{\xi_\Lambda}}$$

with ξ_Λ the consumption-elasticity of mitigation costs. Under the assumption that current mitigation efforts would be distributed proportionally to consumption ($\xi_\Lambda = 1$), the normalization weight of each quintile reduces to the share of quintile consumption in world consumption, $\pi_{rq} = \frac{C_{0rq}}{C_0}$.

3 Results

We turn to the main outcomes of our model along a business-as-usual scenario. When not stated otherwise, we use a decadal depreciation δ of 70%. $\delta = 0.7$ is equivalent to compounding approximately a yearly depreciation of 10%, which is the depreciation rate used in RICE. We also set the labor damage persistence to $\lambda = 0.5$ per year, meaning that half of the damages hitting labor do not dissipate from one year to the next.

We first quantify the effect of capital and labor damages on overall regional damages and the persistence of output losses. Second, we report the distributional outcomes of channel-specific impacts and income elasticities of damages. We then assess how the stronger persistence of damages hitting labor productivity and capital damages and their distributive outcomes affect the social cost of carbon (SCC) and test the sensitivity of the SCC to the key parameters.

3.1 Persistence and growth effects of labor and capital damages

We start by analyzing the effect of capital and labor damages on total damages, the persistence of damages, and output growth. To this end, we allocate up to 100% of recurring and instantaneous damages on the capital and labor stocks. We define our counterfactual "unpersistent" case to be when there are no damages on either capital or labor but only direct output losses, i.e. $f_Y = 1$, or equivalently $f_L = f_K = 0$. In the

rest of this section, we report total and persistent⁷ damages as a share of gross output in this counterfactual case, which we call *unpersistent gross output*.

Table 0.1 displays the ranges of damages as a share of unpersistent gross output for the twelve regions and different allocations of damages across the output, capital, and labor channels. In the unpersistent case ($f_Y = 1$), regional damages as a share of gross output fall in the 3.2 – 13.8% range. The most affected region is India, followed by Africa and the Other Asia region (Figure A4a).⁸ Next, we compare the effect of assigning 10% of all damages to the capital versus the labor channel. As shown in Table 0.1, for 10% channel-specific damages, capital damages have a stronger impact than labor damages on regional damage shares.

$f_K \backslash f_L$	0	0.1	0.5	0.7
0	3.2-13.8%	3.6-15.4 %		
0.1	5.7-22.4%	6-23.8%		
0.3				11.9-39.5%
0.5			14.6-43.4%	

Table 0.1: Range of regional damages as a share of regional unpersistent gross output, for different channel-specific impacts, 2100, $\delta = 0.7$, $\lambda = 0.5$.

We also find that the increase in overall output loss from labor and capital damages occurs proportionally to baseline damages in each region. Figure A4a shows total damages as a share of gross unpersistent output differentiated by region. By 2100, channel-specific damages scale up the baseline damages but do not affect the ordering of regions according to the share of output lost.

Furthermore, the effect of channel-specific damages on total damages and on the persistence of damages depends on the depreciation rate of capital δ and on the persistence of labor damages λ . Figure A5 displays the percentage share of total damages in gross unpersistent output (panel a) and the percentage share of persistent damages in total damages (panel b), for a range of decadal depreciation and persistence of labor damage values. Reducing the decadal depreciation rate δ , or increasing the rate of persistence of labor damages λ , increases the total damage share in every region (Figure A5a), as well as the share of persistent damages in total damages (Figure A5b). A decadal capital depreciation rate of 0.8 (approximately equivalent to a compounded yearly depreciation rate of 0.15) and a labor damage persistence rate of 0.3 result in a share of persistent damages in total damages of 72-80% between 2040 and 2100, whereas a decadal depreciation of 0.6 (approximately equivalent to 0.09 yearly) and

⁷The exact definition of persistent damages can be found in subsection 2.4.

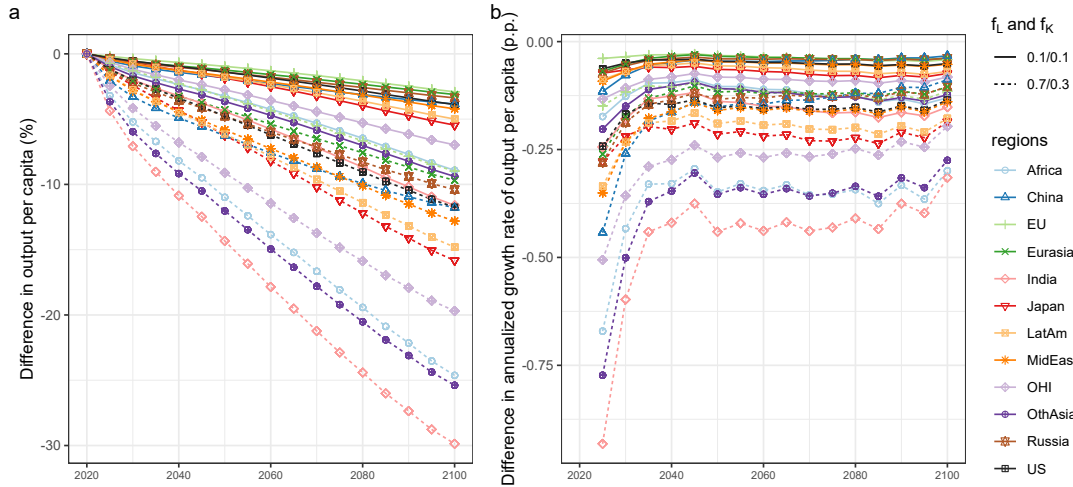
⁸The regional heterogeneity in the unpersistent case follows from the calibration to the COACCH regional damage functions.

a labor damage persistence of 0.7 result in a share of persistent damages of 82-90% between 2040 and 2100.

Compared to the results in Piontek et al. (2019), our findings differ in two main aspects. First, our overall damage levels are larger. This difference can be explained by the use of distinct damage functions. Piontek et al. (2019) use the standard DICE function (Nordhaus, 2014), whereas we apply the regional COACCH damage function (Van Der Wijst et al., 2023). Second, contrary to what we find, Piontek et al. (2019) show labor and productivity damages have a stronger impact than capital damages on output losses. This is likely due to differences in savings rate and production function, in the capital depreciation rate, the (implicit or explicit) persistence level of shocks to productive labor, and to compounding effects of different time steps.

Next, we find that channel-specific damages result in both level and growth effects on per capita output. Figure 1a shows the difference in regional output per capita with respect to the baseline case with damages falling only on output, and Figure 1b shows the difference in annualized growth of per capita output.

Figure 1: Difference in regional output per capita level and growth, compared to the case with damages falling on output only ($f_L = f_K = 0$), $\delta = 0.7$ and $\lambda = 0.5$.



First, a damage composition with 10% on the capital channel and 10% on the labor channel results in continuously increasing level effects, with a reduction in regional output per capita between 3 and 12% in 2100. India, Africa, and Other Asia are the most affected regions, with reductions greater than 9%.⁹ In terms of growth effect, this

⁹LatAm stands for Latin America, MidEast for Middle East, OHI for Other High Income countries, and OthAsia for Other Asia.

case with $f_L = 0.1$ and $f_K = 0.1$ results in long-term reductions in annualized growth of less than 0.25 percentage points.

Second, we assign 100% of damages to the factor-specific channels, keeping the damage composition proportional to the production factor shares. This results in a level effect of over 9% in all the regions, with India, Africa, and Other Asia suffering an output per capita loss of over 24%. Growth effects are larger in the first periods and converge during the century to reductions in annualized regional growth rates approximately between 0.1 and 0.3 percentage points. The regional variation in level and growth effects reflects regional heterogeneity in overall climate change damages, with India, Africa, and Other Asia being more affected by climate damages (Figure A4a).

Moore and Diaz (2015) introduce growth effects in the DICE model by calibrating reductions on total factor productivity growth and capital depreciation with empirical estimates of temperature impacts on GDP growth. In comparison to their findings, our scenario with 100% of damages falling on capital and labor channels in proportion to factor shares results in lower level and growth effects. For poor regions, they find a reduction of 40% in per capita output in 2100, and a reduction in the average annual growth rate of 0.8 percentage points. For richer regions, our results are closer, as they also find a level effect of around 10% and a growth rate reduction of 0.1 percentage points.

Kikstra et al. (2021) implement growth effects through explicit damage persistence calibrated to match empirical evidence. With the central estimate of damage persistence of 50%, they also obtain heterogeneous GDP growth reductions across regions. In Africa, they find larger reductions (0.5 to 1 percentage points in the 21st century) than we do. In the EU, they find an increase of around 0.1 percentage points compared to a scenario with zero persistence. Our model does not allow for a growth increase caused by climate change damages, but our estimate for the growth reduction in the EU is the one closest to zero. Our results coincide with the results from Kikstra et al. (2021) in terms of a large regional heterogeneity, with poorer regions more strongly affected.

3.2 Distributional impacts of labor and capital damages

We now explore how channel-specific impacts affect inequality and income levels of the poorest within regions. We analyze the sub-regional distributional impacts of damages on labor and capital, as well as the role of the labor income elasticity of labor damages, ξ_L , and capital income elasticity of capital stock damages, ξ_K . We first focus on the damage distribution with the Suits index and then turn to impacts on global and regional inequality as well as the effect on the poorest within regions.

Suits index of progressivity of climate damages

The distribution of damages overall can be synthesized by applying the Suits index (Suits, 1977) to the damage shares (2.5.2)

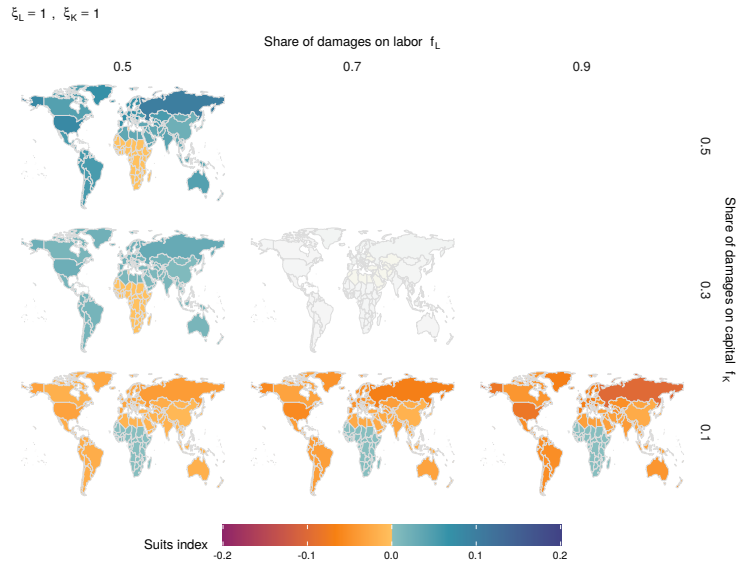
$$S_D \approx 1 - \frac{1}{0.5} \left[\sum_{i=1}^5 \frac{1}{2} \left(\sum_{q=0}^i sh_q^D + \sum_{q=0}^{i-1} sh_q^D \right) sh_i^Y \right]. \quad (3.2.1)$$

The Suits index is based on the Lorenz curve for damage shares. Negative values indicate a regressive distribution of damages, with -1 being the most regressive case (the poorest quintile bears the entire damage loss), and positive values indicate a progressive distribution, with 1 being the most progressive case (the richest quintile bears the entire damage loss). A value of zero reflects damages with the same distribution as total income. There are three determinants of the regressivity of climate damages in our approach: a) the composition of damages between capital and labor damages, b) the income elasticities of capital and labor damages, and c) the pre-damage income inequality.

Figure 2 displays the impact of the composition of damages on the Suits index in 2020, with income elasticities of 1. When 70% of damages fall on labor and 30% on capital, as in the central panel of Figure 2, damages are exactly proportional to income (Suits index equal to zero). This damage distribution reflects that aggregate income is distributed according to factor shares, with $(1 - \alpha) = 0.7$ the labor share. When the composition of damages shifts towards a larger capital share, damages are distributed more progressively, and the Suits index increases. Since capital income is more unequally distributed than labor income, shifting damages toward capital with an income elasticity of one shifts the burden of climate damages towards the richer quintiles. The opposite is true when the composition of damages shifts towards a larger labor share. This pattern occurs in every region except in Africa. For this region, our calibration resulted in very high levels of both capital and labor Ginis, and, contrary to other regions, in a labor income Gini slightly higher than the capital income Gini.

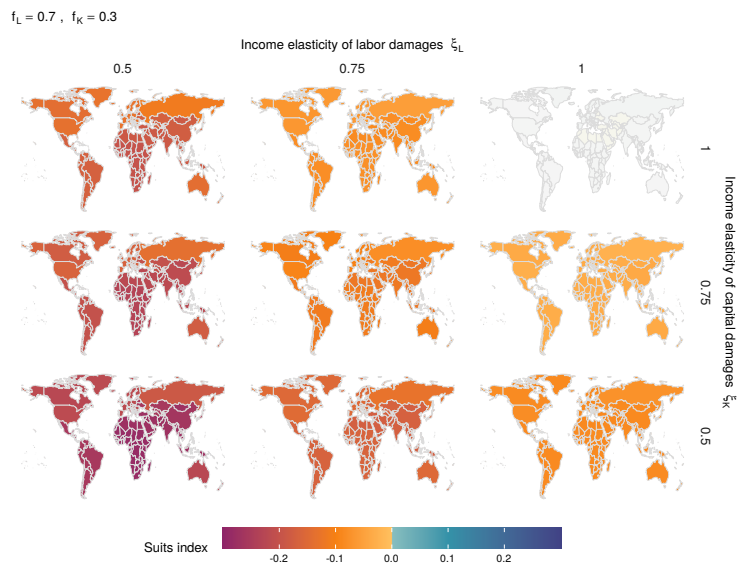
Figure 3 displays the effect of the income elasticities of labor and capital damages (ξ_L and ξ_K), for labor and capital damages shares fixed and proportional to the labor and capital share in income ($f_L = 0.7$ and $f_K = 0.3$). Damages are proportional to total income when both elasticities are equal to one. A decrease of ξ_L or ξ_K from 1 towards 0.5 results in more regressive damages in all regions. Finally, Figure 3 shows, for labor and capital damage shares proportional to the aggregate income shares, that the income elasticity of labor damages ξ_L has a stronger regressive effect than the income elasticity of capital damages ξ_K . The more pronounced impact on the Suits index reflects that labor income makes up a larger share of the income of poorer households.

Figure 2: Suits index of the damage distribution for different levels of capital and labor damage shares, 2020.



Note: white values are approximately equal to zero with a tolerance level of $1e-15$.

Figure 3: Suits index of the damage distribution for different levels of capital and labor income elasticities of damages, 2020.



Note: white values are approximately equal to zero with a tolerance level of $1e-15$.

Global and regional inequality

We start by computing the global Gini index by pooling together all quintile consumption at the world level. [Figure A6](#) shows the global Gini index in the unpersistent case ($f_Y = 1$). In the absence of any channel-specific impact, the Gini index decreases from around 56% in 2020 to 40% in 2100, i.e. a decrease of 16 percentage points (p.p.). This reduction in the baseline global Gini is due to differential growth between regions, with partial convergence, and to changes in the regional inequality driven by the SSP scenario projections.

[Figure 4](#) displays the change in global consumption Gini for different combinations of channel-specific damages and income elasticities of damages, compared to the unpersistent case. First, half of total damages are assigned to the channel-specific damages ($f_Y = 0.5$). For damages proportional to income in both channels ($\xi_L = \xi_K = 1$), the global Gini increases by around 2.5% in 2100. Having damages fall disproportionately on the bottom of the distribution raises the global Gini with respect to the case with damages on output. By 2100, the global Gini index increases by 4% for income elasticities of capital and labor damages of 0.75, and by 7.5% for income elasticities of capital and labor damages of 0.5.

Second, we assign 100% of total damages to the channel-specific damages ($f_Y = 0$). As a result, the global Gini increases compared to the unpersistent case, by around 3.5% for proportional damages and up to around 15% for disproportionate damages with $\xi_L = 0.5$ and $\xi_K = 0.5$, in 2100 ([Figure 4](#)). Hence, for damages falling fully on the labor and capital channels, and regressive damages with channel-specific income elasticities between 1 and 0.5, around a fifth to a third of the baseline decrease in the global Gini is offset.

In addition, we explore the role of damage composition across the labor and the capital channels by assigning the damages in two ways, symmetric (e.g. $f_K = f_L = 0.5$ for a total of 100% of channel-specific damages) or proportional to factor shares (e.g. $f_K = 0.3$ and $f_L = 0.7$ for a total of 100% of channel-specific damages). [Figure 4](#) shows that the impact on the difference in global Gini to the baseline is small when the labor and capital income elasticities of damages are equal, and up to 4 p.p. when $\xi_L = 0.5$ and $\xi_K = 1$.

Next, we focus on the regional Gini index. [Figure A7](#) depicts the regional Gini index with unpersistent damages based on quintile consumption ($f_Y = 1$) following the calibration to the SSP2 scenario. India experiences a large increase in the regional Gini index and becomes the most unequal region at the end of the century (Gini around 35% in 2020 and 50% in 2100). Regions with less pronounced increases or relatively stable Gini index are the US, Russia, Eurasia, EU, Japan, and OHI. In the other regions, the regional consumption Gini decreases. China, the region with the most pronounced decrease, becomes the most equal region at the end of the century in the baseline scenario (Gini around 35% in 2020 and 20% in 2100).

Figure 4: Difference in global consumption Gini index (%) for different levels of channel-specific damages and elasticities, with $\delta = 0.7$, $\lambda = 0.5$.

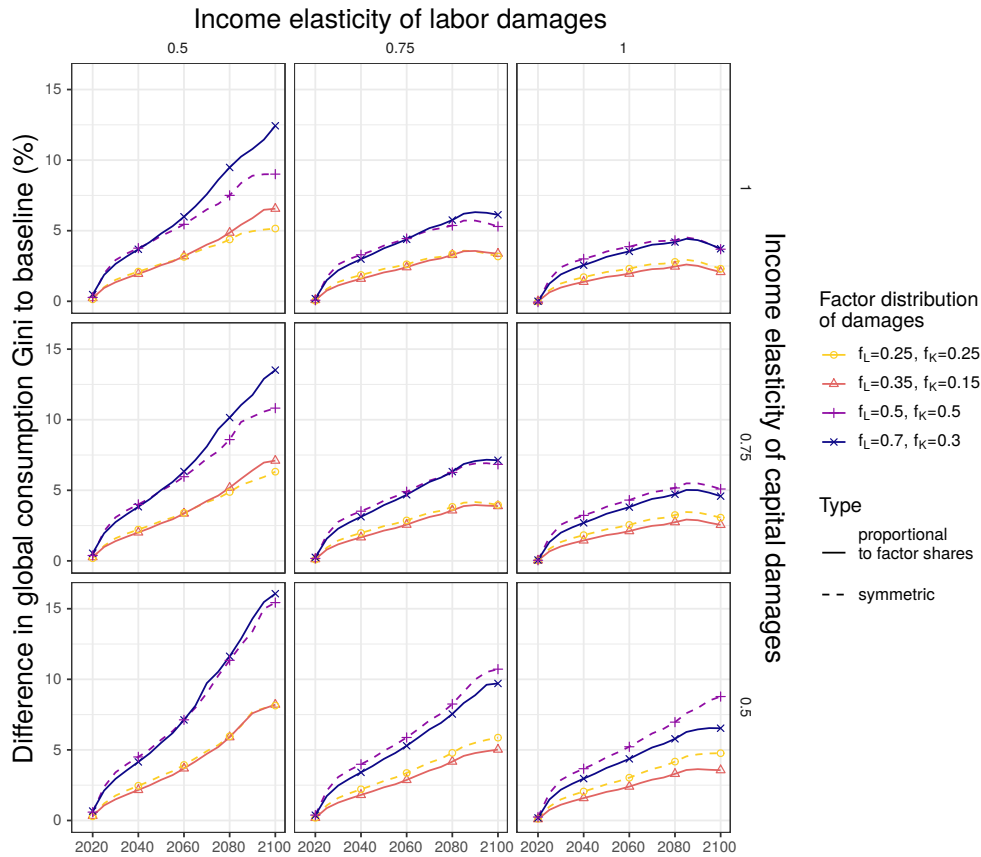
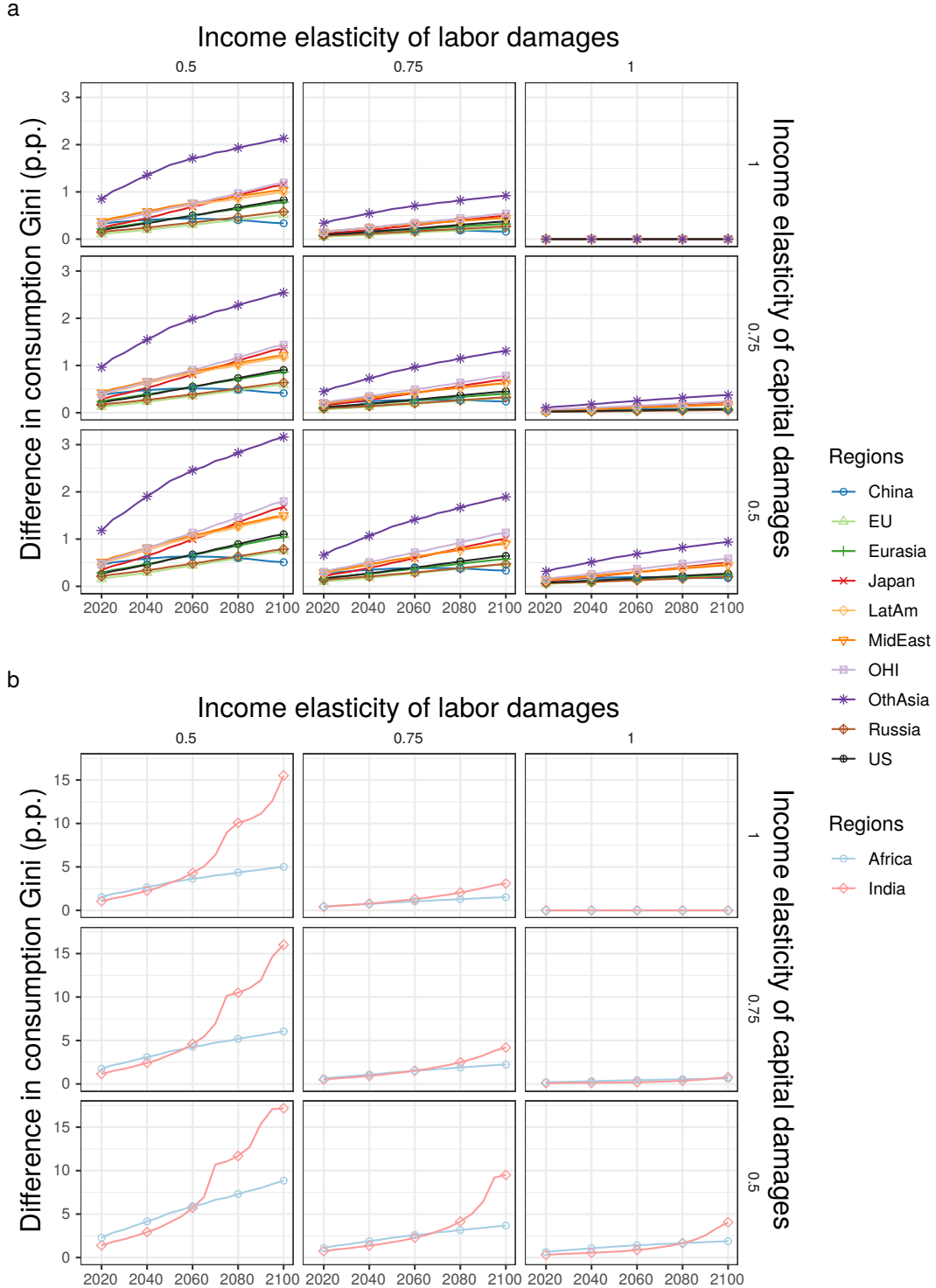


Figure 5 shows the difference in the regional Gini index to the unpersistent case for labor and capital damages proportional to the labor and capital share in income ($f_L = 0.7$ and $f_K = 0.3$) and with different income elasticities of damages. Regressively distributed damages lead to increases in the regional Gini up to 3 p.p. compared to the unpersistent case, with important regional heterogeneity. Regions that witness the largest change in the Gini are the most affected by climate change damages (Figure A4a). Despite being affected by larger regional damages, India initially experiences a smaller change in the Gini index than Africa in most income elasticity combinations and then overtakes Africa in the second half of the century. As India is first more equal and becomes more unequal in the second half of the century than Africa, this showcases the role of pre-existing inequality in the regressivity of climate damages.

Figure 5: Difference in the regional consumption Gini index for different elasticities with damages on capital and labor in proportion to production factor shares ($f_K = 0.3$ and $f_L = 0.7$), $\delta = 0.7$, $\lambda = 0.5$.



Distributional impact on the bottom quintile

We turn to the analysis of distributive outcomes at the quintile level and in particular the impacts of channel-specific damages on consumption levels of the first quintile (or "bottom" quintile).

Figure 6 displays the difference in consumption per capita compared to the unperturbed case for two groups of regions, with different combinations of labor and capital damage shares and income elasticities. We find extreme effects in India and strong effects in other regions. For the first group of regions (Figure 6a), consumption per capita in the bottom quintile is projected to be around 7-13% lower at the end of the century with 25% damages on the labor and capital channels, and around 12-20% lower if damages fall 50% each on labor and capital. The loss in consumption per capita increases to 8-15% and 15-25% with lower values for the income elasticities of damages. For the second group of regions, the decrease in consumption per capita is larger, with reductions of over 13% in 2100. The decrease is most pronounced with regressive channel-specific damages. In India, the reduction amounts to 100% after 2080 with income elasticities of damages of 0.5. Consumption per capita in the first quintile plummets to zero under these scenarios in India. Capital and labor damages elasticities produce relatively symmetrical impacts, with slightly larger effects for regressive labor damages than for regressive capital damages.

Next, Figure 7 shows the change in the net income share of the first quintile in the four most affected regions, for different levels of labor and capital damage shares, and income elasticities of damages of 1 or 0.75. First, when damages are strictly proportional to factor income shares ($\xi_L = \xi_K = 1$), a larger portion of the damages falling on capital slightly increases the income share of the first quintile (Figure 7b). This increase is because the first quintile hardly earns any capital income (Figure A2). For $\xi_L = \xi_K = 1$, having damages fall on the capital stock, instead of directly on output, transfers part of the damage burden to the capital earners i.e. away from the first quintile. The effect does not occur in Africa, where our calibration results in a slightly more unequal labor income distribution than capital income distribution (Figure A2).

Second, for this range of elasticities, labor damages have a stronger impact on the income share loss than capital damages. This effect can be seen by the larger income share loss from disproportional labor damages than from disproportional capital damages (Figure 7a and c), as well as the strongest gradient along the labor damage axis when both capital and labor damages are distributed with an elasticity of 0.75 (Figure 7c). The distributive impacts at the bottom of the distribution are thus more dependent on the share and regressivity of climate damages hitting labor productivity.

Figure 6: Difference in consumption per capita of the first quintile for different levels of channel-specific damages and elasticities, $\delta = 0.7$, $\lambda = 0.5$.

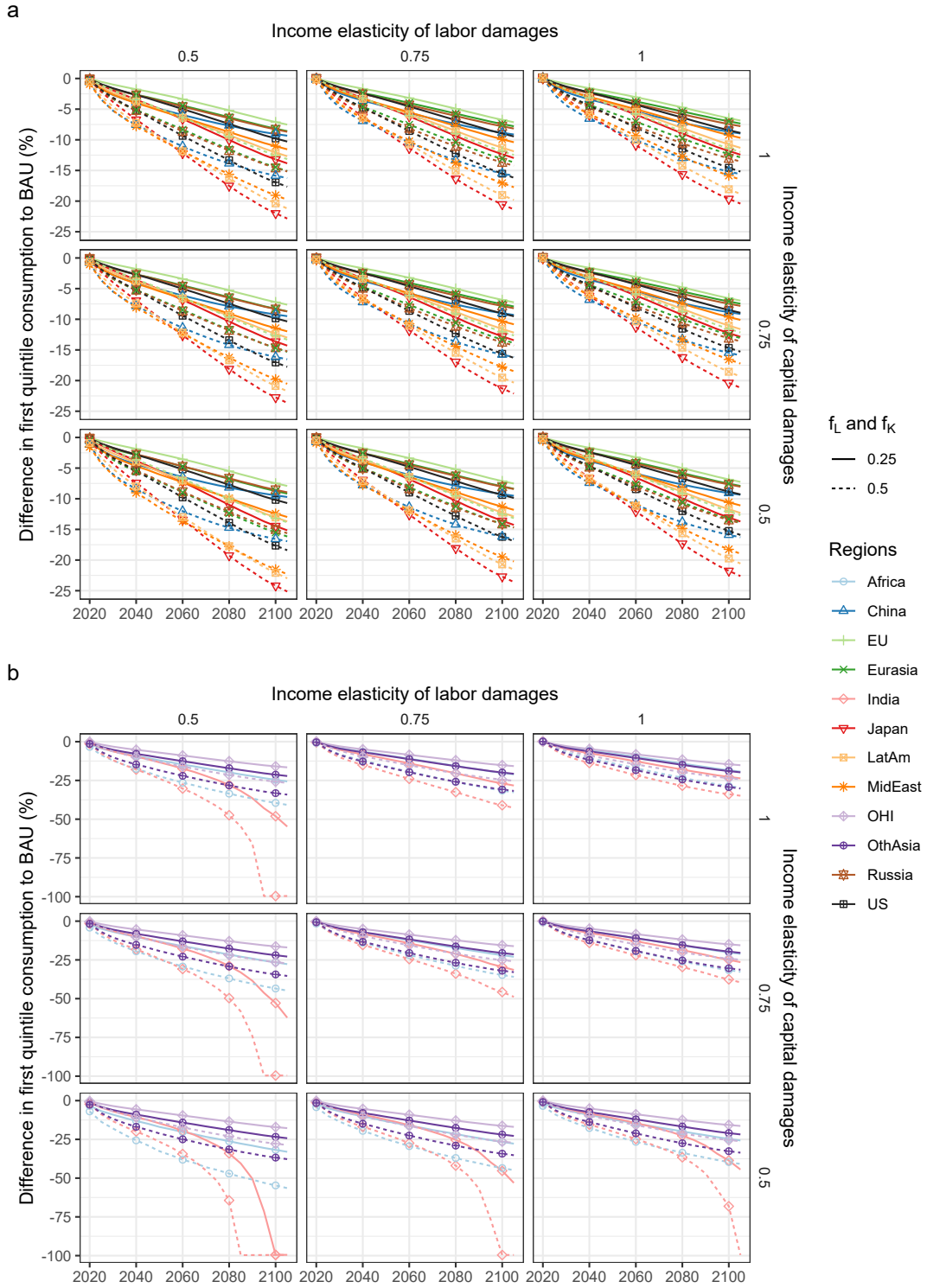
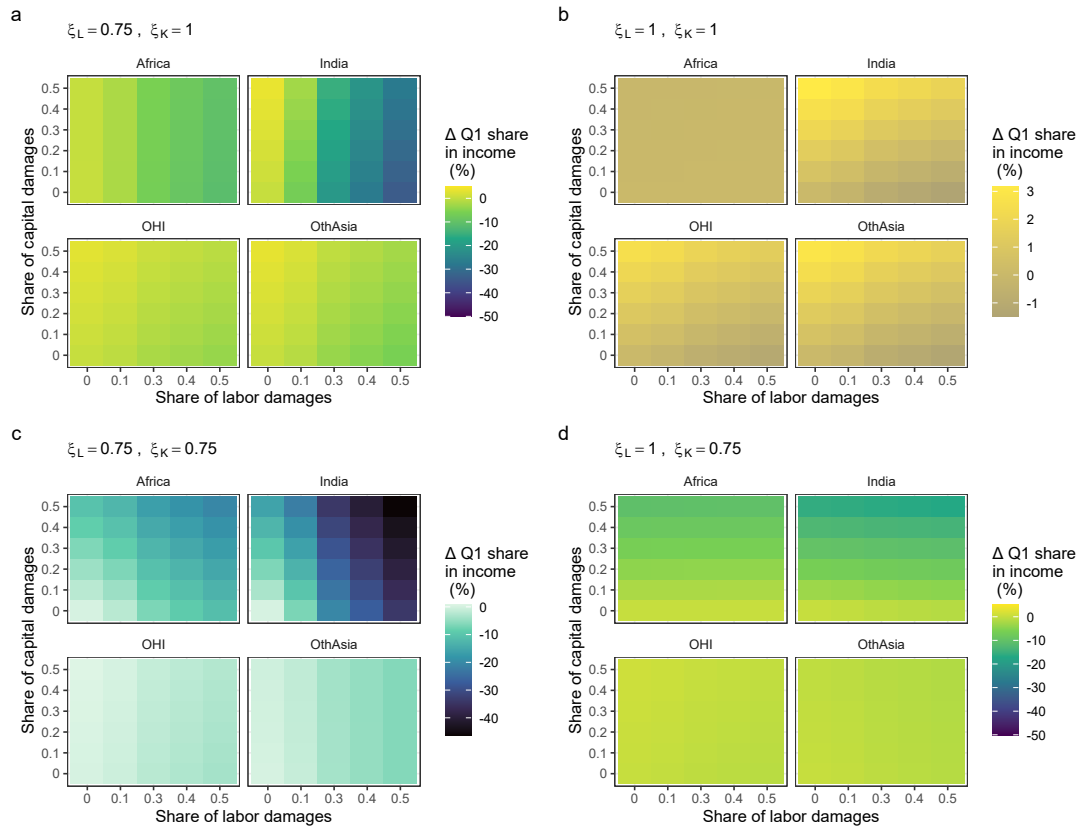


Figure 7: Change in the income share of the first quintile, from pre-damage to net income distribution, for different levels of channel-specific damages and elasticities, 2105, $\delta = 0.7$, $\lambda = 0.5$.



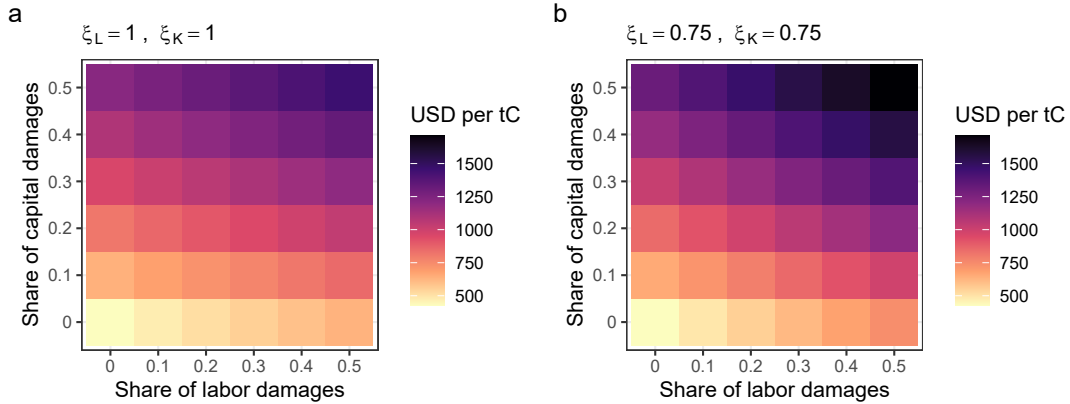
3.3 Social cost of carbon

We now analyze the effect of channel-specific damages and the resulting distributional impacts on the social cost of carbon (SCC) based on quintile consumption per capita. We evaluate the SCC with the same inequality aversion within and across generations¹⁰ ($\eta = \gamma = 2$) and a rate of time preference of $\rho = 0.015$.

Figure 8 displays the SCC based on quintile consumption per capita for 2023, for varying damage shares and different combinations of labor and capital income elasticities of damages. We first focus on the results for damages proportional to income shares ($\xi_K = \xi_L = 1$), which are shown in Figure 8 panel a), and detailed in Table A9a. With all damages falling directly on output, the SCC is 432 dollars per ton of carbon. If damages fall completely on capital and labor (with a share of 50% respectively), the SCC is 1452 dollars per ton of carbon, i.e. 3.4 times larger. With a capital and labor damage share of 0, a rise from 0 to 0.5 in the labor damage share yields a 47% increase in the SCC, while a rise to 0.5 in the capital damage share yields a 180% increase. Hence, for proportional damages, damages hitting the capital stock have a stronger impact on the SCC than damages hitting labor productivity.

Figure 8: The social cost of carbon for different levels of channel-specific damages, 2023.

2017 PPP USD per tC, $\delta = 0.7, \eta = \gamma = 2, \rho = 0.015, \lambda = 0.5$



Next, we explore the results for damages falling slightly disproportionately on the poorer quintiles for the labor and the capital damages ($\xi_L = 0.75$ and $\xi_K = 0.75$) shown in Figure 8b. The SCC amounts to more than 1710 dollars per ton of carbon if damages fall fully on capital and labor, around 260 dollars per ton of carbon larger than with damages distributed proportionally to shares in factor income (see Table A9). With

¹⁰We relax this assumption further down.

slightly regressive damages, the share of capital damages still has a stronger increasing effect on the SCC than the share of labor damages. However, regressive labor damages result in stronger increases in the SCC than regressive capital damages (comparing with SCC with proportional damages in [Figure 8](#) and with the same damage shares). These results show that the income elasticity of labor damages tends to have a stronger impact on the SCC than the income elasticity of capital damages, but that the effect on the value of the SCC is of second order compared to the impact of the share of damages falling on capital. This finding is in line with the result presented in [section 3.2](#) on the stronger effect of labor elasticity on inequality or on consumption of the bottom quintile.

Disentangling the persistence and distributive channels

Capital and labor damages yield persistent output losses and distributive effects. To investigate the contribution of these two effects to the increase in the SCC, we compute SCC_{nodist} , the value of the social cost of carbon for which we neutralize the redistributive effects of channel-specific damages by distributing damages at the quintile level proportionally to total quintile income. That is, quintile income shares remain unaffected by climate change damages by assumption in the computation of SCC_{nodist} . [Table A9b](#) shows the SCC_{nodist} for different shares of capital and labor damages.

With a capital damage share of 0 and a labor damage share of 0.5, the SCC_{nodist} is 629 dollars per ton of carbon, a few dollars lower than the SCC with $\xi_L = \xi_K = 1$ ([Table A9a](#)). On the other hand, with a labor damage share of 0 and a capital damage share of 0.5, the SCC_{nodist} is a few dollars larger than the SCC value. Thus, for proportional damages, the output loss and growth effects of channel-specific damages tend to dominate the within-region distributional effect on the SCC. The distributive effect of capital damages decreases the SCC, whereas the distributive effect of labor damages increases the SCC, which is consistent with the findings in [subsection 3.2](#) that for damages proportional to income shares, a larger portion of damages on capital slightly increases the income share of the first quintile whereas it decreases with a larger portion of labor damages (see [Figure 7b](#)).

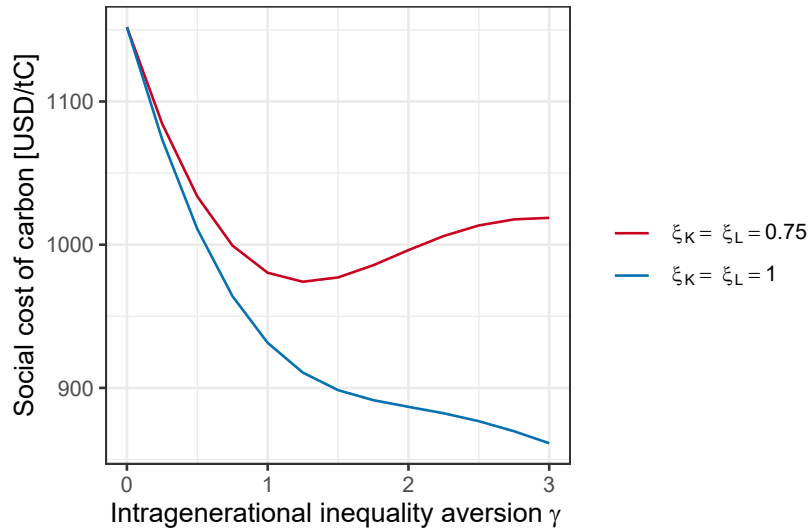
Furthermore, with regressive damages ($\xi_L = \xi_K = 0.75$) and damage shares of 0.5 on the labor or the capital channel, the SCC ([Table A9b](#)) is larger than the SCC_{nodist} ([Table A9c](#)). It implies that, for regressive damage distributions, the distributive and the growth effects of damages increase the SCC for labor and capital damages. For half of damages on labor and half on capital, the SCC with regressive damages is more than 250 dollars higher than the SCC_{nodist} , a 17% increase.

The impact of the distributive channel on the SCC depends on the normative evaluation of damages and mitigation costs. [Figure 9](#) illustrates the relationship between the SCC and the intra-generational inequality aversion γ , keeping the inter-generational inequality aversion η fixed ($\eta = 2$). We fix $f_K = 0.15$ and $f_L = 0.35$ and look at two

scenarios: a first with damages distributed proportionally, and a second with damages distributed regressively to income shares. In the absence of intra-generational inequality aversion ($\gamma = 0$), the two curves overlap and the distribution of damages is irrelevant. As γ increases above zero, the SCC first experiences a decline in both scenarios. With proportionately distributed damages, the SCC falls continuously. With regressively distributed damages, the SCC decreases initially until it reaches a minimum value at γ slightly larger than one, then increases.

Figure 9: The social cost of carbon for different levels of intra-generational inequality aversion γ and income elasticity of damages ξ_L and ξ_K , 2023.

2017 PPP USD per tC, $\delta = 0.7, \lambda = 0.5, \eta = 2, \rho = 0.015, f_K = 0.15, f_L = 0.35$.



The result on the SCC under proportional damages is similar to that in [Anthoff and Emmerling \(2019\)](#). The authors find that the SCC declines with increasing γ . However, they use a poor region for the normalization of the SCC, whereas we implement a "World-fair" normalization assuming proportional distribution of mitigation costs. An increase in γ has two opposing effects¹¹. On the one hand, it increases the current welfare cost of mitigating a marginal unit of emission at the expense of the poor, which tends to decrease the SCC. On the other hand, it increases the welfare costs of disproportionate climate damages from a marginal unit of emissions, which tends to increase the SCC. In addition, baseline global inequality falls over time while average consumption grows, so in the baseline scenario the future world has richer poor and

¹¹These correspond to the effects of γ on the denominator and the numerator of the SCC, see [subsection 2.6](#).

is more equal. When damages fall proportionally ($\xi_L = \xi_K = 1$), an increase in γ thus results in a larger increase in the welfare costs of today's mitigation costs than in the welfare costs of future damages, so the SCC decreases with γ . When damages fall disproportionately on the poor ($\xi_L = \xi_K = 0.75$), the effect on the welfare cost of future damages¹² dominates at larger values of γ , so the SCC increases with γ at these larger values.

Sensitivity analysis

We test the sensitivity of the SCC to the key parameters of the models. We first focus on the income elasticity of damages. [Figure A8](#) in the Appendix shows the SCC for varying damage shares and more disproportionately distributed damages than in [Figure 8](#) (elasticities of 1 and 0.5 instead of 0.75). When the income elasticities of labor and/or capital damages are 0.5, the SCC reaches values of more than 4700 dollars per ton of carbon with capital and labor damages, a fourfold increase compared to the SCC with proportionate capital and labor damages and the same factor-specific damages.

In a number of capital and labor damage combinations, damages exceed income for at least one quintile – specifically, the poorest quintile in India, as can be seen in [Figure 6b](#). As a result, consumption in these quintiles has to be bounded by zero or some positive value. Our CRRA utility function, commonly used in integrated assessment models, features infinite marginal utility at the origin. This implies that the SCC is either unbounded if minimal consumption is set to zero, or is unstable and very sensitive to the boundary value if minimal consumption is set to a positive value¹³. This issue can be related to the debate on the welfare evaluation of catastrophic outcomes sparked by Weitzman's "dismal theorem" ([Weitzman, 2009](#)). As [Millner \(2013\)](#) points out, technical problems surrounding the sensitivity of welfare computations to the behavior of the utility function at low consumption levels are in fact ethical questions regarding how to socially value catastrophic outcomes, such as a quintile losing all means of subsistence in our setting. Given that our current framework is not equipped to address questions of population ethics, we chose not to compute the SCC when the income share of a quintile falls to zero, and instead mark these cases in grey in [Figure A8](#). The proportion of greyed labor and capital damage combinations is large with a labor income elasticity of damages of 0.5 ([Figure A8a and c](#)), indicating the potential for regressive labor damages to result in catastrophic outcomes for the poorest.

¹²In this case, the reduction in global inequality over the century is lower than in the proportionate case, see [Figure 4](#).

¹³Alternatively, [Kikstra et al. \(2021\)](#) implement a convergence system to the boundary value to ensure that an additional ton of carbon yields additional consumption loss even when the consumption level is close to the boundary. With our model, the SCC become unstable and very sensitive to marginal changes in the labor and capital damages shares. Yet another option would be to bound utility directly, which leads to similar issues.

Finally, [Figure A9](#) displays the sensitivity of the social cost of carbon to the main parameters. We modify one parameter value at a time while keeping the other parameters at their central value. The SCC amounts to around 1000 USD/tC with our central choice of parameter values. [Figure A9](#) indicates a strong sensitivity of the SCC to the normative parameters η (inter-temporal inequality aversion) or ρ (pure rate of time preference). For low values of η or ρ , the SCC reaches more than 23000 and 3000 USD/tC, respectively, but can also fall to around 500 USD/tC for high values of η or ρ . The SCC is also very sensitive to the value of the labor damage elasticity ξ_L as already observed in [Figure A8](#). We mark the range for ξ_L as unbounded at the upper end because the income share of the poorest quintile in India falls to the lower bound of zero with $\xi_L = 0.5$. Finally, the persistence of labor damages λ and the capital and labor damage share f_K and f_L also have a significant impact, albeit smaller than the parameters mentioned above. The SCC is least sensitive to changes in the capital damage elasticity ξ_K , the capital depreciation δ , and the intra-temporal inequality aversion γ .

4 Discussion

Our results remain conditional on a number of assumptions. In the section, we discuss our choices of a fixed savings rate and a constant factor share.

We keep the savings rate fixed as in the original NICE¹⁴ ([Dennig et al., 2015](#)). This assumption could lead to larger impacts of factor-specific damages, as we are missing a possible readjustment channel. [Piontek et al. \(2019\)](#) show that for a large one-time shock followed by a recovery, a fixed savings rate leads to larger damages in the case of a capital shock and to a lesser extent in the case of an output shock, and to smaller damages in the short run followed by slightly larger damages in the long run in the case of a labor shock¹⁵. They also show that the savings rate responds less with a Cobb-Douglas production function. So endogenizing the savings rate while keeping an elasticity of substitution of one would not necessarily result in a strong readjustments.

Turning next to recurring and anticipated shocks, as in our setting, [Fankhauser and Tol \(2005\)](#) highlight the ambiguous effects of capital damages on an endogenous savings rate: although savers would want to compensate for the loss of capital with an increased savings rate, they also factor in the lower returns on capital investments. In this case, [Piontek et al. \(2019\)](#) show that using a fixed instead of an endogenous savings rate results in larger welfare and growth rate reductions for the capital channel, but

¹⁴In the NICE, the fixed saving rate is derived following [Golosov et al. \(2014\)](#), as the optimal rate chosen by private savers. Under a set of assumptions, the endogenous savings rate will be fixed and a function of the capital share α and the pure rate of time preference, ρ .

¹⁵They show that for a capital or output shock, the endogenous savings rate increases which hastens the recovery, while for a labor shock, the drop in labor results in overcapitalization with respect to the steady state level, leading initially to a decrease in the savings rate.

has very small effects on the output and labor channels. These findings indicate that the assumption of a fixed savings rate in our setting could be resulting in larger and more persistent damages from the capital channel, leading to an over-estimation of the impact of growth effects with respect to distributional effects on the SCC. The effect is likely to be smaller through the output and labor channel. Finally, the response of an endogenous savings rate to simultaneous damages on labor and capital would likely be ambiguous in the short to medium run and depend on the respective shares of output, labor and capital damages, given that labor damages would tend to decrease the savings rate while capital damages would tend to increase it.

The constant factor share results from applying a Cobb-Douglas production function, a special case of the constant elasticity of substitution production function when the elasticity of substitution is equal to one. Instead, the factor share could be interpreted in a neo-classical fashion as reflecting relative factor prices, as in [Piontek et al. \(2019\)](#) and [Tsigaris and Wood \(2019\)](#). In this vein, a shock on the stock of either capital or productive labor would increase the relative price of the shocked input. Depending on the elasticity of substitution, the shock would affect the share of this factor in income and ultimately earnings (distributive effect). In [Piontek et al. \(2019\)](#), the change in the factor share of capital and productive labor compared to the case without climate change damages is most pronounced with impacts on capital. Following from their assumption of an elasticity of substitution of 0.5, the capital income share increases in this scenario. With an elasticity larger than one, the capital income share would decrease with impacts on capital.¹⁶

To obtain these endogenous changes in the factor income share, the elasticity of substitution needs to be different from one. [Tsigaris and Wood \(2019\)](#) and [Piontek et al. \(2019\)](#) show that the elasticity of substitution also alters the ability of the economy to cope with climate change damages. In [Tsigaris and Wood \(2019\)](#), a higher elasticity of substitution reduces the deviation from the path without climate damages, no matter which damage type. In [Piontek et al. \(2019\)](#), the impact depends on the damage type. A higher elasticity reduces the average GDP per capita growth rate more strongly with output and capital damages but less so with labor damages. Our findings could be mitigated or amplified, depending on the magnitude of the aggregate and the distributive effect of an elasticity of substitution different from one.

5 Concluding Remarks

We study how introducing channel-specific damages and composition of income affects inequality, the well-being of the future poor, and ultimately the social cost of

¹⁶Another approach would be to attribute the net share of income to capital owners as in [Tsigaris and Wood \(2019\)](#), given by $(\frac{\partial Y}{\partial K} - \delta) * \frac{K}{Y_{net}}$. Even with a Cobb-Douglas production function, the share of income to capital would then depend on the capital to income ratio.

carbon. We split both income and damages into a capital and a labor component, and parameterize the proportionality of damages. As a result, the model encompasses damages that interact with the labor, capital, and total income distributions, and are endogenously persistent.

We find that including damages that fall directly on the factors production results in level and growth impacts on per capita output and in increased inequality, with heterogeneity across regions. With all damages falling on the labor and capital stocks proportionally to factor shares, regional annualized growth rates fall by 0.1 to 0.3 percentage points. The heterogeneity of damages across regions, combined with regressive impacts within regions, leads to an increase in the global Gini with respect to the baseline case with damages falling only on output. With half of damages falling on the capital channel and half on the labor channel, the global Gini increases by 5% in 2050 and 15% in 2100 relative to the baseline. We show that labor damages and their distribution are key to the outcomes of households at the bottom of the distribution.

We investigate the impact of channel-specific damages on the social cost of carbon. We find that the social cost of carbon increases four times if damages fall half on the capital and half on the labor channels and damages are slightly regressive, compared to a baseline in which all damages fall directly on output.

We further disentangle the persistence and distributional effects of factor-specific damages on the social cost of carbon by having damages fall on labor and capital while keeping the ex-post distribution of income fixed. Under our benchmark calibration with slightly regressive damages and the same inequality aversion within and between regions, we find that the growth channel accounts for the bulk of the effects on the SCC. With slightly regressive damages, the SCC increases by 17% compared to the SCC with neutralized distributional impacts.

Our results remain conditional on a number of assumptions. The basis for the distribution of damages could be developed by including further insights from the empirical literature on ongoing climate impacts. More research is needed to determine relevant parameters such as the persistence and the income elasticity of labor damages. Furthermore, our income decomposition remains a coarse approach to the many factors determining the distributional effects of climate policies. Future work could expand our framework of disentangled damages and inequality to include more dimensions of social heterogeneity, such as health, gender, or spatial inequalities. The role of adaptation in reducing or exacerbating the persistence and regressivity of climate damages could also be explored.

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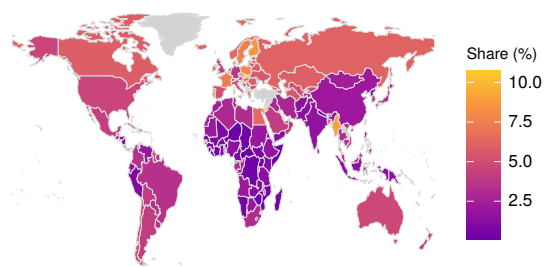
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Appendix

Figure A1: Maps of input data for inequality

Labor income share of the first quintile, 2019, ILOSTAT



Wealth Gini index, 2019, Credit Suisse (based on Davies et al., 2017)

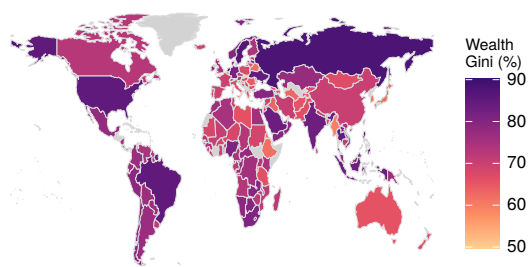


Figure A2: Calibrated distributions for capital income and labor income

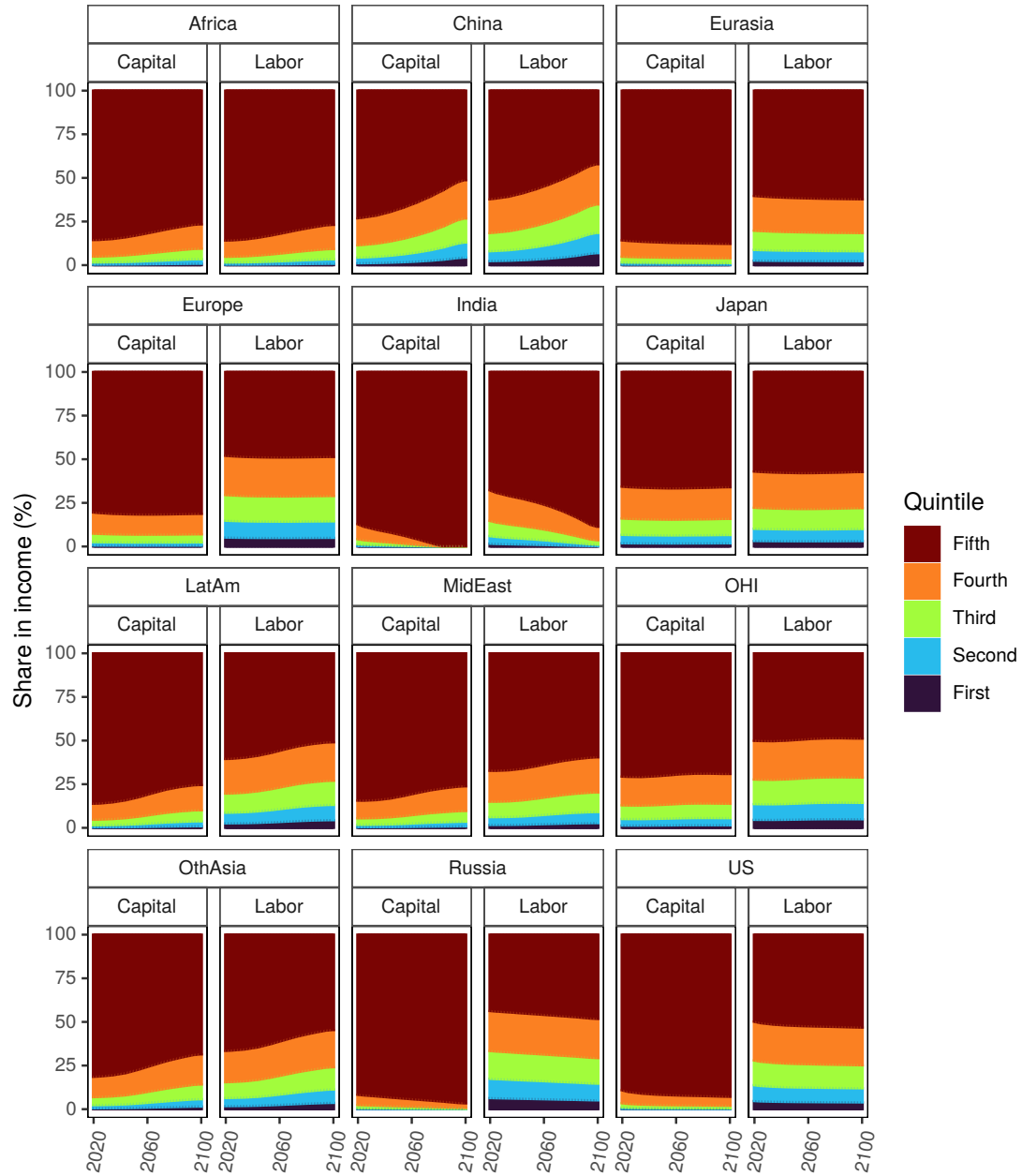


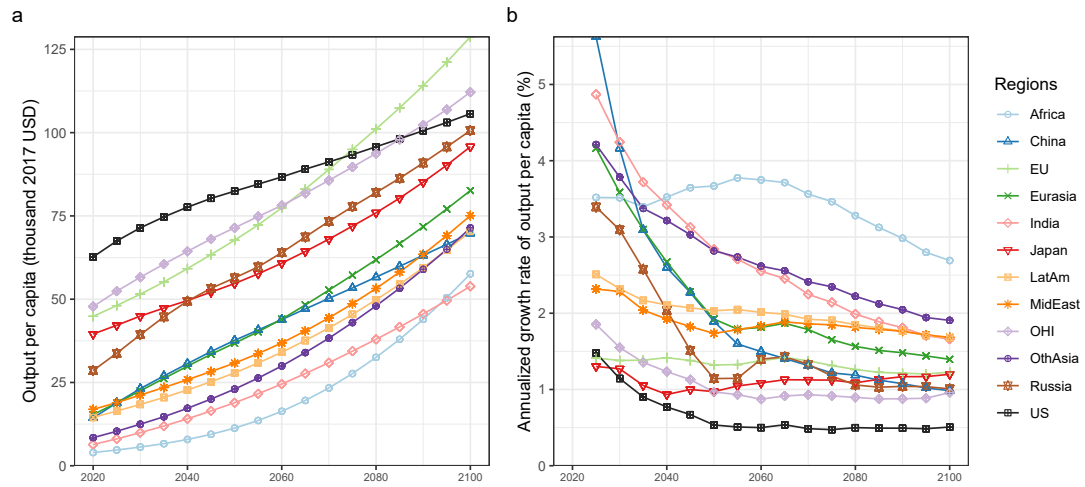
Figure A3: Regional output per capita and growth with output damages only, $\delta = 0.7$ 

Figure A4: Impact of channel-specific damages on overall damages and on share of persistent damages, $\delta = 0.7$, $\lambda = 0.5$.

Note: Panel a) shows the total damages in each regions, as a share of gross output in the counterfactual scenario with no persistence of damages. Panel b) shows the share of total damages which stem from the persistence of damages.

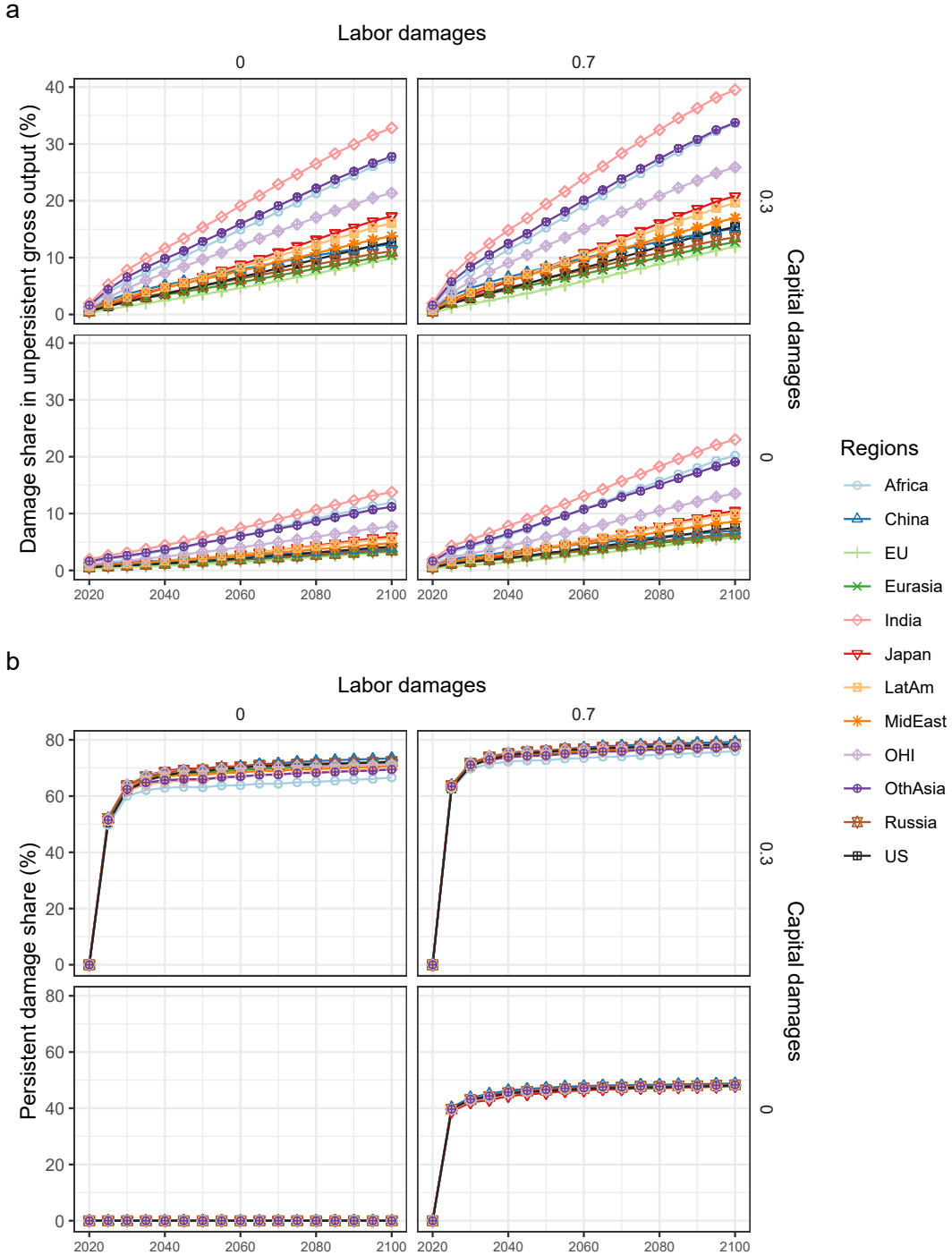


Figure A5: Share of total damages in gross unpersistent output (a) and Share of persistent damages in total damages (b), for different values of the decadal depreciation rate δ and of the persistence of labor damages λ , $f_K = 0.5$ and $f_L = 0.5$.

Note: In panel b) the share of persistent damages is shown starting in 2030 instead of 2020.

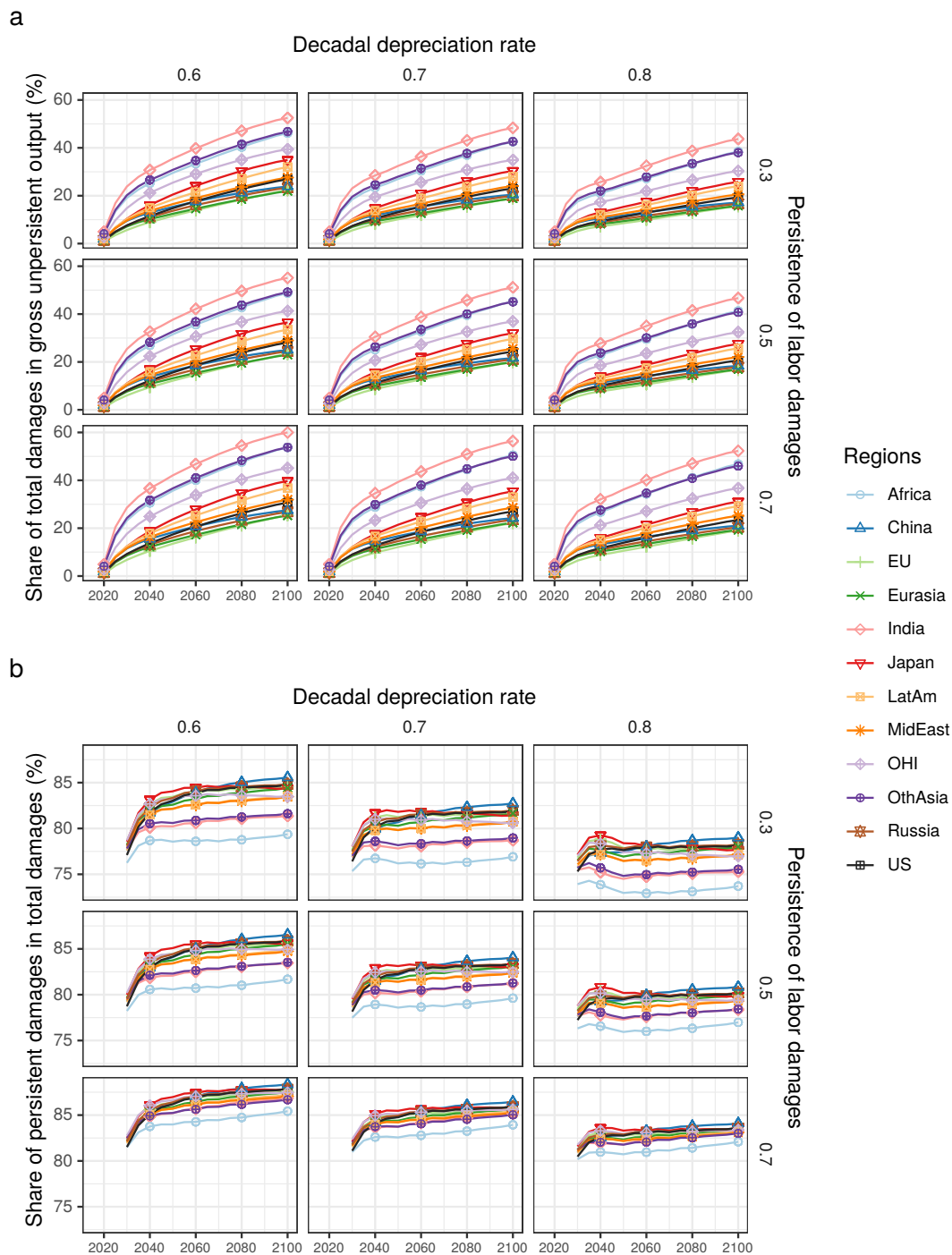


Figure A6: Global Gini index in the baseline case with all damages falling on output ($f_Y = 1$), $\delta = 0.7$, $\lambda = 0.5$.

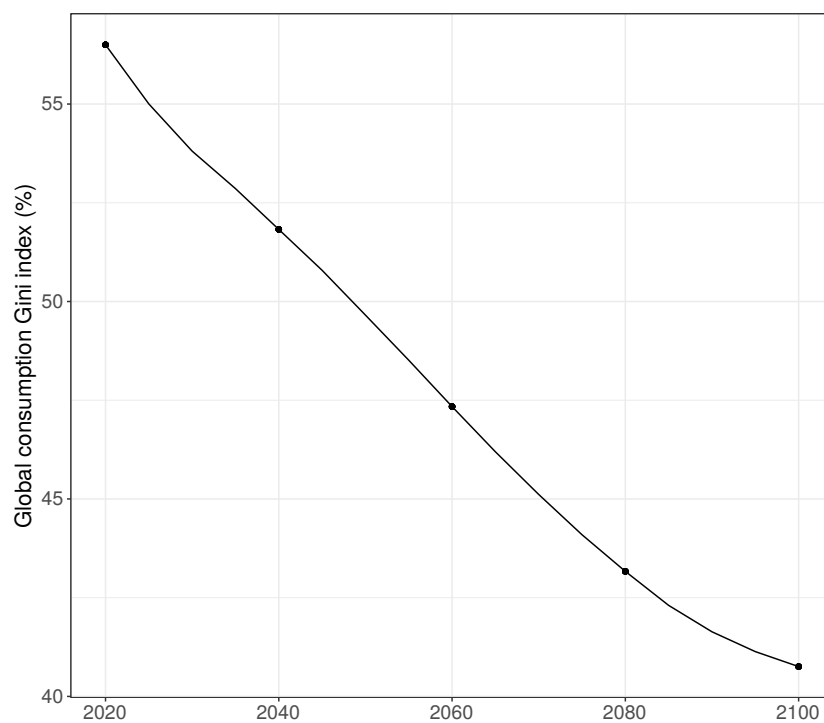


Figure A7: Regional Gini index in the baseline case with all damages falling on output ($f_Y = 1$), $\delta = 0.7$, $\lambda = 0.5$.

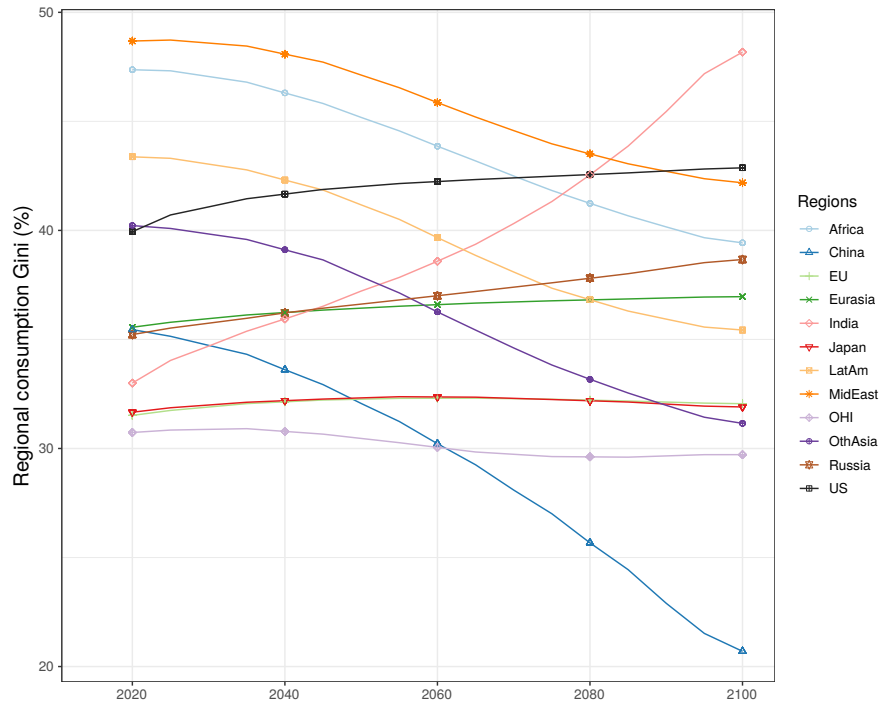
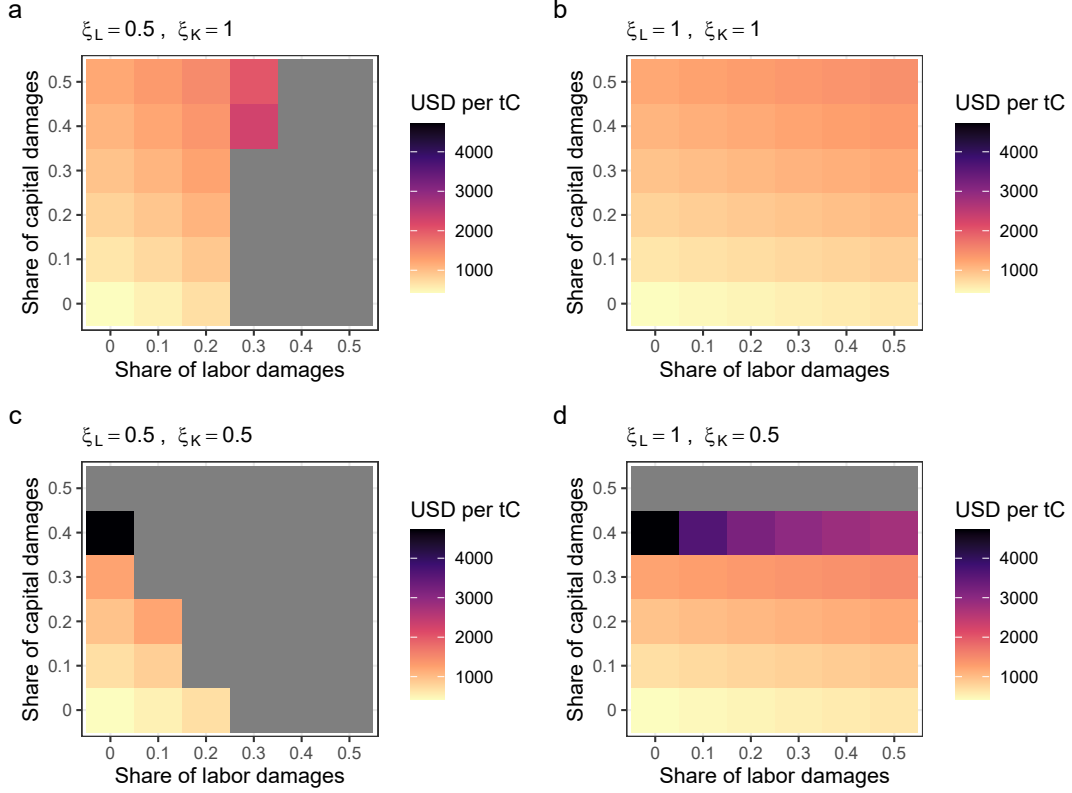
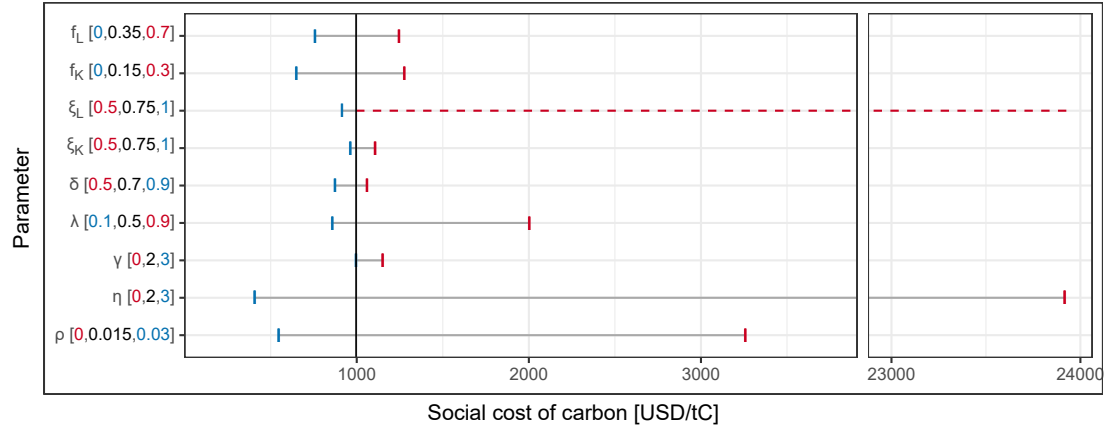


Figure A8: The social cost of carbon based on quintile CPC welfare function for different levels of channel-specific damages and combinations of elasticities ($\xi \in (0.5, 1)$), 2023, 2017 PPP USD, $\delta = 0.7, \eta = \gamma = 2, \rho = 0.015, \lambda = 0.5$



Note: The grey values indicate the combinations of capital and labor damages shares for which we do not compute the SCC because consumption drops to the boundary value of zero for a least one quintile.

Figure A9: Social cost of carbon based on quintile CPC welfare function for different levels of main parameters, holding all other parameters fixed at their central value, 2023.



Note: The SCC corresponding to the central parameter values (black) is marked by the vertical line. A blue (red) parameter value correspond to the lower (higher) SCC value. The x-axis is split at around 4000USD/tC. With $x_{i_L} = 0.5$ the income share of the poorest quintile in India reaches the boundary of zero.

Table A9: Social cost of carbon with quintile consumption per capita, for different channel-specific impacts (2023) in 2017 USD per tC, $\delta = 0.7$, $\lambda = 0.5$, $\rho = 0.015$, $\eta = \gamma = 2$.

a)	$SCC, \xi_K = \xi_L = 1$		
	$f_K \backslash f_L$	0	0.5
	0	432	634
	0.5	1212	1452

b)	$SCC, \xi_K = \xi_L = 0.75$		
	$f_K \backslash f_L$	0	0.5
	0	432	744
	0.5	1313	1710

c)	SCC_{nodist}		
	$f_K \backslash f_L$	0	0.5
	0	432	629
	0.5	1223	1458

Note: SCC is the social cost of carbon from quintile consumption per capita, and SCC_{nodist} is the social cost of carbon from quintile consumption per capita with damages proportional to total income by assumption (distributional impact of channel-specific damages neutralized).

Chapter 2

Different taxes or redistribution: How to shape a just global climate policy

Different taxes or redistribution: How to shape a just global climate policy?

Marie Young-Brun¹ Aurélie Méjean² Stéphane Zuber³

Abstract

This paper compares the effects of differentiated carbon taxes with those of a global harmonized tax associated with revenue recycling. Using a global Integrated Assessment Model representing national economies, we find that a uniform global carbon tax with lump-sum per capita recycling is the most welfare enhancing and inequality reducing policy. It can bring a welfare improvement equivalent to several percents of average global consumption until 2050. This scheme however implies large international transfers between countries. A more modest scheme, where 5% of global carbon revenues are targeted to compensate loss and damage in poor countries particularly vulnerable to the impacts of climate change, can result in strong inequality reductions, and significant welfare increases for low income countries. Differentiated taxes with country-level redistribution can have positive effects, especially on inequality, but those mainly happen after 2050, when poorer countries have larger carbon tax revenues to redistribute.

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1 Introduction

Climate change is one of the most pressing issues that societies have been facing for decades. However, research on climate policy often highlights the trade-off between taking action to address climate change and ensuring fairness. Indeed, evidence suggests that the burden of climate mitigation disproportionately falls on the poor (Ohlen-dorf et al., 2021). Additionally, poorer nations are less able to afford mitigation and adaptation policies (Dellink et al., 2009). In addition, the effects of climate change are not equally distributed, and vulnerable countries and households are disproportionately affected. This has led to growing concerns about climate justice, because those who suffer more from climate change are not necessarily those who contribute more to greenhouse gas emissions. These concerns have hindered the political acceptability of climate policy.

The equitableness of climate policy can be related to its design. One of the key mechanisms for addressing climate change is the implementation of a carbon tax. The tax is used to internalize the cost of carbon emissions, making polluters pay for the damages they cause. However, carbon taxes can have differential impacts on different groups and countries, depending on their income level, geographic location, and reliance on fossil fuels. This suggests that perhaps different groups should be taxed differently. Also, many policy proposals neglect the possibility of using the revenues from a carbon tax to address fairness concerns. Revenue recycling has been extensively studied, and the option of equal per capita refunds has been identified as a viable solution. Evidence suggests that recycling carbon tax revenues in a progressive way within a country can benefit most citizens immediately, and foster political acceptance (Klenert et al., 2018; Carattini et al., 2019). Global recycling also has potential to garner public support (Dechezleprêtre et al., 2022), and can address concerns about inequality and poverty (Soergel et al., 2021; Budolfson et al., 2021; Davies et al., 2014).

Global recycling of (part of) the carbon tax could entail transfers between different countries. Although it is sometimes considered difficult to implement such transfers, the idea that more developed countries should help developing ones to ensure their transition and adaptation to climate change is widely accepted in international negotiations. For instance, the Paris Agreement envisions financial transfers in the form of assistance (Paris Agreement, Article 9 UNFCCC, 2015):

- “1 - Developed country Parties shall provide financial resources to assist developing country Parties with respect to both mitigation and adaptation in continuation of their existing obligations under the Convention.
- 2 - Other Parties are encouraged to provide or continue to provide such support voluntarily.”

More generally, the recent debates about funding the “Loss and Damage” faced by developing countries have renewed the concerns that some transfers from developed

countries could be necessary to create a Loss and Damage fund. It is not completely settled how such a fund should be financed. Many of the financing mechanism to address Loss and Damage in developing countries listed in the Warsaw International Mechanism rely on voluntary contributions to subsidized risk management frameworks (e.g. catastrophe risk insurance, or catastrophe bonds). However, those approaches may become more expensive with increasing climate damages, and are not adequate to face slow-onset events or non-economic Loss and Damage (Gewirtzman et al., 2018). Robinson et al. (2021) argue that levies and taxes should instead be used, because they are seen as relatively fair, predictable, adequate, transparent, and additional. A global carbon tax on some types of emissions – for instance emissions from air travel and ship fuels that are not currently taxed – is a prominent solution being discussed (Roberts et al., 2017). Emissions from air travel and ship fuels amount to about 5% of total CO₂ emissions from human activities and could thus represent about 5% of the carbon tax if the tax is levied on all emissions.

In this paper, we study the effects of carbon taxation and its redistribution on consumption, inequality and welfare. To do so, we use an Integrated Assessment Model (IAM) in the spirit of Nordhaus (2017), which is built on the NICE model (Dennig et al., 2015; Budolfson et al., 2021). Our new version includes distribution, damages and mitigation at the country level – allowing to better assess the difference between country-level policies and more global policies that allow transfers between countries. We compare the effects of different policy designs for a transition meeting a 2°C temperature increase target: optimally differentiated taxes versus a global carbon tax; and in the case of the global carbon tax, different redistribution schemes – at the country level, at the global level, or somewhere in-between to reflect a loss and damage policy. The comparison is based on average consumption, on an inequality index (the Gini index), and on a more comprehensive welfare measure based on Atkinson (1970). To the best of our knowledge, our paper is the first to compare the effects of differentiated taxes with those of a global harmonized tax associated with recycling of the carbon tax revenue in an Integrated Assessment Model that includes within country distributions of income.

We find that uniform global carbon taxation with global per capita recycling would decrease global inequality and improve global welfare the most – with a gain equivalent to several percents of average global consumption until 2050 compared to the scenario without climate policy. However, governments might be reluctant to participate in revenue sharing at such a scale. If intergovernmental transfers are limited, our results show that differentiated taxes with domestic recycling of the revenues have the strongest impact on global inequality; while the most welfare gains can be achieved through uniform global taxation with 5% of revenues targeted to poor countries experiencing Loss and Damage and 95% of revenues recycled domestically.¹ The recycling

¹The 5% of revenues correspond to the 5% of emissions related to air travel and international ship-

option with 5% of global revenues targeted to Loss and Damage can result in strong inequality reduction, and significant welfare increases for low income countries particularly vulnerable to the impacts of climate change, while leaving middle and high income countries with resources to recycle domestically. In addition, we find that the gains from differentiated or global taxes with domestic recycling of revenues differ in terms of timing: a uniform tax yields larger benefits around 2040 in most countries, but differentiated taxes yield larger benefits earlier for rich countries and later for middle income countries.

2 Literature

It is often said that optimal global climate policy requires a worldwide single carbon tax. [Chichilnisky and Heal \(1994\)](#) have however shown that this is only the case if distributional issues are ignored, or if transfers are made between countries. Otherwise, a policy in which different regions face different carbon prices may be superior to one with a single global carbon price. [Sandmo \(2006\)](#) investigated the general question of optimal Pigouvian taxes for a global externality in a static framework. Similarly to [Chichilnisky and Heal \(1994\)](#), when lump-sum transfers are not possible, he found that optimal Pigouvian taxes on the externality should not be equalized across countries, but rather that poor countries should impose lower taxes than rich countries. [D’Autume et al. \(2016\)](#) show that the results carry over in a second-best setting in which governments have to resort to distortionary taxation to finance the public good. Recently, [Fleurbaey and Kornek \(2021\)](#) have shown in a general framework that the single price result holds only when income taxation transfers are possible, but that otherwise personalized prices for an externality can enhance social welfare if they are redistributive. [Hourcade and Gilotte \(2000\)](#) show that several factors of heterogeneity between countries make a uniform global carbon tax non optimal (in particular, utility from energy services, uneven access to the best available technologies, and country-specific side effects of a tax). Similarly, [Bataille et al. \(2018\)](#) argue that, with country-specific development objectives and constraints, multiple market failures and limited international transfers, carbon prices do not need to be uniform across countries.

Most of those results are in theoretical models, or in static frameworks. Very few papers have studied differentiated carbon prices (or carbon taxes) in IAMs. [Tol \(2001\)](#) and [Tol \(2002\)](#) have looked at differentiated emission abatement rates for different regions based on several approaches to global justice. Reviewing the literature, [Engström and Gars \(2015\)](#) argue that in IAMs in the vein of Nordhaus and Yang 1996’s RICE model, near zero lump-sum transfers and a uniform tax rate are optimal by as-

ping. [Lee et al. \(2021\)](#) compute that global aviation operations contribute to 3.5% of the net anthropogenic effective radiative forcing. [Traut et al. \(2018\)](#) mention that CO₂ emissions from international shipping represent about 2.2% of the global total CO₂ emissions.

sumption, due to the use Negishi weights. Of course, Negishi weights have been criticized precisely because they tend to cancel any concerns about inequalities between world regions. [Anthoff \(2009\)](#) calculates optimal differential prices using the FUND IAM without such Negishi weights. He finds that optimal mitigation is less stringent when using differentiated prices. [Budolfson and Dennig \(2020\)](#) perform the same exercise in the multi-region IAM NICE. They find that this entails significant welfare gains over the single price case.

The papers studying differentiating carbon prices typically do not take into account that the proceeds of a carbon tax can be redistributed at the country level or globally. However, many studies provide evidence that recycling a carbon tax can reduce inequality, limit poverty, and improve welfare. This has been shown with Computable General Equilibrium (CGE) models for several countries (see [Felder and van Nieuwkoop, 1996](#), for Switzerland; [Fragkos et al., 2021](#), for the European Union Member States; [Beck et al., 2016](#), for Canada; [Garaffa et al., 2021](#), for Brazil; [Rausch et al., 2011](#), for the USA) and also from input-output models with surveys (see [Vogt-Schilb et al., 2019](#), for sixteen countries of Latin America and the Caribbean). Using a CGE model of the Chinese economy, [Liang and Wei \(2012\)](#) have also shown that lump-sum transfers are the only revenue recycling scheme that can fully prevent the widening of income gap between rural and urban households due to the carbon tax. Similarly, [Young-Brun \(2023\)](#) provides evidence that recycling revenues from a carbon tax can limit the differential impacts for rural and urban households in some European countries. Some papers have also used microsimulation models to assess the distributional effects of carbon pricing with and without redistribution, and highlighted that lump-sum taxes can benefit the poorest households (see [Williams et al., 2015](#), for the USA; [Berry, 2019](#), and [Ravigné et al., 2022](#), for France; [Callan et al., 2009](#), for Ireland; [Steckel et al., 2021](#), for several countries in Asia). More generally, in a review of the empirical literature, [Köppl and Schratzenstaller \(2022\)](#) gather evidence that lump-sum transfers are better suited to mitigate the regressive effects of carbon taxes on lower income groups than a reduction of labour taxes. This suggests that we should focus on lump-sum transfers as a recycling scheme, which is what we do in the present paper.

The papers above focus on the distributive and welfare effects of redistributing carbon tax revenues within a country. [Feindt et al. \(2021\)](#) use a micro-simulation model to examine how a European carbon price will affect households in twenty-three countries of the European Union, and compare within country vs. European-wide redistribution. They show that national lump-sum redistribution can yield a progressive incidence, but that European-wide redistribution is more effective for the most affected households. Beyond the regional level, some papers have investigated the ability of a global carbon tax to improve access to infrastructures or to reduce inequality and poverty. [Jakob et al. \(2016\)](#) assess the potential of using revenues from global uniform carbon taxation to finance investment in infrastructure. They focus on a global carbon price pathway

for a 2°C scenario and find that recycling revenues at the country-level could be sufficient to finance universal access to most types of infrastructure, except in Sub-Saharan African countries, but that global redistribution schemes are necessary to finance such universal access in all countries. Using the integrated assessment model AIM, [Fuji-mori et al. \(2020\)](#) compare the revenues raised by a global carbon tax to the income gap relative to the absolute poverty line in 1.5 and 2°C climate scenarios. They argue that a share of carbon tax revenues from high-income countries could be used to help eradicate poverty in low-income countries. [Soergel et al. \(2021\)](#) assess the impact of a sustainable development pathway that combines climate policy with other policy interventions, including a climate and development scheme (international redistribution of part of carbon tax revenues, and within region equal per capita redistribution of the carbon tax revenues). They show that the sustainable development pathway can achieve a large reduction in inequality within regions, measured by the fraction of the population in relative poverty (below 50% of the national median income). Such a pathway can also significantly reduce extreme (absolute) poverty, although poverty does not completely disappear by 2030.

The paper closest to ours on the question of redistributing carbon tax revenues is [Budolfson et al. \(2021\)](#), which also uses the NICE model to study the distributive impact of climate policy. They focus on the case of a uniform global carbon tax where redistribution is made on an equal per capita basis within each of the original twelve regions of the RICE model. They show that equal per capita global redistribution of carbon tax revenues may yield positive welfare effects, at least in poorer regions and at the global level. We depart from their work by having redistribution at the country (rather than region) level, combined in two of our scenarios with some international transfers towards the poorest countries. To achieve this improved granularity, we develop a version of NICE with 179 countries. To the best of our knowledge, only the RICE50+ model by [Gazzotti \(2022\)](#) achieves a similar degree of granularity in an IAM including income heterogeneity within a region. However, they do not include within-country inequality and do not have country-level modelling for many Sub-Saharan African countries that are likely benefiting the most from a global redistribution.

One of the main contribution of our paper is to bridge the gap between the approaches proposing differentiating the carbon tax and those studying the potential benefits of international transfers and redistribution in the case of a uniform carbon tax. We ask the following questions. Assume that we cannot achieve international transfers, how much welfare gains can differentiated carbon taxes still bring? Assume on the contrary that we need a uniform carbon tax (for efficiency reasons, or to avoid carbon leakage), how much welfare gains can stem from implementing appropriate transfers? Those question are similar to those raised by [Bauer et al. \(2020\)](#). They use the ReMIND-MAgPIE integrated assessment model to study the efficiency-sovereignty²

²Sovereignty referring to the "nation states' aim to maintain governing control of economic re-

trade-off of using uniform versus differentiated carbon tax in a 2°C scenario. Their objective is different from ours in that they focus on implementing an “equitable effort sharing” rule across the twelve ReMIND regions, rather than maximizing welfare or reducing inequality. In addition, they do not represent income heterogeneity within regions, thus loosing some of the benefits of redistribution for within country inequality. And they also work at the more aggregate twelve regions levels, not the country level.

3 Methods: A global integrated assessment model with inequality within countries

We update the Nested Inequalities Climate Economy model (NICE), a global climate policy model that features within-region inequality for the twelve regions of the RICE2010 model (Dennig et al., 2015) with sub-regional consumption quintiles. We build on the latest version of the model, which allowed for carbon tax revenue recycling (Budolfson et al., 2021). We modify the model to investigate carbon tax and revenue recycling scenarios at the country and global levels. To do so, we augment the granularity of the model, and disaggregate the twelve original regions into 179 countries³.

3.1 Within country inequality and distributional impacts

While the previous versions of the NICE model featured consumption quintiles (Dennig et al., 2015; Budolfson et al., 2021), we here introduce consumption deciles. We calibrate baseline deciles using country income gini projections until 2100 in the SSP2 scenario, as provided by Rao et al. (2018). We assume that for each country i , income is distributed across deciles according to a lognormal distribution $LN(\mu_i, \sigma_i)$. We can deduce standard deviations σ_i from country Gini indices.⁴ From the standard deviations σ_i , we can deduce a Lorenz curve for each country and each time step, from which we obtain country income deciles over time. We use a transformation vector to derive consumption deciles from income deciles, following the approach proposed by Pinkovskiy and Sala-i Martin (2009).

sources by limiting international transfer payments”.

³This set of countries corresponds to the set represented in the Shared Socioeconomic Pathways, with Somalia, Venezuela, New Caledonia and Trinidad and Tobago removed due to data limitations.

⁴Cowell (2011) indeed show that, in the case of a lognormal distribution, we have the following relation:

$$\sigma_i = \sqrt{2} \cdot \Phi^{-1} \left(\frac{Gini_i + 1}{2} \right),$$

where Φ^{-1} is the inverse of the cumulative distribution function of a standard normal distribution.

Climate damages, mitigation costs and carbon tax burdens are distributed across deciles using consumption elasticities (see [Dennig et al., 2015](#), for the use of elasticities in the modelling of distributional impacts in NICE). The initial burden of a carbon tax is the distribution of mitigation costs and carbon tax payments before tax revenues are recycled and redistributed. Within each country, mitigation costs and carbon tax payments are assumed to be distributed across deciles using the same consumption elasticity of the initial burden for a given country at a given time. Consumption elasticity of the initial burden is calibrated using the estimation provided in [Budolfson et al. \(2021\)](#), which they derive from a review of the literature on the initial burden of carbon taxation across countries before the redistribution of tax revenues. The consumption elasticity of the initial burden $w_{i,t}$ of country i at time t is thus given by: $w_{i,t} = \hat{\alpha} + \hat{\beta} \cdot \log y_{i,t}$, with y the GDP per capita. Parameters $\hat{\alpha}$ and $\hat{\beta}$ are set at 3.22 and -0.22, respectively. This elasticity is thus endogenous, as it depends on GDP per capita computed by the model at each time step.

The distribution of climate damages across deciles could range from being inversely proportional to consumption (damage elasticity of consumption $\xi = -1$), to being proportional to consumption ($\xi = 1$) or more than proportional to consumption ($\xi > 1$). The literature does not yet provide empirical estimates available across countries on the differentiated impact of climate damages across income or consumption quantiles. In absolute value, the richest will suffer more from climate change than the poorest, simply because they have more to lose. Therefore, we can assume that the distribution of damages across deciles will not be flat, i.e., $\xi > 0$. We assume that damages are likely to be less than proportional to income or consumption, i.e., $\xi < 1$. We set the consumption elasticity of damages at 0.9.

3.2 Country level emissions and abatement

Country level emissions intensities of output are computed until 2100 from projected GDP streams based on the SSP2 trajectory, and from emission trajectories based on the ReMIND model in a business-as-usual scenario.

Next, we model country level mitigation trajectories. We use the same abatement cost function as in [Barrage and Nordhaus \(2023\)](#), but differentiate the multiplicative parameter by country. As a result, the cost of abatement as a share of gross output in country i for a mitigation rate of μ_i is

$$\Lambda_{it} = \theta_{1,it} \mu_{it}^{\theta_2},$$

with $\theta_2 = 2.6$. We calibrate the multiplicative parameter $\theta_{1,it}$ using the global backstop price from [Barrage and Nordhaus \(2023\)](#) and the assumption that the marginal cost of abatement at a 100% mitigation rate per unit of emission (in USD per unit of emissions) is equal to the global backstop price in every country. Details can be found

in Appendix A.1. As a result, a global and uniform carbon tax leads to the same abatement rate trajectory in every country, but to heterogeneous abatement costs in terms of share of gross output. Finally, we rule out negative emissions by setting the maximum mitigation rate to 100%.

3.3 Country level climate damages

The global temperature change caused by greenhouse gas emissions is modeled using mimiFaIRv2 (Errickson et al., 2022), a Julia implementation of the Finite Amplitude Impulse Response model (FaIR). FaIR is a climate model designed to reproduce the global climate system's response to greenhouse gas emissions with good accuracy, and to capture non-linearities in the carbon cycle, while keeping complexity level and run-time low (Leach et al., 2021). The global temperature anomaly is downscaled to a country level temperature anomaly with pattern scale coefficients taken from the Coupled Model Intercomparison Project Phase 6 (CMIP6, O'Neill et al., 2016).

Following the usual practice in the literature, we assume that climate damages as a share of GDP are a function of the temperature anomaly. But contrary to most existing approaches (in particular models derived from the RICE model by Nordhaus and Yang, 1996), the country damage function depends on the local temperature anomaly that we obtain through our downscaling methodology. More specifically, the country-level damage function has the generic form:

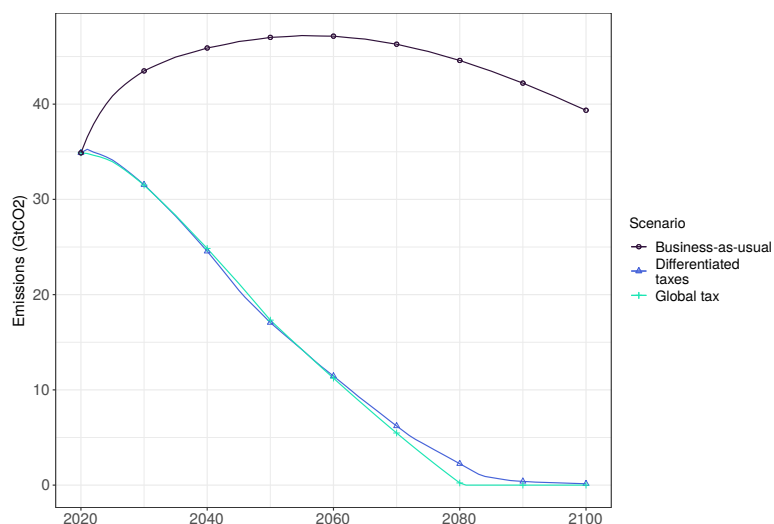
$$\delta_i(\Delta_i T) = \beta_{i1} \cdot \Delta_i T + \beta_{i2} \cdot (\Delta_i T)^2,$$

where $\Delta_i T$ is the local temperature anomaly and $\delta_i(\Delta_i T)$ is the damage loss measured as a share of GDP lost for a given temperature anomaly. Parameters β_{i1} and β_{i2} are country-specific parameters that are calibrated to represent a general relationship between temperature increase and climate damages, as predicted in the econometric analysis by Kalkuhl and Wenz (2020). More details can be found in Appendix A.2.

3.4 Globally uniform and differentiated carbon taxes by country

We implement 2°C scenarios with either a global uniform tax or differentiated taxes by country. For the global uniform tax, we find a carbon tax trajectory that abides to that constraint and that is linearly increasing with time. For the differentiated tax by country, we use a rule derived from maximisation of the sum of country utilities under an emission budget constraint. The rule expresses the ratio of carbon taxes in a country relative to the reference as a function of the savings rate and marginal utility of the country and the reference. We choose the United States as the reference, and find the linear tax trajectory that best approximates the global carbon tax trajectory in terms of emissions before 2050. The detailed method is presented in Appendix A.3.

Figure A10: CO_2 emissions ($GtCO_2$) for the business-as-usual scenario SSP2 (black), and for the 2°C scenarios implemented via a global uniform tax (blue green) and via differentiated taxes across countries (dark blue).



The resulting emissions are presented in Figure A10: the 2°C emission trajectories are very close, and total carbon budgets over the 2020-2100 period differ only by 16 $GtCO_2$ (1.4% of the total carbon budget compatible with limiting global temperature increase to 2°C). Figure A.1 in the Appendix presents a few examples of implemented tax trajectories in the differentiated tax alternative of the 2°C scenario (dark blue) for countries on all continents and with various income levels (Guinea, India, China, Indonesia, Brazil, Dominican Republic, Republic of Korea, Germany and the USA), and the global uniform carbon tax (blue-green). By construction, the global uniform carbon tax is always lower than the differentiated taxes in high income countries (e.g., USA, Germany and the Republic of Korea).

3.5 Alternative revenue recycling options

Our two carbon tax scenarios compatible with 2°C result in aggregate revenues up to 4 trillion dollars (up to 1.5% of global GDP) for the uniform global tax, and up to 3 trillion dollars (up to 1.25% of global GDP) for the differentiated taxes (Figure A.8). We consider six alternatives regarding the distribution of carbon tax revenues.

In the case of differentiated taxes by country, we explore two options: one where the recycling of revenues is neutral, i.e., carbon tax revenues are refunded within each country according to the initial income distribution; the other where carbon tax revenues are redistributed as equal per capita payments within countries.

In the case of a global uniform carbon tax, we consider four alternatives. The first two options mirror the previously described scenarios for differentiated taxes: the first one assumes a redistribution of the revenues of the global carbon tax which does not change the initial distribution, the second assumes that the revenues of the global tax are redistributed on an equal per capita basis within each country.

Two additional alternatives are considered. The first one assumes that all tax revenues are collected globally and redistributed equally per capita at the global level. This scheme thus induces international transfers between countries, i.e., revenues raised in a given country are not necessarily redistributed within that country.

The last option seeks to represent a possible Loss and Damage policy. It assumes that a given share of the revenues are redistributed to low and low-middle income countries⁵ only, and proportionally to the value of a risk index derived from the INFORM Index for Risk Management (Marin-Ferrer et al., 2017).⁶ Denoting J the set of low and low-middle income countries, the share of country $i \in J$ in the global Loss and Damage transfers π_t^{LD} writes

$$\frac{\pi_{it}^{LD}}{\pi_t^{LD}} = \frac{\iota_i N_{it}}{\sum_{j \in J} \iota_j N_{jt}} \quad (3.5.1)$$

with ι_i the risk index of country i and N_{it} the population of country i in period t .

We set the share of revenues allocated to Loss and Damage transfers at 5% of global carbon tax revenues. As explained in the introduction, this option can be seen as imposing a global carbon tax, but only taxation related to air travel and ship fuels is used to finance a Loss and Damage fund that is directed towards poorer countries. With our assumption, the rule for allocating resources to countries is based on their vulnerability to climate risk assessed by our Risk Index. This can be thought of as an implementation of the Loss and Damage fund currently discussed. In that scenario, the remaining carbon tax revenues are redistributed within countries on an equal per capita basis. In Section 4.4, we discuss other possible implementations based on the damages faced by the poorest countries.

The results section below describes the consequences of these policy alternatives.

4 Results

4.1 Global results

Introducing a global carbon tax or differentiated carbon taxes at the country level implies very different burden sharing of emission reductions. The burden sharing in the

⁵World Bank classification, see Appendix A.5 for the list.

⁶See Appendix A.6 for a description of our modification of the INFORM Risk Index.

differentiated tax case is only based on fairness considerations – not efficiency considerations. On the contrary, a global carbon tax equalizes the marginal cost of abatement in all countries, which is more cost-effective for a given level of global emission reduction. So, unsurprisingly, we find that differentiating carbon taxes implies higher total abatement costs at the global level. Figure A11 indeed represents the percent change in average per capita consumption at the global level compared to business-as-usual (BAU) in the two tax scenarios.

Figure A11: Difference in consumption per capita in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives. Note that all global tax curves coincide (red line), and both differentiated tax curves coincide (blue line).

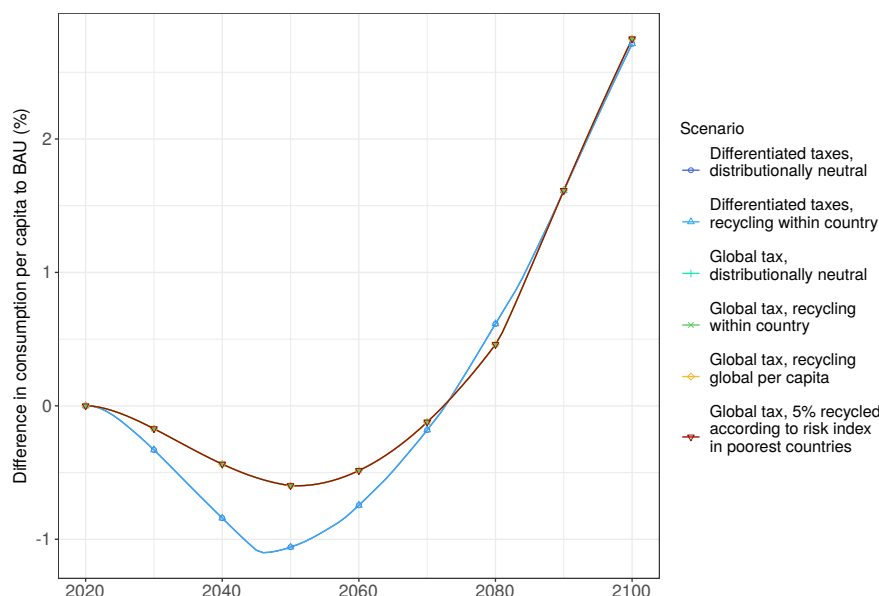
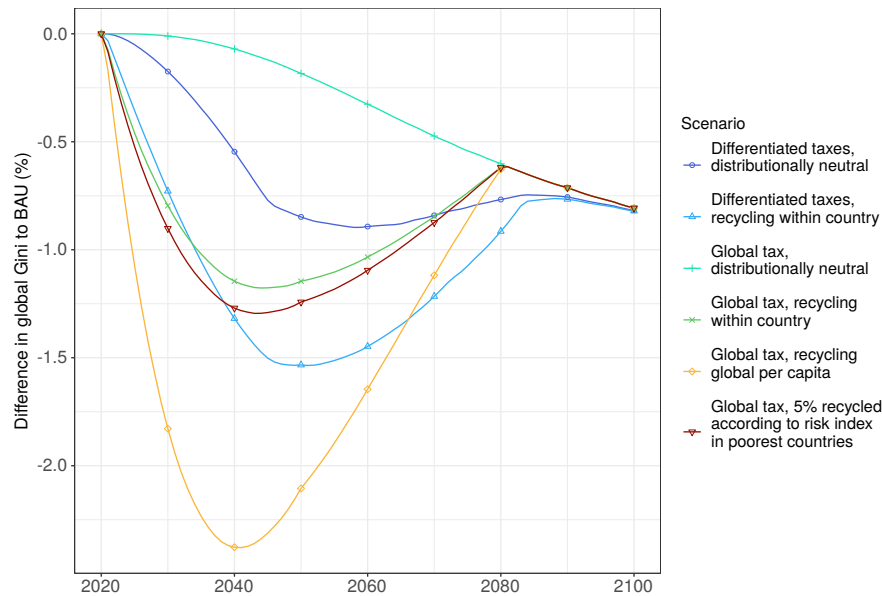


Figure A12 shows contrasted results in terms of global inequality measured by the global consumption Gini. The global consumption Gini is calculated using per capita consumption of all deciles in all countries, weighted by the population of each decile. The results show that global inequalities are reduced in all 2°C scenarios compared to the business-as-usual, including in both cases where tax revenues do not alter the distribution (blue-green and dark blue). This is because damages are assumed to be distributed disproportionately to consumption across deciles (the consumption elasticity of damages is set to 0.9), and those damages are partly avoided in the 2°C scenario. In addition, the mitigation costs are progressive in some poorer countries in the shorter run.

As argued before, differentiated taxes can, in the absence of redistribution, improve fairness and equity. Comparing the cases with distributionally neutral recycling, differentiated taxes (dark blue) result in a larger reduction in the global Gini than a uniform global tax (blue-green). In the absence of international transfers and within country lump-sum recycling, differentiated taxation indeed improves global equity with respect to uniform taxation.

Figure A12: Difference in the global consumption Gini index in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives.

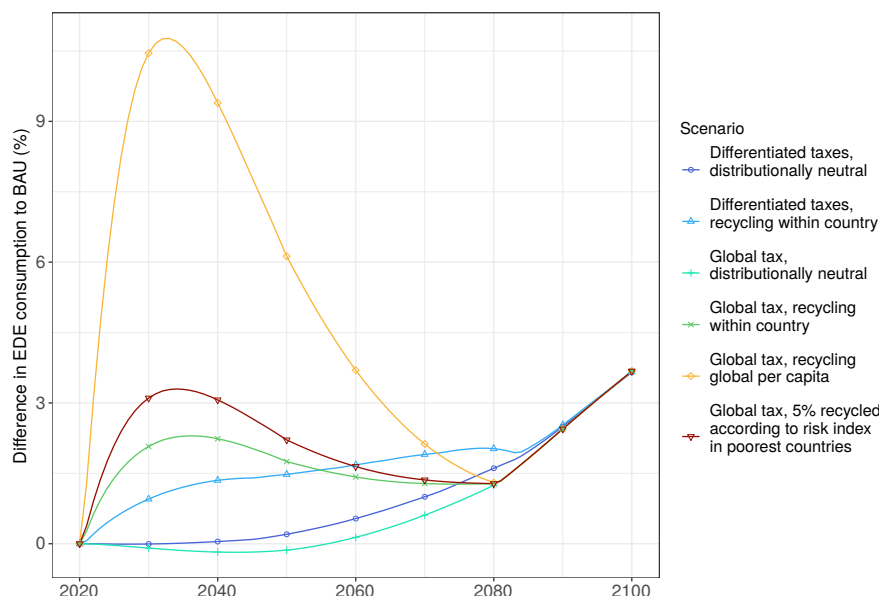


Next, all redistribution schemes reduce inequalities compared to a neutral redistribution, until carbon tax revenues fall to zero (in 2080 in the case of a global carbon tax, in 2100 in the case of differentiated taxes). The policy alternative that reduces global inequalities the most is the global uniform tax with equal per capita revenue recycling (orange). It is superior to other policy alternatives until after 2060, when carbon tax revenues start to dwindle.

Looking at the schemes with recycling within countries, uniform and differentiated carbon taxes yield approximately the same reduction in the global Gini until the middle of the 2030s. After that point, differentiated taxes with intra-country recycling (light blue) result in larger Gini reductions than a global tax with intra-country recycling (green). The "Loss and damage" scenario (red), where 5% of a global carbon tax revenues are recycled to the poorest countries according to a climate risk index, gives

slightly superior but similar results in terms of consumption Gini as a global tax with recycling within countries (green).

Figure A13: Difference in the equally distributed equivalent (EDE) consumption in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives.



The equally distributed equivalent (EDE) consumption is the level of consumption that, if given to each member of a given population, yields the same level of welfare as the actual distribution of consumption. Its calculation is described in Appendix A.7. This is a measure of welfare, and can be used to rank policy alternatives. Our results show that a global uniform tax with equal per capita redistribution of carbon tax revenues is superior to all other policy alternatives according to that metric (Figure A13). This result mirrors the global consumption Gini presented above. The rest of the hierarchy of policies that prevailed in terms of global consumption Ginis is not fully preserved here, as the global tax with a "Loss and Damage" fund (red) is superior to the differentiated taxes with recycling within countries (light blue) in terms of equally distributed equivalent consumption gains until 2060. This is because welfare gains combine gains (and losses) of average consumption on the one hand, and inequality reduction on the other hand (see Appendix A.7). The differentiated tax case induces efficiency loss (i.e., larger losses in terms of average consumption) compared to a global carbon tax. The gain of equally distributed equivalent consumption in 2°C scenarios compared to the BAU also depends on the assumed inequality aversion, here set at $\eta = 1.5$, in line with Barrage and Nordhaus (2023). Our sensitivity analysis (Appendix

A.9) shows that a lower inequality aversion does not change the ranking of policies in terms of EDE consumption. As expected, the size of the overall welfare gain decreases when inequality aversion decreases in the all scenarios with redistribution.

4.2 Regional results

We compute aggregates for twenty geographical regions from the World Population Prospects (UN, 2022). We display the results for twelve of those twenty regions.

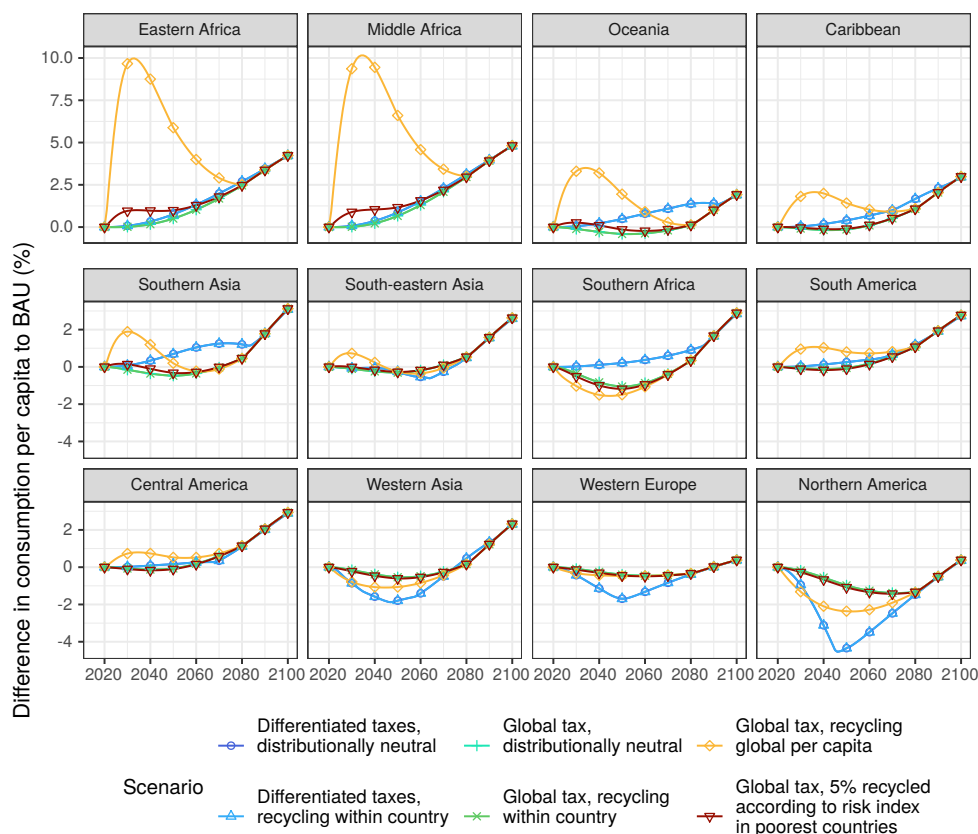
While the global results show an aggregate loss in consumption per capita in the 2°C scenario compared to the business-as-usual in the short to medium term (Figure A11), regional results can give a more contrasted view, depending on the policy alternative (Figure A14).

In the scenarios without international transfers, differentiated taxes (dark blue and light blue) and a uniform global tax (blue-green and green) tend to increase consumption per capita in the poorest regions and decrease consumption per capita in the richest regions with respect to the BAU. This is because, in those regions, the gains from avoiding damages quickly exceed the costs of reducing emissions. For the poorest regions, such as Eastern Africa or Middle Africa, differentiated and uniform taxes result in very similar increases in consumption per capita. This is explained by large avoided climate damages and low costs from emissions reduction (because emissions are low in the short run). For middle income regions, differentiated taxes tend to raise consumption per capita by a few percents with respect to the BAU, whereas a global tax tends to slightly decrease consumption per capita. By contrast, in the richer regions, both differentiated and global taxes result in a decrease in consumption per capita before 2080, and differentiated taxes decrease consumption per capita more than a global uniform tax. These differences reflect how, in the absence of international transfers, the differentiated carbon tax shifts part of the burden of emissions abatement to richer regions.

In the case of a global uniform tax where tax revenues are recycled on an equal per capita basis (orange), high income regions (Northern America, Western Europe) experience a relative loss in consumption per capita compared to the BAU, while several lower income regions gain in the short to medium term (e.g., Eastern Africa, Middle Africa, Southern Asia, South America, the Caribbean). Those regions benefit from the global redistribution of carbon tax revenues. Finally, in the Loss and Damage scenario, which features a transfer of 5% of global revenues to the low and middle income countries in proportion to a population weighted climate risk index, most regions are very little affected, while the poorest regions gain a few percents in consumption per capita.

Next, we study the impact of the tax and recycling schemes on regional inequality. Figure A15 shows the regional Gini, computed from the consumption deciles of countries within the region. A global uniform tax with equal per capita transfers results

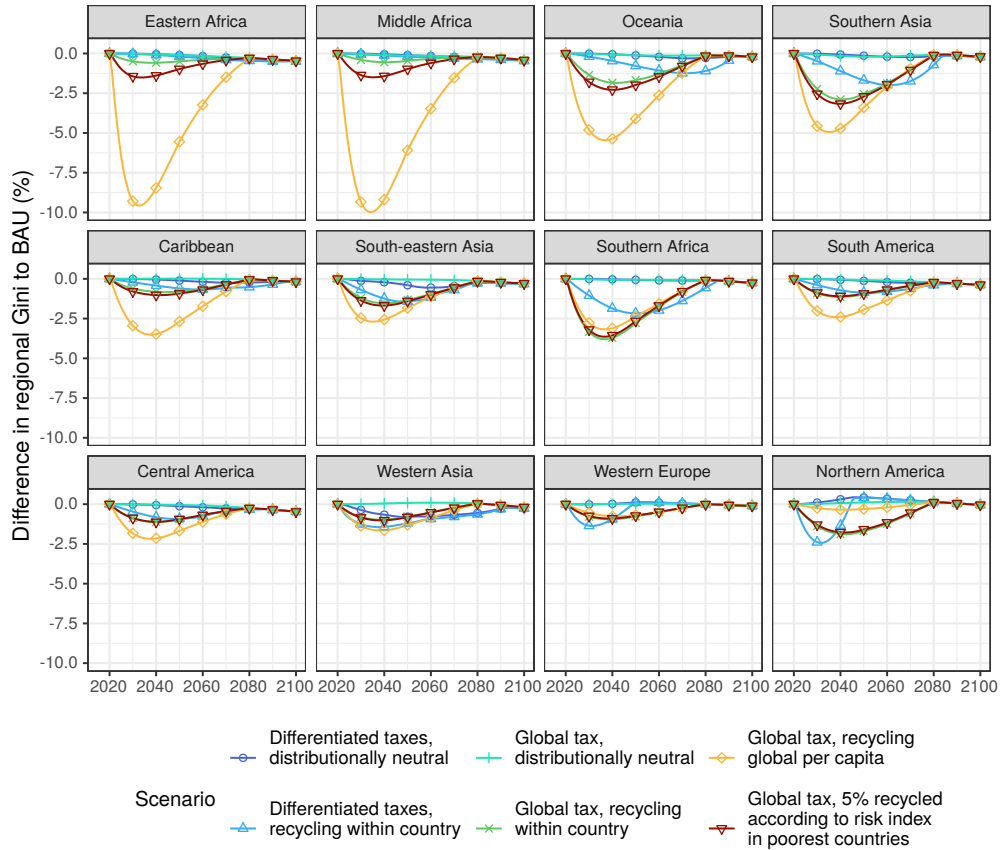
Figure A14: Difference in regional consumption per capita in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives.



in the strongest inequality reduction in most regions. The only exceptions are richer regions where the carbon tax revenue per capita is higher than the global average.

Comparing differentiated taxes and global uniform taxes with within-country recycling, the ranking in terms of inequality reduction is heterogeneous across regions and time. In the poorest regions such as Eastern and Middle Africa, emissions are low in the BAU, resulting in limited potential for carbon taxation to raise revenues for recycling at the domestic level. In middle income regions, uniform taxation with domestic recycling (green) brings stronger inequality reductions earlier on in the century compared to differentiated taxation with domestic recycling (light blue). The reverse occurs in richer regions such as Western Europe or Northern America, where differentiated taxes bring stronger inequality reduction early on, due to the revenues generated

Figure A15: Difference in the regional consumption Gini in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives.

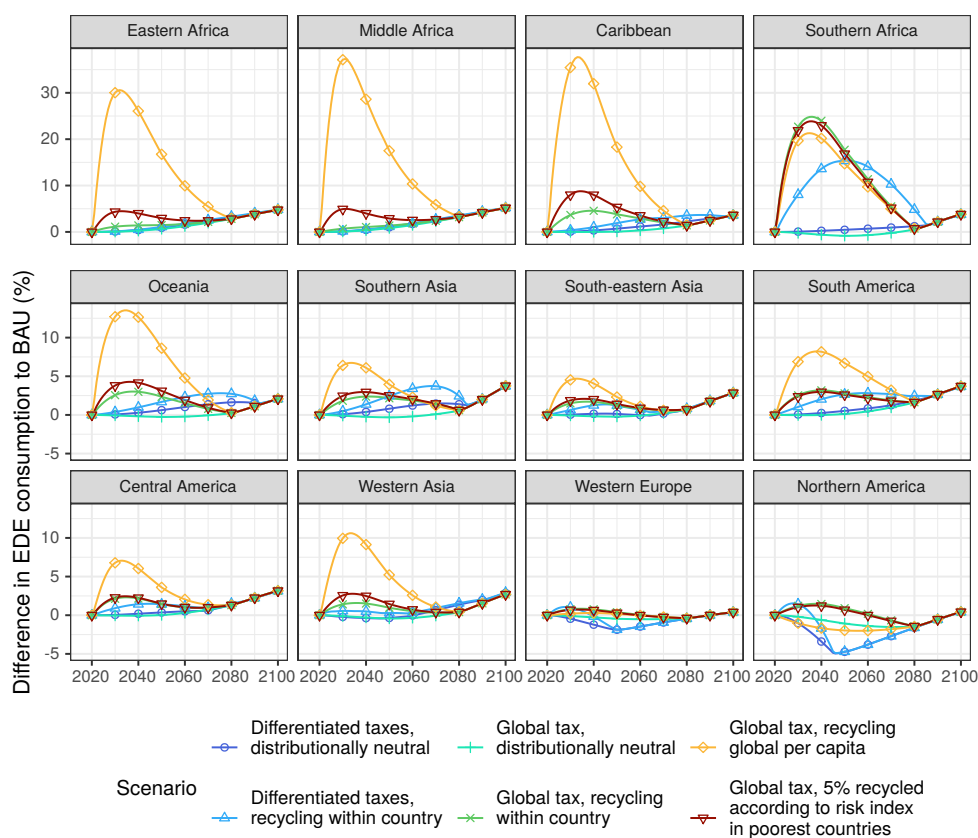


in the first decades by stronger mitigation policy.

The contrast between regions is even more salient when looking at regional equally distributed equivalent consumption (Figure A16). In the scenarios without international transfers, recycling tax revenues within countries brings welfare gains with respect to the distributionally neutral scenarios. For differentiated and uniform taxes, within-country recycling increases EDE consumption with respect to the business-as-usual in middle income and rich countries, during the period before full regional decarbonization. The impact is particularly notable in regions with strong within-country inequality, such as Southern Africa. In addition, in high income regions, the differentiated tax alternative with no recycling (dark blue) brings losses in EDE consumption compared to business-as-usual of the same magnitude as the consumption per capita

losses, implying that the shift in the decarbonization efforts to richer regions is not at the expense of more inequality within the richer regions.

Figure A16: Difference in the equally distributed equivalent (EDE) regional consumption in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives.



Both scenarios with international transfers (orange and red) result in increases in EDE consumption with respect to the business-as-usual in most regions, except the richest. This is even the case for some regions where consumption per capita decreases with respect to the BAU in these scenarios, e.g., Southern Africa, which experiences losses in consumption per capita, but gains 20% in EDE consumption with respect to the BAU in the case of a global tax with global per capita recycling.

The gains in inequality-weighted welfare reflect the impact of the tax and transfers schemes on between-country and within-country inequalities. First, the global

uniform tax, associated with global per capita recycling or Loss and Damage targeted recycling, results in transfers from richer and more emitting countries to poorer countries, thus reducing between-country inequality. Second, recycling tax revenues via lump-sum transfers within countries renders the policy progressive at the country level (Felder and van Nieuwkoop, 1996; Fragkos et al., 2021; Beck et al., 2016; Garaffa et al., 2021; Rausch et al., 2011; Vogt-Schilb et al., 2019).

Global per capita recycling is the option that results in the highest increases in EDE consumption in most regions. Exceptions are richer regions such as Western Europe and Northern America or very unequal regions such as Southern Africa, for which the uniform tax with within-country recycling (green and red) performs best.

4.3 National level results

In this section, we discuss the results in terms of equally distributed equivalent consumption for all policy alternatives (Figures A17 and A18).

National results mirror to some extent regional results in terms of the various impacts of 2°C policies. High-income countries experience welfare losses in scenarios with distributionally-neutral recycling or with global recycling, and even in some cases in scenarios with per capita recycling within countries (especially for differentiated taxes and in 2050, top right maps in Figures A17 and A18). On the contrary, poorer countries experience gains both in the nearer term (2030) and in the longer run (2050), whatever the scenario. But gains are larger and more widespread in the case of a global recycling per capita (bottom left maps in Figures A17 and A18).

The maps with country results highlight the very large diversity of country-level welfare impacts in scenarios with per capita recycling: the welfare impact ranges from losses larger than 5% to gains larger than 5% of welfare equivalent per capita consumption. Even within a region, individual country situations can vary substantially. For instance, in Western Asia, there are very contrasted situations in terms of average consumption level, emissions and inequalities, that can result in different preferred policies across countries. In 2030, the global tax with global recycling would be the worst scenario for Saudi Arabia, Oman and the United Arab Emirates, but among the best scenarios for Yemen, Syria and Jordan. Generally, the preferred policy depends on baseline inequality, the level of emissions (and cost of abatement), and the level of development.

Note also that, in the case of per capita recycling within a country, some rich countries can benefit more from the differentiated tax scheme than poorer countries. This is for instance the case of the USA in 2030, having more welfare gains than Brazil or Algeria (top right map in Figure A17). This may seem counter-intuitive as differentiated taxes are usually thought to be a better solution to mitigate transition costs in developing countries compared to a globally uniform tax when unlimited intergovernmental transfers are impossible (Chichilnisky and Heal, 1994; Hourcade and Gilotte, 2000;

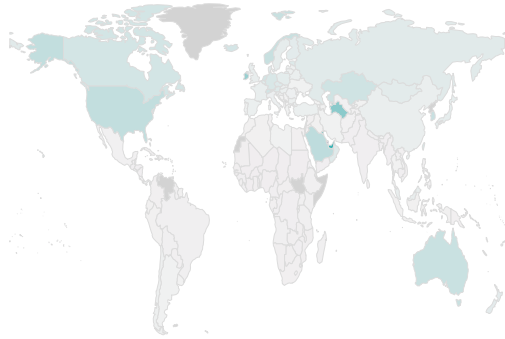
[D'Autume et al., 2016](#)). But this seemingly paradoxical conclusion can be explained by the fact that our scenarios include revenue recycling, which is not usually considered in other works. Recycling tax revenues can bring welfare benefits, especially in more unequal countries.

It is also noticeable that different countries face different timing for gains and losses. Some poor countries (e.g., India, but also South American countries like Bolivia), tend to gain more in the near term (2030) in the global uniform tax alternative compared to the differentiated tax setting (in the case with within country recycling). But then the differentiated tax setting can become preferable in the longer run (2050). The reverse is true for richer countries like the US.

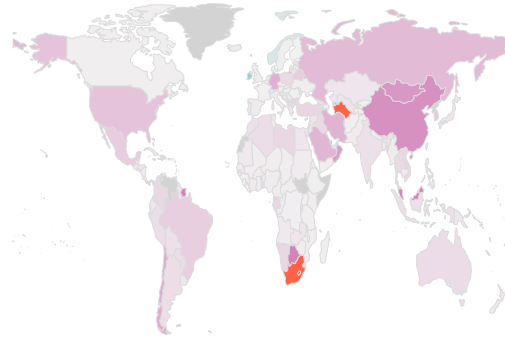
Figure A17: Difference in the equally distributed equivalent (EDE) consumption in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives, in 2030.

Difference in EDE consumption to BAU (%), 2030

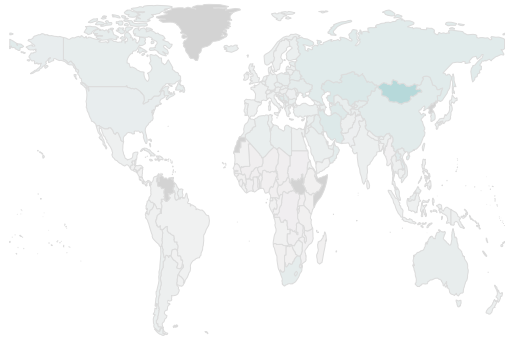
Differentiated taxes, distributionally neutral



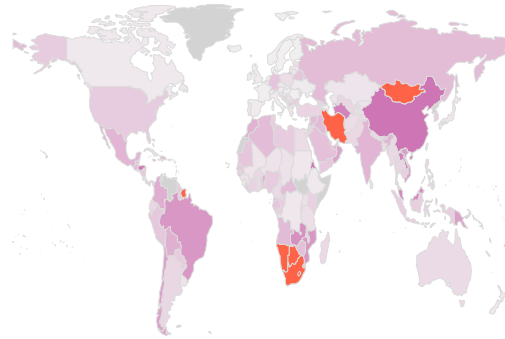
Differentiated taxes, recycling within country



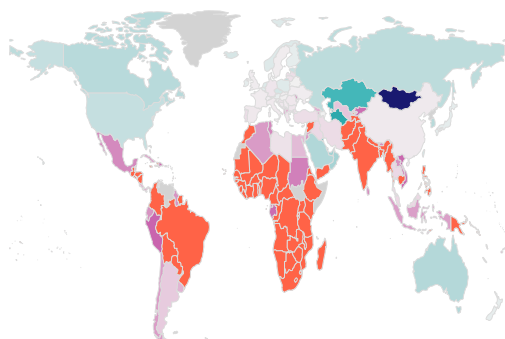
Global tax, distributionally neutral



Global tax, recycling within country



Global tax, recycling global per capita



Global tax, 5% recycled according to risk index in poorest countries

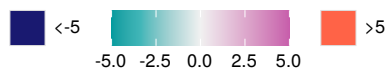
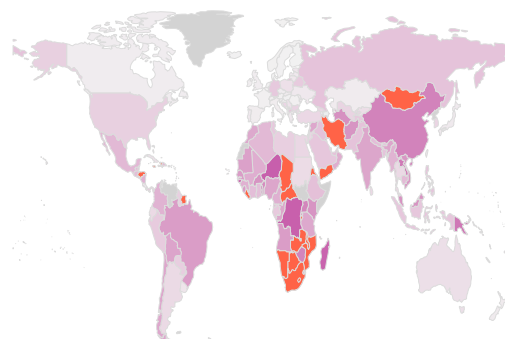
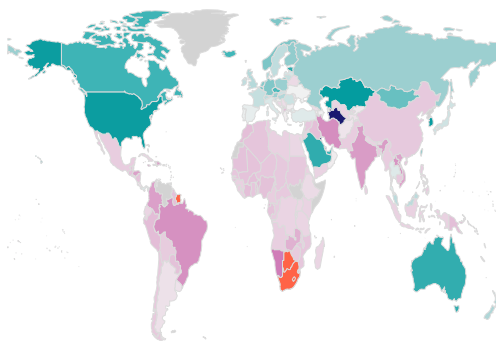
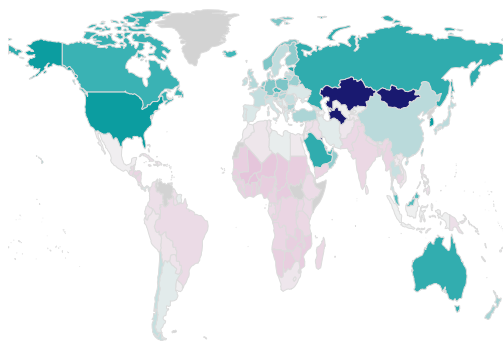


Figure A18: Difference in the equally distributed equivalent (EDE) consumption in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives, in 2050.

Difference in EDE consumption to BAU (%), 2050

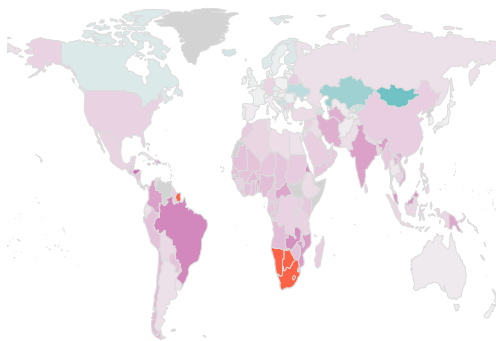
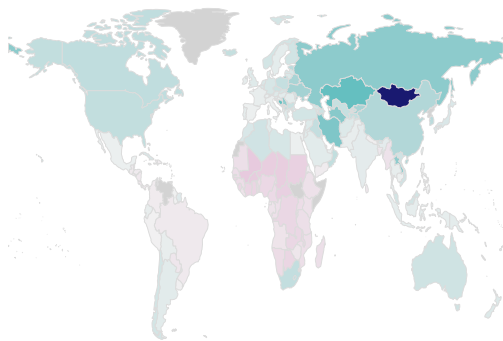
Differentiated taxes, distributionally neutral

Differentiated taxes, recycling within country



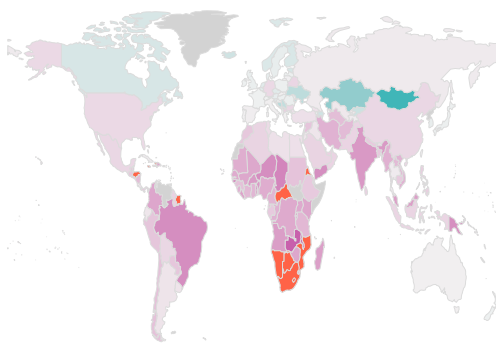
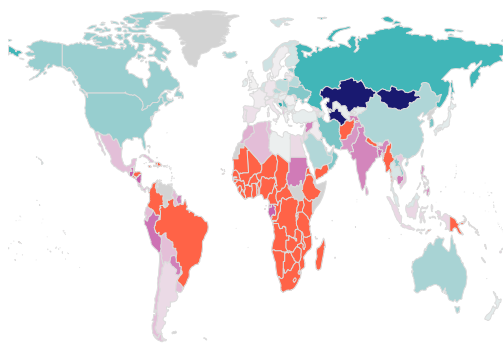
Global tax, distributionally neutral

Global tax, recycling within country



Global tax, recycling global per capita

Global tax, 5% recycled according to risk index in poorest countries



4.4 Alternative Loss and Damage redistribution schemes

In the main results, we have used a risk index to target transfers in the Loss and Damage redistribution scheme. Using such a risk index would mean focusing on catastrophic and/or extreme climate events when compensating poorer countries. We could then neglect slow-onset events or non-economic impacts that may be very significant parts of the Loss and Damage experienced in some countries. For instance, small islands are very vulnerable to sea-level rise that may jeopardize their mere existence.

We thus test two alternative redistribution schemes that are based on modeled climate damages. Climate damages give a more comprehensive picture of the impacts poor countries will face. The first scheme uses population-weighted relative damages, i.e., damages as a share of output. Denoting J the set of low and low-middle income countries⁷, the share of country $i \in J$ in the global Loss and Damage transfers π_t^{LD} writes

$$\frac{\pi_{it}^{LD}}{\pi_t^{LD}} = \frac{\delta_{it} N_{it}}{\sum_{j \in J} \delta_{jt} N_{jt}} \quad (4.4.1)$$

with δ_{it} climate damages as a share of gross output and N_{it} the population of country i in period t . The second scheme is based on absolute damages in monetary value. The share of country $i \in J$ in the global Loss and Damage transfers becomes

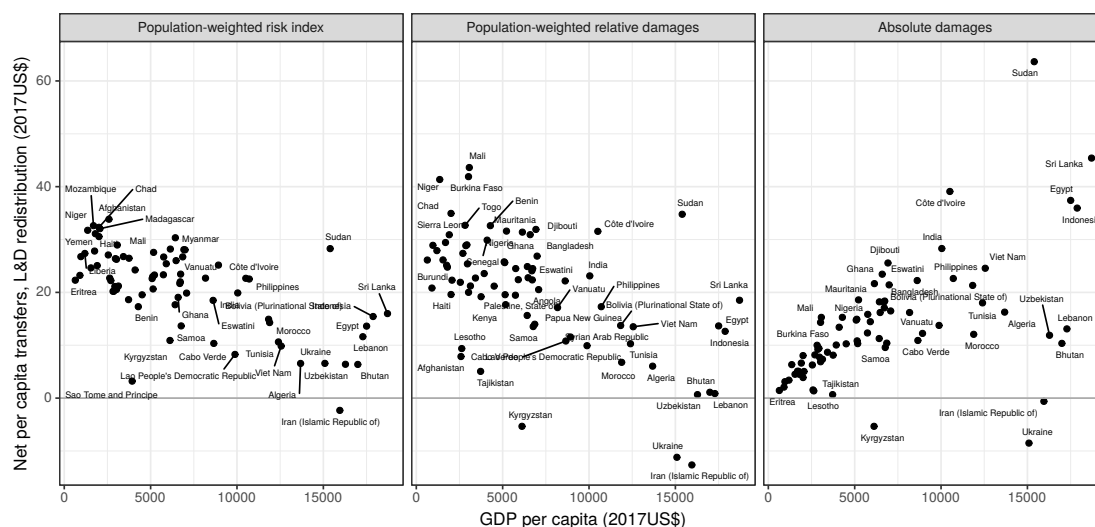
$$\frac{\pi_{it}^{LD}}{\pi_t^{LD}} = \frac{\delta_{it} Y_{it}}{\sum_{j \in J} \delta_{jt} Y_{jt}} \quad (4.4.2)$$

with $\delta_{it} Y_{it}$ absolute damages in 2017 USD.

Countries receive different net per capita transfers depending on the characteristics of the Loss and Damage redistribution scheme. In the case where the transfers are calculated in proportion to a population-weighted risk index (our baseline assumption), there is a negative correlation between the net transfers received by a country and its GDP per capita (Figure A19). This is because the risk index is negatively correlated to GDP. The maximum amount of transfers in 2030 is around 30-35 USD per capita, for instance in Niger, Mozambique, Chad, Afghanistan or Yemen. Iran is the only low-income country with a negative transfer in 2030 in that scenario. In the case of transfers proportional to population-weighted relative damages, a similar trend is found, but the maximum transfers are slightly higher (closer to 40-45 USD per capita) and directed towards different countries (Mali, Burkina Faso). In the case where net per capita transfers are proportional to absolute damages, there is a positive correlation between those and GDP per capita, as larger economies suffer larger absolute losses. These differences point to the crucial issue of redistribution design in a Loss and Damage scheme, which can significantly alter the financial situation of individual countries.

⁷See [subsection A.5](#) for the list.

Figure A19: Net per capita transfers for three alternative Loss and Damage redistribution schemes, in 2030



5 Concluding remarks

In this paper, we analyze the impact of different types of carbon taxes and revenue recycling schemes on global inequality and welfare, using a global integrated assessment model that represents distribution, damages and mitigation at the country level.

We find that a uniform global carbon tax with global per capita recycling would be the most effective in decreasing global inequality and improving global welfare until 2050. However, governments may be hesitant to participate in revenue sharing on such a large scale. If international transfers are limited, our results suggest that good alternative policies could be to implement differentiated taxes with domestic revenue recycling, or to implement a uniform global tax with 5% of revenues targeted to poor countries experiencing loss and damages and 95% of revenues recycled domestically. The latter policy could bring strong inequality reduction and significant welfare increases for low-income countries that are particularly vulnerable to climate change impacts.

In addition, we find that the timing of the benefits from differentiated and global taxes with domestic recycling of tax revenues differs. A uniform tax yields larger benefits around 2040 in most countries, while differentiated taxes yield larger benefits earlier for rich countries, and later for middle-income countries.

Our results remain conditional on a number of assumptions, and could be extended.

First, we assume that revenue can be redistributed at a negligible cost, either at the domestic or global levels. While this assumption might be a good approximation at the country level because states already operate fiscal and distributive systems, collecting and distributing funds at a global level would lead to additional bureaucratic costs. Taking those into account could reduce the magnitude of the benefits of implementing the climate policies we consider.

Next, our global and differentiated tax trajectories compatible with 2°C, as well as the sharing of mitigation efforts that they imply, depend on our assumptions about national abatement costs. To calibrate our country level abatement cost functions, we make two assumptions. First, we assume that the abatement cost functions have the same convexity. Second, we rely on the same approach as in the RICE model (Nordhaus and Yang, 1996), and assume that marginal abatement costs at 100% mitigation rate, in dollars per unit of emissions, are equal across countries. As a result, a global uniform carbon tax leads to equal mitigation rates across countries (but with heterogeneous abatement costs). Future work could explore the sensitivity of our results to these assumptions, and test alternative calibrations of the abatement costs.

Finally, our analysis could be extended to better examine the mechanisms underlying our results. In particular, we could disentangle within-country and between-country inequality effects in our global and regional results on inequality by implementing metrics such as Atkinson indices or the Theil index.

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Appendix A Appendix

A.1 Abatement cost

For country i at time t , the cost of abatement in terms of share of gross output is

$$\Lambda_{it} = \theta_{1,it} \mu_{it}^{\theta_2} \quad (\text{A.1.1})$$

with μ_{it} abatement rate, $\theta_{1,it}$ country-specific parameters and $\theta_2 = 2.6$. It follows that the cost of abatement in dollars per unit of emission is

$$C_{it}(\mu_{it}) = \frac{\Lambda_{it} Y_{it}}{E_{it}} \quad (\text{A.1.2})$$

$$= \frac{\theta_{1,it} \mu_{it}^{\theta_2}}{\sigma_{it}} \quad (\text{A.1.3})$$

with σ_{it} the emissions intensity of country i .

We compute $\theta_{1,it}$ for each country from the global price per tCO₂ that enables full decarbonization (backstop price) such that

$$\frac{\partial C_{it}}{\partial \mu_{it}}(1) = p_t^{\text{backstop}}, \quad (\text{A.1.4})$$

which results in

$$\theta_{1,it} = p_t^{\text{backstop}} \frac{\sigma_{it}}{\theta_2}. \quad (\text{A.1.5})$$

We use the trajectory of the price for full decarbonization from Nordhaus & Barrage (2023), who perform a statistical analysis on the ENGAGE study (Riahi et al., 2021). Converted into 2017US\$ per tCO₂, this implies a backstop price of 495 2017US\$ per tCO₂ in 2050. We also assume the backstop price decreases by 1% by year between 2020 and 2050, and by 0.01% after 2050. This results in a price for full decarbonization in 2020 of 670 2017US\$.

A.2 Damage functions

Assume that the share of damages (as a fraction of gross GDP in a country) is given by:

$$\delta(T) = 1 - e^{-\beta_1 T - \beta_2 T^2}, \quad (\text{A.2.1})$$

with T the average annual temperature in the country, and $\delta(T)$ the share of damages.

To calibrate parameters β_1 and β_2 , we use the results by [Kalkuhl and Wenz \(2020\)](#) on the reduction of economic output from a 1°C increase in temperature. ([Kalkuhl and Wenz, 2020](#), Table 9) obtain that, in their preferred econometric specification, a 1°C increase in temperature implies a 0.8% in output when the initial temperature is 10°C. And they obtain that 1°C increase in temperature implies a 3.5% in output when the initial temperature is 25°C. From these numbers, we obtain $\beta_1 = -0.01128$ and $\beta_2 = 0.00092$.

Next, we want to compute country-specific damage functions that depends on the climate anomalies from pre-industrial temperature in that region, that we denote \bar{T}_i , where i is the index for the country. Remark that we have:

$$(1 - \delta(T)) = \frac{1 - (\delta(T) - \delta(\bar{T}_i)) - \delta(\bar{T}_i)}{1 - \delta(\bar{T}_i)} (1 - \delta(\bar{T}_i)) \quad (\text{A.2.2})$$

The share $\delta(\bar{T}_i)$ would be lost anyway in the absence of climate change (when the climate anomaly is nil), so the share of output lost in country i due to climate change is simply:

$$\delta_i(T) = 1 - \frac{1 - \delta(T)}{1 - \delta(\bar{T}_i)} = 1 - e^{-\beta_1(T - \bar{T}_i) - \beta_2(T^2 - (\bar{T}_i)^2)}. \quad (\text{A.2.3})$$

This can be written as a function of the local temperature anomaly, $\Delta_i T = T - \bar{T}_i$:

$$\delta_i(\Delta_i T) = 1 - e^{-\beta_1 \Delta_i T - \beta_2 (\Delta_i T)^2 - 2\beta_2 \bar{T}_i \Delta_i T} \approx (\beta_1 + 2\beta_2 \bar{T}_i) \Delta_i T + \beta_2 (\Delta_i T)^2. \quad (\text{A.2.4})$$

We thus obtain the country-specific damage function $\delta_i(\Delta_i T) = \beta_{i1} \cdot \Delta_i T + \beta_{i2} \cdot (\Delta_i T)^2$, with $\beta_{i1} = \beta_1 + 2\beta_2 \bar{T}_i$ and $\beta_{i2} = \beta_2$. To calibrate parameters β_{i1} and β_{i2} , we only need to know parameters β_1 and β_2 (already calibrated above) and the local pre-industrial temperature.

For the local pre-industrial temperature, we use the average annual temperature in the country for the period 1900-1909, based on the population weighted temperature in [Dell et al. \(2012\)](#). The temperature in period 1900-1909 is not significantly different from the pre-industrial temperature at the global level, hence the choice of the period.

A.3 A simple model of optimally differentiated carbon tax

Assume that there is a set of countries $I = \{1, \dots, n\}$, with i the index of the country and consider a specific period t . Assume that we have the objective to emit at most E_t at the global level. How should emissions be shared between the different countries?

To answer the question, let Y_{it} be the gross production in country i at period t . We assume that pre-abatement emissions in that country are given by $E_{it} = \sigma_{it} Y_{it}$, with σ_{it} a technology parameter that relates (gross) production to emissions. We want to define the optimal emissions in the country. For an abatement effort μ_{it} , the emissions in the country will be $(1 - \mu_{it})E_{it}$.

The abatement cost (as a share of gross production) is given by a function $\Lambda_{it}(\mu_{it})$ that depends on the abatement effort μ_{it} .⁸ Given the population N_{it} in the region, per capita consumption is given by:

$$c_{it} = (1 - s_{it}) \left(1 - \Lambda_{it}(\mu_{it}) \right) \frac{Y_{it}}{N_{it}}, \quad (\text{A.3.1})$$

with s_{it} the savings rate in the country.

We assume that we want to fix optimal abatement efforts that maximize the sum of utilities from consumption. The objective is thus to maximize

$$\sum_i N_{it} u(c_{it})$$

with the constraint that the sum of emissions is less than E_t : $\sum_i (1 - \mu_{it}) E_{it} \leq E_t$.

Using the equations above, we obtain the following maximization problem:

$$\begin{aligned} \max_{(\mu_{it})_i} \quad & \sum_i N_{it} u \left((1 - s_{it}) \left(1 - \Lambda_{it}(\mu_{it}) \right) \frac{Y_{it}}{N_{it}} \right) \\ \text{s.t.} \quad & \sum_i (1 - \mu_{it}) \sigma_{it} Y_{it} \leq E_t \end{aligned}$$

The first order condition with respect to each μ_{it} yields:

$$(1 - s_{it}) \frac{\partial \Lambda_{it} / \partial \mu_{it}}{\sigma_{it}} u'(c_{it}) = \lambda,$$

with λ the multiplier associated with the constraint.

Denote τ_{it} the carbon tax in country i . The abatement cost per emission in the model is $C_{it}(\mu_{it}) = \frac{\Lambda_{it}(\mu_{it}) Y_{it}}{E_{it}} = \frac{\Lambda_{it}(\mu_{it})}{\sigma_{it}}$. In equilibrium, the carbon tax should be equal to the marginal abatement cost per emission, so we should have $\tau_{it} = C'_{it}(\mu_{it}) = \frac{\partial \Lambda_{it} / \partial \mu_{it}}{\sigma_{it}}$. We obtain a formula for the optimal level of the carbon tax in country i at period t :

$$\tau_{it} = \frac{(1 - s_{it})}{(1 - s_{1t})} \frac{u'(c_{1t})}{u'(c_{it})} \tau_{1t}. \quad (\text{A.3.2})$$

Thus, we have a relation between the tax rate in any country and the tax rate in the first country that we take as a reference.

⁸We write $\Lambda_{it}(\mu_{it})$ instead of Λ_{it} that we used in Section to make explicit the dependence on μ_{it} , given that we will maximize with respect to the abatement effort.

Also, as mentioned before, we assume that $\Lambda_{it} = \theta_{1,it} \mu_{it}^{\theta_2}$. We also assume that $u(c) = c^{1-\eta}/(1-\eta)$ (see the next section). So, from previous results we see that mitigation efforts at the country-level are controlled by the level of carbon tax in the reference country. Indeed:

$$\frac{\theta_2 \theta_{1,it}}{\sigma_{it}} \mu_{it}^{\theta_2-1} = \frac{\partial \Lambda_{it} / \partial \mu_{it}}{\sigma_{it}} = \frac{(1-s_{it})}{(1-s_{1t})} \frac{u'(c_{1t})}{u'(c_{it})} \tau_{1t},$$

so that (also using that $\theta_{1,it} = p_t^{backstop} \frac{\sigma_{it}}{\theta_2}$ in our calibration):

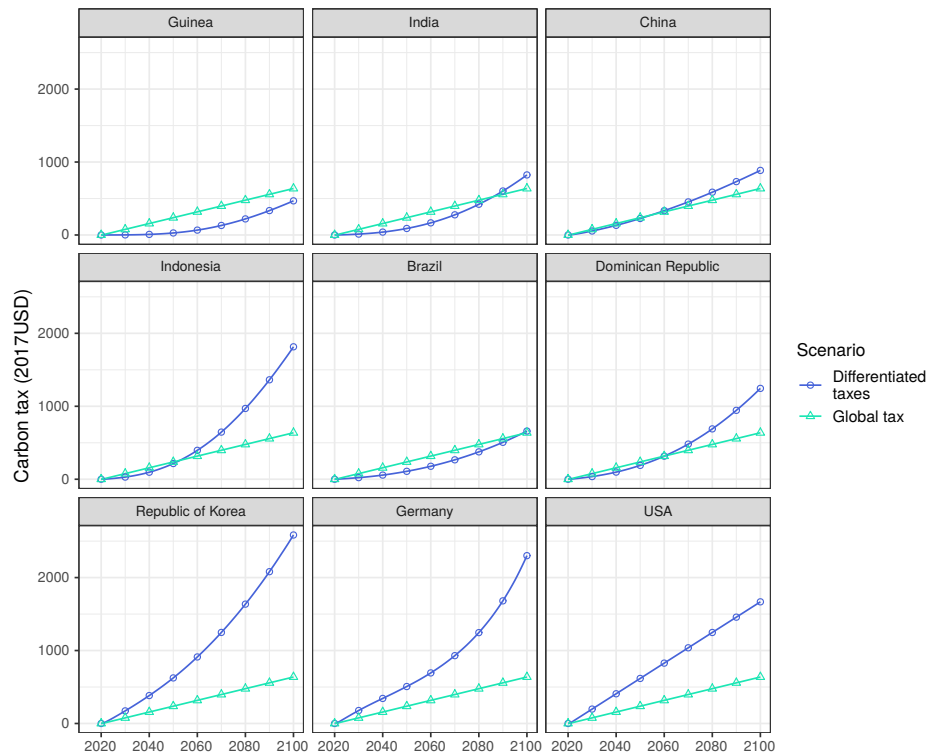
$$\mu_{it} = \left(\frac{(1-s_{it})}{p_t^{backstop} \times (1-s_{1t})} \frac{c_{1t}^{-\eta}}{c_{it}^{-\eta}} \tau_{1t} \right)^{\frac{1}{\theta_2-1}}.$$

To close the model, we do not use c_{it} as defined above but the approximation by:

$$\tilde{c}_{it} = (1-s_{it}) \frac{Y_{it}}{N_{it}}.$$

A.4 Carbon tax trajectories for selected countries

Figure A.1: Carbon taxes (USD/tCO₂) for a selection of countries, for the 2°C scenarios implemented via a global uniform tax (blue green) and via differentiated taxes across countries (dark blue).



A.5 List of low and low-middle income countries

Low income countries: Afghanistan, Burundi, Burkina Faso, Central African Republic, Democratic Republic of the Congo, Eritrea, Ethiopia, Guinea, The Gambia, Guinea-Bissau, Liberia, Madagascar, Mali, Mozambique, Malawi, Niger, The Democratic People's Republic of Korea, Rwanda, Sudan, Sierra Leone, Somalia, South Sudan, Syrian Arab Republic, Chad, Togo, Uganda, Yemen, Republic of Zambia.

Low-middle income countries: Angola, Benin, Bangladesh, Bolivia, Bhutan, Côte d'Ivoire, Cameroon, Republic of the Congo, Comoros, Cabo Verde, Djibouti, Algeria, Arab Republic of Egypt, Federal States of Micronesia, Ghana, Honduras, Haiti, Indonesia, India, Islamic Republic of Iran, Kenya, Kyrgyz Republic, Cambodia, Kiribati,

Lao People's Democratic Republic, Lebanon, Sri Lanka, Lesotho, Morocco, Myanmar, Mongolia, Mauritania, Nigeria, Nicaragua, Nepal, Pakistan, Philippines, Papua New Guinea, West Bank and Gaza, Senegal, Solomon Islands, El Salvador, São Tomé and Príncipe, Eswatini, Tajikistan, Timor-Leste, Tunisia, Tanzania, Ukraine, Uzbekistan, Vietnam, Vanuatu, Samoa, Zimbabwe.

A.6 Constructing a climate risk index

The risk index used to distribute Loss and Damage funding among poorer countries is based on the INFORM Risk Index. The objective of the INFORM Risk Index is to identify the countries at a high risk of humanitarian crisis that are more likely to require international assistance. Specifically, the index is designed to facilitate an objective allocation of resources for disaster management as well as for coordinated actions focused on anticipating, mitigating, and preparing for humanitarian emergencies.

The INFORM Risk Index is based on a methodology also discussed by the IPCC that considers three dimensions of risk: Hazards & Exposure, Vulnerability and Lack of Coping Capacity. For each of these dimensions, a normalized index (between 0 and 1) is constructed based on a number of other indicators. Then the three dimensions are combined using a geometric mean.

In the paper we use a modified version of the INFORM index designed to take into account only climate-related natural risks. We thus only modify the Hazards & Exposure index that we compute as a combination (through a geometric mean) of three indices for specific climate-related natural risks: flood, tropical cyclone, and drought. We combine our new index for Hazards & Exposure at the country level with the INFORM country indices for Vulnerability and Lack of Coping Capacity. Our computations use the latest release of the INFORM Risk Index dataset ([INFORM, 2022](#)).

A.7 Welfare measurement via equally distributed equivalent consumption

Instantaneous welfare in country i and period t is

$$\frac{P_{it}}{N_q} \sum_q \frac{c_{iqt}^{1-\eta}}{1-\eta} \quad (\text{A.7.1})$$

with N_q the number of quantiles and η inequality aversion.

Instantaneous equally distributed equivalent consumption ([Atkinson, 1970](#)) in country i is defined as the level $c_{EDE,it}$ such that

$$\frac{P_{it}}{N_q} \sum_q \frac{c_{EDE,t}^{1-\eta}}{1-\eta} = \frac{P_{it}}{N_q} \sum_q \frac{c_{iqt}^{1-\eta}}{1-\eta}. \quad (\text{A.7.2})$$

Hence,

$$c_{EDE,it} = \left(\frac{1}{N_q} \sum_q c_{iqt}^{1-\eta} \right)^{\frac{1}{1-\eta}} \quad (\text{A.7.3})$$

Denote \bar{c}_{it} the average consumption in country i and period t , remark that we have the following decomposition:

$$c_{EDE,it} = \bar{c}_{it} \times \left(\frac{1}{N_q} \sum_q \left(\frac{c_{iqt}}{\bar{c}_{it}} \right)^{1-\eta} \right)^{\frac{1}{1-\eta}} = \bar{c}_{it} \times (1 - A_{it}^\eta),$$

where A_{it}^η is the so-called Atkinson inequality index for consumption in country i and period t . So, we can decompose the welfare effect into an effect on average consumption and an effect on inequality (Atkinson, 1970).

We can also compute welfare at the global level. The global equally distributed equivalent consumption is defined as $c_{EDE,t}$ such that

$$\sum_i \frac{P_{it}}{N_q} \sum_q \frac{c_{EDE,t}^{1-\eta}}{1-\eta} = \sum_i \frac{P_{it}}{N_q} \sum_q \frac{c_{iqt}^{1-\eta}}{1-\eta}. \quad (\text{A.7.4})$$

Resulting in

$$c_{EDE,t} = \left(\frac{\sum_i \frac{P_{it}}{N_q} \sum_q c_{iqt}^{1-\eta}}{\sum_i P_{it}} \right)^{\frac{1}{1-\eta}} \quad (\text{A.7.5})$$

$$= \left(\frac{\sum_i P_{it} (c_{EDE,it})^{1-\eta}}{\sum_i P_{it}} \right)^{\frac{1}{1-\eta}} \quad (\text{A.7.6})$$

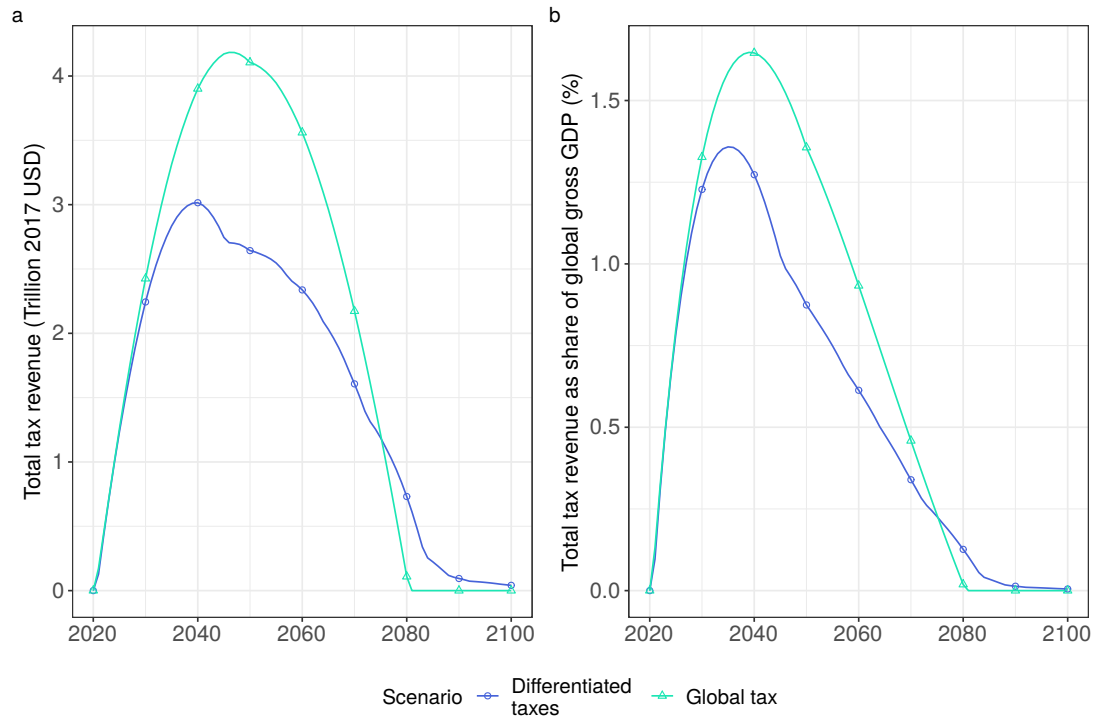
Denoting \bar{c}_t the average consumption at the global level in period t , we again obtain the Atkinson decomposition:

$$c_{EDE,t} = \bar{c}_t \times \left(\frac{\sum_i \frac{P_{it}}{N_q} \sum_q \left(\frac{c_{iqt}}{\bar{c}_t} \right)^{1-\eta}}{\sum_i P_{it}} \right)^{\frac{1}{1-\eta}} = \bar{c}_t \times (1 - A_t^\eta),$$

where A_t^η is the Atkinson inequality index for global consumption in period t .

A.8 Global revenues from the carbon tax

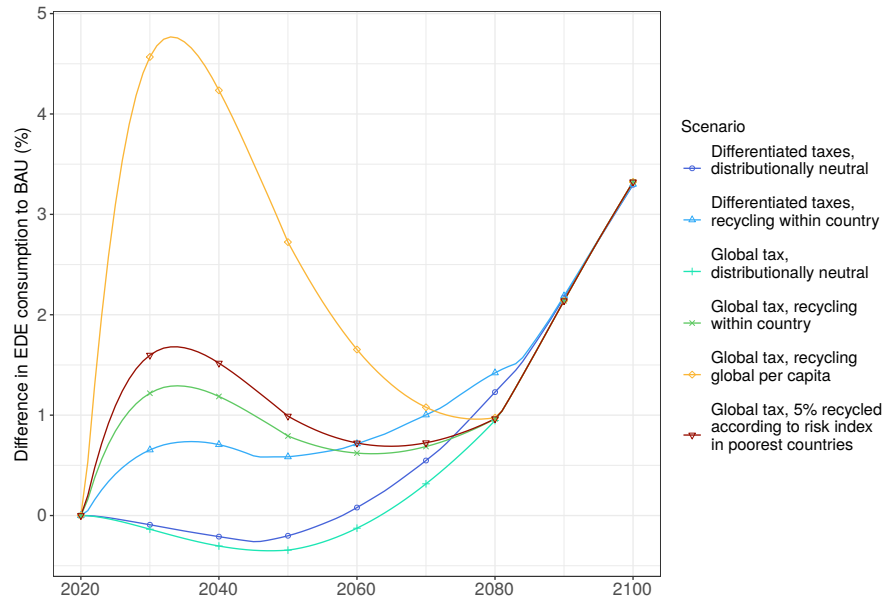
Figure A.2: Global carbon tax revenues in the 2°C scenario, in a) trillion 2017USD, and b) share of global gross output (%).



A.9 Sensitivity analysis: inequality aversion

Figure A.3: Difference in the equally distributed equivalent (EDE) consumption in the 2°C scenario compared to the business-as-usual scenario (%) for the six carbon tax and revenue recycling scheme alternatives, and $\eta = 1$.

Note: we use the same differentiated taxes pathways as in the main analysis.



Public acceptability of carbon taxation: a model of political support with income and urban-rural inequality

Public acceptability of carbon taxation: a model of political support with income and urban-rural inequality

Marie Young-Brun^{‡‡}

Abstract

Carbon taxation is a flagship climate policy aimed at efficiently reducing greenhouse gas emissions. Yet, it fails to garner sufficient political support in many countries. This paper investigates the role of urban-rural inequalities in this lack of domestic support. I develop a model of household support for carbon taxation at a national level, with income inequality and heterogeneous Stone-Geary utility. Rural households need to consume more necessary energy goods than urban households. I characterize the conditions for the existence of a majority voting equilibrium and perform a calibration of the model with budget survey data for twenty European countries.

I find that the majority voting tax may be at a higher rate than the optimal carbon tax. However, the calibration suggests that the optimal rate tends to exceed the majority voting rate by a few percent. I demonstrate that political support among rural households is always below that of urban households. The numerical exercise reveals a gap between 15 and 45 %, at the median income. I show that recycling the revenues from carbon taxation as lump-sum or means-tested transfers renders the tax and rebate scheme progressive, but has only a limited effect on political support.

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2 Introduction

Keeping global temperature increase under 2°C compared to pre-industrial levels, as stated in the Paris Agreement, requires timely and ambitious policies to reduce greenhouse gas emissions. Carbon pricing is a flagship climate policy put forth by economists for its cost-effectiveness. Yet, implementation of carbon prices, in the form of carbon taxation, emissions trading systems, and even reductions in fossil fuel subsidies, has been slow. The main reason for this is the fact that carbon taxes are widely unpopular among citizens. For instance, carbon taxation has failed to achieve a majority in votes in many countries, such as in Switzerland in 2015. It has also resulted in protests, such as in France with the yellow vests movement. Political constraints limit the feasibility of carbon taxes because governments and political parties need political support and wish to avoid voiced opposition from a segment of the electorate.

Concerns about fairness and distributive impacts of carbon pricing play a key role in the acceptability of carbon taxation (see [Maestre-Andrés et al. \(2019\)](#) for a review of the literature). Carbon taxation results in two types of distributional impacts. First, households with different levels of income face different tax burdens, in proportion to their income. In high-income countries, the consumption of emission-intensive goods increases with income, while each additional unit of income tends to emit less, i.e., the income elasticity of polluting goods is less than one. Thus, richer households tend to consume more emission-intensive goods in absolute value, but less in proportion to their income. As a result, carbon taxation is usually regressive in high-income countries ([Ohlendorf et al., 2021](#)). Second, there is significant variation in tax burdens for households at the same income level (e.g., [Gill and Moeller 2018](#); [Cronin et al. 2019](#); [Douenne 2020](#); [Tomás et al. 2020](#) for respectively Germany, the US, France, and Spain). A particularly salient source of this variation is location-based, as rural households may consume more fuel and energy to meet their transport and housing needs than urban households. Distributional impacts of carbon taxation hinge upon income inequality as well as urban-rural inequality, i.e., *vertical* and *horizontal* inequalities.

Optimal taxation frameworks focusing on energy and greenhouse gas emissions taxation have recently included horizontal inequality ([Fischer and Pizer, 2019](#); [Hänsel et al., 2022](#)). Efficient policies that result in heterogeneous costs and benefits can create losers with costs that are not compensated ([Sallee, 2019](#)). This, in turn, may lead to political opposition from losers. In the survey literature, location and dependence on fossil fuels have a stronger impact on acceptability than income. Households that live in rural areas, have less efficient heating, or are more car-dependent tend to oppose carbon taxes more strongly ([Umit and Schaffer 2020](#); [Douenne and Fabre 2020](#); [Boyer et al. 2020](#); [Povitkina et al. 2021](#)).

The literature on the political economy of carbon taxation studies political support using voting models. It was first developed by [Cremer et al. \(2004\)](#), who explore the

double dividend hypothesis with a majority voting model. They find that recycling tax revenues as income tax reduction enhances the political feasibility of carbon taxation. [Aidt \(2010\)](#) shows how a polluter lobby may favor refunding tax revenues to voters if it results in larger environmental tax cuts. [Habla and Roeder \(2013\)](#) combine majority voting with an overlapping generations model to study the effect of aging on the voted tax.

This paper makes a novel contribution to this literature by including urban-rural inequality in a majority voting framework. The political feasibility of carbon taxation is proxied by the level of carbon tax achieved under majority voting. I capture heterogeneity within income groups in the cost of carbon taxation by modeling households that differ in the quantity of carbon-intensive goods they are constrained to consume. I consider urban households living in high-density areas and rural households living in less dense areas. Rural households have higher subsistence consumption of the emission-intensive good than urban households, reflecting their higher energy needs for transport and housing. I evaluate the extent to which the intersecting income and urban-rural inequalities can limit political support for carbon taxation, and whether countries with higher levels of urban-rural inequality face tighter political constraints. To achieve further insights, I perform a numerical calibration of the model using household budget survey data for twenty European countries.

I find that urban-rural inequality results in lower political support for the carbon tax among rural households than among urban households. The numerical exercise reveals a gap in the accepted carbon tax rate across the median urban and rural households of up to 45%. I determine the conditions for the existence of a majority voting equilibrium over the carbon tax and show that a very large urban-rural inequality can lead to polarization of political support. That is to say, a majority voting equilibrium in which there are no urban and rural households with the same level of supported carbon tax, and in which the median voter is urban or rural depending on which group is in majority in the population. My findings highlight that horizontal inequality could imply equity-efficiency-acceptability trade-offs¹ in the design of carbon tax schemes.

Second, I show that the effect of income on political support for carbon taxation in the model depends on the relative strength of the environmental concern and the preference for consuming carbon-intensive goods. A rise in household income increases the level of politically supported carbon taxation if the willingness to mitigate greenhouse gas emissions, scaled by the effectiveness of mitigation, is greater than the marginal budget share of the carbon-intensive good. In addition, an increase in income is more likely to positively affect support for carbon taxation for households with a larger budget share devoted to constrained consumption of carbon-intensive goods.

¹Acceptability refers to the overall public support for the carbon tax, equity to the normative evaluation of the distributive effects of the tax, and efficiency to its capacity to mitigate emissions at the lower social cost.

This reflects how relaxing the budgetary constraint due to the necessary consumption of carbon-intensive goods can make room for more climate mitigation efforts.

Third, I compare the majority voting carbon tax to the optimal carbon tax, i.e., the carbon tax chosen by a social planner taking into account both vertical and horizontal inequality. My results show that the majority voting tax rate can be at a higher or lower level than the optimal tax rate. The social planner takes into account the tax burden of every household and hence incorporates the equity-efficiency trade-off. The median voter, on the other hand, only factors in their own tax burden. If the median voter is an urban household with a low carbon tax burden, the majority voting tax rate can thus be higher than that of the social planner. However, in the numerical exercise, I find that the tax resulting from majority voting is lower than the tax chosen by the social planner in every country. This occurs although the social planner and every household share the same level of environmental preference by assumption.

Lastly, I study the effect of recycling the revenue generated by a carbon tax. Rebates have been put forth as a means of improving the progressivity of carbon taxation (e.g., [Cronin et al., 2019](#); [Ravigné et al., 2022](#)). For instance, the European Union *Fit for 55* policy package includes a Social Climate Fund that is set up to provide “temporary direct income support for vulnerable households” ([European Commission, 2021](#)). I analyze whether transfers are sufficient to overcome the regressive distributional impacts of the tax and whether this is likely to increase political support for the carbon tax. I examine the effects of three types of transfers: lump-sum, targeted at households with an income below the median, and targeted to rural households.

I find that recycling the tax revenues as a lump-sum or means-tested transfer renders the tax scheme progressive. However, lump-sum or means-tested transfers result in heterogeneity across households in the net impact, with rural households benefiting less than urban households. The distributive impact of transfers targeted to rural households depends on the distribution of income across the urban and rural populations in each country. When households are myopic to the rebound effect of transfers on emissions, an increase in income has two effects. On the one hand, it raises the marginal willingness to mitigate greenhouse emissions. On the other hand, it increases the demand for carbon-intensive goods. Thus, transfers raise the acceptability of carbon taxation only if the pro-mitigation effect is stronger than the increased demand effect. The numerical calibration reveals that the impact of transfers on the carbon tax rate chosen by majority voting is positive but weak, with an increase of a few percent. The results also suggest that no transfer type is a one-size-fits-all, as the impact of each transfer structure—lump-sum, means-tested, or targeted at rural households—is different across countries.

The layout of the paper is as follows. In section 2, I present a model of carbon taxation with income and urban-rural inequality, and derive the optimal carbon tax. Section 3 shows the existence of a median voter determining the result of majority

voting and describes its characteristics. Section 4 presents the results from a calibration of the model to European countries using household budget survey data. Section 5 concludes.

3 Carbon taxation in a model with vertical and horizontal inequality

3.1 The economy

The economy comprises households consuming a polluting—or carbon-intensive—good x , and a non-polluting good c . The size of the population and the price of non-polluting good c are normalized to one. The price of the polluting good x is p . Aggregate consumption of the carbon-intensive good, X , produces emissions that result in climate change damages.

Households differ in two aspects. First, they differ with respect to the amount of polluting good they are constrained to consume. A rural household, of type $h = r$, needs to consume a larger amount of carbon-intensive good than an urban household, of type $h = u$. The share of urbans in the population is $0 \leq \alpha \leq 1$. Second, households differ by their level of income. Household i earns income y_i^h which is distributed over $[y^-, y^+] \subset \mathbb{R}^+$. In addition, median income \tilde{y} is assumed to be below average income \bar{y} .

Consumption preferences

I follow the optimal carbon taxation literature and use Stone-Geary preferences (Klenert and Mattauch, 2016; Aubert and Chiroleu-Assouline, 2019; Jacobs and van der Ploeg, 2019). This choice is made to model in the most straight-forward way a demand for the polluting good which both increases in income and results in an income elasticity that is below one (Pottier, 2022). I assume that preferences over the carbon-intensive good are heterogeneous (as in Hänsel et al. (2022)), and differ according to the type of the household, rural or urban. The constrained consumption parameter, which determines the minimum amount that must be consumed in order to achieve positive utility, is larger for a rural household than an urban household. For a household i of type $h = \{u, r\}$, sub-utility corresponding to consumption is

$$u(c_i, x_i) = c_i^{1-\gamma-\beta} (x_i - x_0^h)^\gamma$$

with $x_0^r \geq x_0^u$ and $\gamma + \beta < 1$. u_c is defined only if the household consumes at least an amount x_0^h of the polluting good.

The demand derived from the maximization of $u(c_i, x_i)$ subject to the budget constraint $y_i = c + px$ is

$$x_i^* = \frac{1}{(1-\beta)} \left(\frac{\gamma}{p} y_i + (1-\gamma-\beta)x_0^h \right). \quad (3.1.1)$$

In turn, the following income elasticity can be derived from the demand for the polluting good

$$\frac{\partial x_i}{\partial y_i} \frac{y_i}{x_i} = \frac{1}{1 + \frac{(1-\gamma-\beta)}{\gamma} \frac{px_0^h}{y_i}} < 1.$$

The income elasticity of demand for the carbon-intensive good thus decreases towards zero as constrained consumption x_0^h increases. It increases towards one as income y_i increases. In other words, a larger amount of subsistence consumption renders demand for the polluting good more inelastic, while the reverse is true for higher levels of income.

Finally, aggregate demand for the carbon-intensive good, with a population comprised of a share α of urbans and $(1-\alpha)$ of rurals, writes

$$\begin{aligned} X &= \int_{y^-}^{y^+} (\alpha x_i^{u*} + (1-\alpha)x_i^{r*}) dF(y_i) \\ &= \frac{1}{(1-\beta)} \left(\frac{\gamma}{q} \bar{y} + (1-\gamma-\beta)\bar{x}_0 \right) \end{aligned}$$

with $\bar{x}_0 := (\alpha x_0^u + (1-\alpha)x_0^r)$ the average amount of subsistence consumption in the population.

Environmental preferences

Aggregate consumption of the carbon-intensive good results in emissions that lead to climate change, thus degrading environmental quality $E(X)$ (with $E(X) \geq 0$ and $\frac{\partial E}{\partial X} < 0$). Households do not take into account the externality resulting from their consumption of the carbon-intensive good in their consumption choice, but have a preference over the economy's mitigation performance, i.e. environmental quality. The literature on optimal carbon taxation and on the political economy of carbon taxation usually models additive environmental damages (e.g., [Aubert and Chiroleu-Assouline 2019](#); [Jacobs and van der Ploeg 2019](#); [Habla and Roeder 2013](#)), which leads to a negative relationship between income (or expenditure) and support for environmental taxation. This feature is explained by the larger tax payments of richer households, in *absolute value*. Yet, it is at odds with the survey literature, and with the carbon tax incidence literature which uses *relative* tax burden to study regressivity and fairness issues. Surveys on the determinants of political support find that income has a positive or non-significant effect on tax support (e.g. [Levi 2021](#); [Bergquist et al. 2022](#)). I depart from

this assumption by using CES preferences over consumption and environmental quality. As will be shown in (4.1), this specification results in a more flexible relationship between income and support for the carbon tax. Total utility then writes:

$$U(c_i, x_i, E) = c_i^{1-\gamma-\beta} (x_i - x_0^h)^\gamma E(X)^\beta.$$

Non-additive utility from environmental quality means that the willingness to pay for mitigation increases when basic needs are met. For instance, compare the amount of polluting good consumption x that a household is willing to forego for an additional unit of environmental quality E in this specification relative to the additive case². In the additive case, the amount of carbon-intensive good that the household will forego decreases with consumption of the non-polluting good and does not depend on environmental quality. With the CES specification, the household will forego more consumption of the carbon-intensive good when environmental damages are larger, irrespective of the level of non-polluting good consumption.

Carbon taxation

The polluting good is taxed at a rate τ to mitigate emissions and avoid climate damages. This results in a consumer price for the carbon-intensive good of $q = p + \tau$. Aggregate polluting good consumption decreases with the carbon tax. The proceeding of the tax can be rebated through a lump-sum transfer, T , that adds up to income y_i .

I analyze how the intersecting vertical and horizontal inequalities affect support for the carbon tax. Individual support is modeled as the preferred tax rate of a household, given their income and urban-rural characteristics. Following the literature studying majority voting over an environmental tax, political support is captured by the median voter's preferred tax rate if preferences are single-peaked (Cremer et al., 2004; Habla and Roeder, 2013). The tax supported by the median voter can then be compared to the optimal tax benchmark.

To find the household's preferred tax level, indirect utility is maximized over the tax rate. In the case without transfer, it writes

$$V(q, y_i, x_0^h) = \frac{a}{q^\gamma} (y_i - qx_0^h)^{(1-\beta)} E(X)^\beta,$$

with $a = \frac{(1-\gamma-\beta)^{(1-\gamma-\beta)} \gamma^\gamma}{(1-\beta)^{(1-\beta)}}$. Defining $v(q, y_i, x_0^h) := \frac{a}{q^\gamma} (y_i - qx_0^h)^{(1-\beta)}$, this can be rewritten as

$$V(q, y_i, x_0^h) = v(q, y_i, x_0^h) E(X(q))^\beta,$$

²The marginal rate of substitution between environmental quality and the emission-intensive good is $MRS_{E,x} = \frac{\frac{\partial U}{\partial E}}{\frac{\partial U}{\partial x}} = \frac{\beta}{\gamma} \frac{(x_i - x_0^h)}{E}$. The marginal rate of substitution with environmental quality entering utility additively, such that $U^{add} = c_i^{1-\gamma} (x_i - x_0^h)^\gamma + E(X)$, is $MRS_{E,x}^{add} = \frac{1}{\gamma} \left(\frac{x_i - x_0^h}{c_i} \right)^{1-\gamma}$.

with $v(\cdot)$ indirect utility from consumption and $E(\cdot)^\beta$ from the environmental quality.

3.2 Social planner tax rate

I characterize the pigouvian tax, chosen by a social planner maximizing the weighted sum of indirect utilities over the carbon tax, in the absence of lump-sum transfers. The social planner solves

$$\max W = \theta \int_{y^-}^{y^+} V(q, y_i, x_0^u) dF(y_i^u) + (1 - \theta) \int_{y^-}^{y^+} V(q, y_i, x_0^r) dF(y_i^r)$$

with $\theta = \frac{\alpha \omega^u}{\alpha \omega^u + (1 - \alpha) \omega^r}$ the generalized weight of urbans and ω^h the social weight associated to households of type h .

After some algebra (see Appendix A.1), the first order condition for the social planner results in the following implicit optimal tax rate

$$\tau_{sp} = \frac{\beta \varepsilon_{E,\tau}}{\frac{\gamma}{q_{sp}} + (1 - \beta) \left(\frac{\theta x_0^u \mathbb{E}[(y_i - q_{sp} x_0^u)^{-\beta}] + (1 - \theta) x_0^r \mathbb{E}[(y_i - q_{sp} x_0^r)^{-\beta}]}{\theta \mathbb{E}[(y_i - q_{sp} x_0^u)^{(1-\beta)}] + (1 - \theta) \mathbb{E}[(y_i - q_{sp} x_0^r)^{(1-\beta)}]} \right)}, \quad (3.2.1)$$

with $\varepsilon_{E,\tau} := \frac{\partial E}{\partial \tau} \frac{\tau}{E(X)}$ the tax elasticity of environmental quality. The optimal carbon tax rate equalizes the social marginal costs and benefits. The costs reflect the welfare loss from a more expensive carbon-intensive good, which depends on the demand shift towards non-polluting consumption and the subsistence amount of emission-intensive consumption that cannot be substituted. The social planner weights the losses of rural and urbans with their share in the population α as well as the equity weights ω . The benefits stem from the reduction in emissions which are determined by the tax-elasticity of environmental quality.

4 Support for carbon taxation and median voter tax

4.1 Characteristics of household support for carbon taxation

Next, I characterize the preferred tax rate of each household, with respect to their income and urban-rural type. The program for a household with income y_i and type $h = \{u, r\}$ is

$$\max_{\tau} V(q, y_i, x_0^h) = v(q, y_i, x_0^h) E(X(q))^\beta.$$

Applying Roy's identity to consumption sub-utility $v(q, y_i, x_0^h)$, i.e. $\frac{\partial v(\cdot)}{\partial \tau} = -\frac{\partial v(\cdot)}{\partial y_i} x_i^*$, the first-order condition of the household is

$$\frac{\partial V(\cdot)}{\partial \tau} = -\frac{\partial v}{\partial y_i} x_i^* E(X(q))^\beta + v(q, y_i, x_0^h) \frac{\partial E(X(q))^\beta}{\partial \tau} = 0. \quad (4.1.1)$$

After some algebra and using $\varepsilon_{E,\tau} = \frac{\partial E}{\partial \tau} \frac{\tau}{E(X)}$, the tax elasticity of environmental quality, the preferred tax rate τ of household i of type h can be written implicitly as

$$\tau^h(y_i) = \frac{\beta \varepsilon_{E,\tau}}{\frac{\gamma}{q} + (1 - \beta) \frac{x_0^h}{y_i - q x_0^h}}.$$

Compared with equation (3.2.1), the household takes into account the same benefits from mitigating climate change, but only considers their own cost, which depends on their income and constrained consumption of the carbon intensive good. It appears that income increases the preferred level of tax, while constrained consumption decreases it. Because this equation only implicitly defines the preferred level of tax, I derive these relationships more robustly in what follows.

Effect of income household preferred tax rate

I assume that the environmental utility function $E()$ is such that preferences are single-peaked (locally concave, as shown in Appendix A.2). The voter's preferred tax rate is defined implicitly by equation (4.1.1) so the comparative statics needed to characterize the median voter must be derived by implicit differentiation. Let

$$\begin{aligned} G(\tau^h(y_i), y_i) &= -\frac{\partial v(\tau^h(y_i), y_i, x_0^h)}{\partial y_i} x_i^*(\tau^h(y_i), y_i) E(X(\tau^h(y_i)))^\beta \\ &\quad + v(\tau^h(y_i), y_i, x_0^h) \frac{\partial E(X(\tau^h(y_i)))^\beta}{\partial \tau}, \end{aligned}$$

with $\tau^h(y_i)$ the solution to the problem of a voter of type h with income y_i and $G(\tau(y_i), y_i) = 0$. The effect of income on preferred tax rate is

$$\frac{\partial \tau^h(y_i)}{\partial y_i} = -\frac{\frac{\partial}{\partial y_i} G(\tau^h(y_i), y_i)}{\frac{\partial}{\partial \tau} G(\tau^h(y_i), y_i)}$$

with $\frac{\partial G(\tau^h(y_i), y_i)}{\partial \tau} = \frac{\partial^2 V(\tau^h(y_i))}{\partial \tau^2} < 0$ by local concavity (Appendix A.2). Using short notation,

$$\text{sign}\left(\frac{\partial \tau^h(y_i)}{\partial y_i}\right) = \text{sign}\left(-\frac{\partial v}{\partial y_i} \frac{\partial x_i^*}{\partial y_i} E^\beta - \frac{\partial^2 v}{\partial y_i^2} x_i^* E^\beta + \frac{\partial v}{\partial y_i} \frac{\partial E^\beta}{\partial \tau}\right).$$

There are two opposing effects. On the one hand, an increase in income raises the demand for carbon-intensive consumption and increases the indirect utility cost of the tax. On the other hand, an increase in income reduces the marginal utility of consuming the carbon-intensive good and increases the benefits of mitigation. Either effect can dominate depending on the trade-offs between carbon-intensive consumption and environmental quality, as described in the following proposition:

Proposition 1. *When carbon-intensive subsistence expenditure is strictly positive and strictly below income ($0 < \frac{qx_0^h}{y_i} < 1$), the preferred tax rate of a household of type h and income y_i increases weakly with income if and only if*

$$\varepsilon_{E,q} + \frac{1}{\left(\frac{qx_0^h}{y_i}\right)^{-1} - 1} \geq \frac{\gamma}{\beta}.$$

Proof: Appendix A.4.

The left-hand side captures the effect of marginal income on willingness to mitigate. The first term, the price elasticity of environmental quality $\varepsilon_{E,q}$, reflects how effectively a higher carbon tax reduces emissions. The second term captures the effect of carbon-intensive subsistence consumption. A larger budget share of subsistence consumption $\frac{qx_0^h}{y_i}$ makes mitigation less affordable and increases the impact of marginal income on willingness to mitigate. The right-hand side is the ratio of the marginal budget share of carbon-intensive consumption γ (before rescaling by environmental concerns) to the environmental quality preference parameter β .

Proposition 2. *(Corner cases)*

When carbon-intensive subsistence expenditure is zero, the preferred tax rate increases weakly with income if and only if $\beta\varepsilon_{E,q} \geq \gamma$.

When carbon-intensive subsistence expenditure equals income, an increase in income always results in a (weakly) increase in preferred tax.

Proof: Appendix A.4.

Effect of urban-rural type on household preferred tax rate

Next, I compare the preferred tax rate of a rural and an urban household with the same level of income. To do so, I consider the difference in the first derivative of the indirect utility of an urban and a rural household, given the same tax rate. I then evaluate this difference at the preferred tax of an urban household with the given income, and characterize the gap in preferred tax rates³. The subtraction of equation (4.1.1) for both types, evaluated at the same income y and at the preferred tax rate of the urban τ^u , writes

$$\frac{\partial}{\partial \tau} V_i^r(\tau^u(y), y) \Big|_y = \frac{\partial V^r}{\partial \tau}(\tau^u(y), y) - \frac{\partial}{\partial \tau} V^u(\tau^u(y), y) < 0$$

³This can be done because $\frac{\partial}{\partial \tau} V^u(\tau^u(y_i), y_i) = 0$ by definition of $\tau^u(y_i)$ (solution of the first order condition), and all other parameters in $V()$ are fixed exogenously.

Proposition 3. *For a same level of income, a rural household prefers a strictly lower tax rate than an urban household.*

Proof: Appendix A.5.

This reflects the cost of the larger subsistence consumption of carbon-intensive good by the rural household.

4.2 Majority voting

I now turn to country level results. I use majority voting to capture political support at the aggregate level. Unlike what the denomination could suggest, the use of a majority voting equilibrium is not intended to represent a democratic election or legislative process, but rather a measure of public preferences. This can be thought of as the opinion of the domestic constituency, which can then be taken into account by the ruling government.

The preferred tax rate of a household is

- i) a unique global maximum (single-peaked preferences) if $\frac{\partial}{\partial q} \varepsilon_{E,q} \leq 0$, with $\varepsilon_{E,q}$ the price-elasticity of environmental quality
(Proof: Appendix A.3)

- ii) weakly increasing with income iff $\varepsilon_{E,q} + \frac{1}{\left(\frac{qx_0^h}{y_i}\right)^{-1} - 1} \geq \frac{\gamma}{\beta}$

- iii) lower for a rural household than an urban household, all other things equal.

The result of majority voting can thus be characterized by the tax rate chosen by the median voter (Kramer, 1972) in the whole population. I start by studying the median voter in the urban and rural population separately, then move on to the study of the median voter when all voters are pooled.

Majority voting in the urban and rural populations

Let \tilde{y}^h denote the income of the median voter of type $h = \{u, r\}$, when voters are separated according to their type, along the urban-rural divide. By definition, the income of the median voter inside a type population, \tilde{y}^h , is the income such that $F(\tilde{y}^h) = \frac{1}{2}$, with $F^h(\cdot)$ the cumulative distribution of income of households of type h over $[y^-, y^+]$. If income has the same distribution inside the rural and urban populations, the income of the median voter is identical for both populations, i.e. $\tilde{y}^u = \tilde{y}^r$.

A rural household always prefers a strictly lower tax rate than an urban household for a same level of income. Thus, the tax rate chosen by majority voting inside the

rural population only is lower than the tax rate inside the urban population only when $\tilde{y}^u = \tilde{y}^r$.

$$\tau^u(\tilde{y}^u) > \tau^r(\tilde{y}^r).$$

Majority voting in the whole population

I now turn to the result of majority voting in the total population, comprised of a proportion α of urban and $(1 - \alpha)$ of rural.

At a given level of tax, the cumulative distribution of votes is the sum of the urban and rural distributions, weighted by the proportion of each type in the population. By the median voter theorem, the majority voting tax rate in the whole population is the median voter tax rate τ_{mv} such that

$$\alpha F^u(y^u(\tau_{mv})) + (1 - \alpha) F^r(y^r(\tau_{mv})) = \frac{1}{2},$$

with $y^h(\tau_{mv})$ the income of a voter of type h whose preferred tax rate is τ_{mv} . In the following, let $y_{mv}^h = y^h(\tau_{mv})$ denote the income of the median voter of type h in the total population majority voting.

Under some conditions on the ordering of voters along preferred tax levels, the median voter can be characterized further:

Proposition 4. *If $\varepsilon_{E,q} + \left(\left(\frac{qx_0^h}{y_i} \right)^{-1} - 1 \right)^{-1} \geq \frac{\gamma}{\beta}$ for all $y_i \in [y^-, y^+]$ and $h = \{u, r\}$, and if there is no overlap between the preferred tax rates of urban and rural (i.e. $\tau^r(y^+) < \tau^u(y^-)$), then the median voter is*

- i) *an urban household poorer than the median household when urban are in majority ($\alpha > \frac{1}{2}$)*
- ii) *a rural household richer than the median household when rural are in majority ($\alpha < \frac{1}{2}$)*

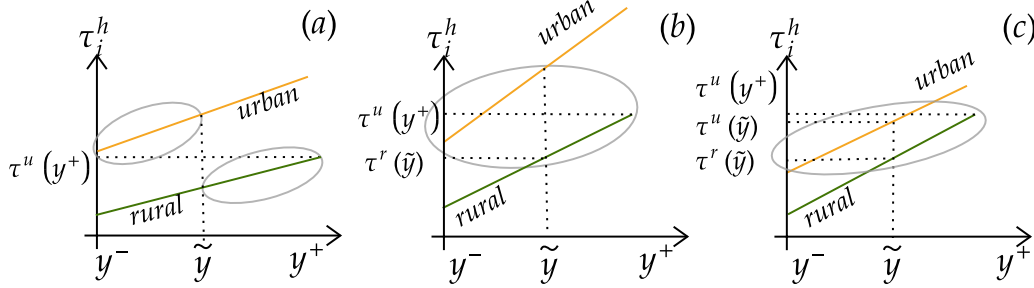
If on the contrary $\varepsilon_{E,q} + \left(\left(\frac{qx_0^h}{y_i} \right)^{-1} - 1 \right)^{-1} \geq \frac{\gamma}{\beta}$ for all $y_i \in [y^-, y^+]$ and $h = \{u, r\}$, and if there is no overlap between the preferred tax rates of urban and rural (i.e. $\tau^r(y^-) < \tau^u(y^+)$), then the median voter is

- i) *an urban household richer than the median household when urban are in majority ($\alpha > \frac{1}{2}$)*
- ii) *a rural household poorer than the median household when rural are in majority ($\alpha < \frac{1}{2}$)*

Under either of these two sets of conditions, the urban-rural inequality in subsistence carbon-intensive consumption is sufficiently large to lead to a polarization of votes along the urban-rural divide. The polarization means that no household from the group (urban or rural) in minority supports the majority voting tax.

When these conditions do not hold, the median voter can be either an urban, a rural, or both an urban and a rural household with different incomes. The different cases are illustrated in Figure A4.

Figure A4: Majority voting tax rate when $\frac{\partial \tau^h(y_i)}{\partial y_i} \geq 0$



Note: The graph shows how the preferred tax rate changes with income between minimum income y^- and maximum income y^+ , for urban and rural households. The gray circles represent the possible location of the median voter in terms of income and urban-rural dimensions.

Panel (a) displays the case in which there is no overlap between the tax rates of the rural and the urban, which leads to a polarized majority vote. In panel (b), the median voter can be either a rural, an urban household, or both. In panel (c), the median voter tax rate is always the preferred tax rate of both an urban and a rural.

How does the majority voting tax rate compare to the social planner rate?

The majority voting tax rate can now be compared to the social planner benchmark to analyze whether income and urban-rural inequalities lead to insufficient political support for the socially optimal carbon tax. I evaluate the first order condition of the social planner at the majority voting tax rate. A strictly positive value of the evaluated social planner first order condition implies that the majority voting tax rate is lower than the pigouvian rate.

Proposition 5. Denoting $q_{mv} = p + \tau_{mv}$ the carbon-intensive good price at the majority voting tax rate and y_{mv}^h the income of the median voter of type h , the majority voting tax

rate τ_{mv} is strictly lower than the social planner tax rate τ_{sp} if and only if

$$\begin{aligned} & (\beta\varepsilon_{E,q} - \gamma) \left(\sum_{j=\{u,r\}} \left(\theta^j \mathbb{E} \left[(y_i - q_{mv} x_0^j)^{1-\beta} \right] \right) - (y_{mv}^h - q_{mv} x_0^h)^{1-\beta} \right) \\ & - (1 - \beta) \left(\sum_{j=\{u,r\}} \left(\theta^j \frac{q_{mv} x_0^j}{\mathbb{E} \left[(y_i - q_{mv} x_0^j)^\beta \right]} \right) - \frac{q_{mv} x_0^h}{(y_{mv}^h - q_{mv} x_0^h)^\beta} \right) > 0 \end{aligned} \quad (4.2.1)$$

with $\theta^u = \theta$ and $\theta^r = 1 - \theta$ the generalized welfare weight.

Proof: Appendix A.6.

Whether τ_{mv} is smaller or larger than is socially optimal depends on how the individual costs of the median voter compare to the social evaluation of the cost for the whole population. The first term corresponds to the relative strength of preference for mitigation versus carbon-intensive consumption. When the marginal willingness to pay to improve environmental quality ($\beta\varepsilon_{E,q}$) is larger than the adjusted marginal budget share for the polluting good (γ), the preferred tax rate increases with income (Proposition 1). The social planner takes into account a socially weighted income, net of type-specific subsistence expenditure and aggregated over the whole distribution. If this socially weighted net income is larger than the net of subsistence expenditure income of the median voter, and if, in addition, the tax rate increases with income, then the social planner carbon tax tends to be larger than the majority voting tax.

The second term captures the additional cost of the tax from the constrained consumption of the carbon-intensive good. The median voter only takes into account their own subsistence expenditure, which is larger if the median voter household is rural rather than urban. On the other hand, the social planner considers a socially weighted average of the cost for both urban and rural households. Thus having a rural median voter tends to push the majority voted tax to a lower level than the social planner tax.

To get further insights into the role of income and urban-rural inequality, this result can be contrasted with the special case in which there is no subsistence consumption, i.e. $x_0^h = 0$ for urban and rural households. In this case, the necessary and sufficient condition for the majority voting tax rate to be strictly lower than the social planner rate is

$$(\beta\varepsilon_{E,q} - \gamma) \left(\mathbb{E} \left[y_i^{1-\beta} \right] - (y_{mv}^h)^{1-\beta} \right) > 0$$

The second term in equation (4.2.1) disappears since it reflected horizontal heterogeneity, and only the term capturing the relative preference for mitigation and polluting consumption remains. In the absence of any urban-rural inequality, the median voter will earn the population's median income, i.e. $y_{mv}^h = \tilde{y}$. When the preferred tax rises with income ($\beta\varepsilon_{E,q} - \gamma > 0$), the skew of the income distribution towards higher income leads the majority tax rate to be lower than the social planner tax.

Impact of transfers on political support

The government can recycle the revenues generated by the carbon tax to the households. Transfers can be lump-sum or targeted on demographic variables, such as to urban or rural households or to households with income lower than a given threshold. Furthermore, keeping the same level of carbon tax, redistribution is likely to increase the level of greenhouse gas emissions in aggregate. This rebound effect is due to the increase in income for part or all of the population that partly translates into increased consumption of the carbon-intensive good. The government budget constraint is thus

$$nT = \tau X(q, \bar{y}, T),$$

with n the proportion of the population receiving the transfer. Replacing the expression for aggregate emissions and solving for the transfer yields

$$T = \frac{\tau}{n((1-\beta) - \gamma \frac{\tau}{q})} \left[\frac{\gamma}{q} \bar{y} + (1 - \gamma - \beta) \bar{x}_0 \right].$$

I focus here on lump-sum transfers, i.e. $n = 1$, and explore two sets of assumptions regarding the anticipation by households of transfers and second order effects. In the calibration exercise, I also test for the impact of transfers targeted to the rural household or income-based.

Lump-sum transfers with full anticipation

In the first case, households fully anticipate the transfer amount they receive as a function of the tax rate, as well as the impact of transfers on aggregate consumption of the carbon intensive good.

In the absence of any limit on payment capacity by the rural household, an urban household's leftover disposable income (i.e. income net of lump-sum transfers and subsistence consumption, $y_i + T - qx_0^u$) would tend towards infinity as the tax rate τ becomes arbitrarily large⁴. This is not the case for a rural household. The reason is that an increase in tax levels decreases the variable component of aggregate carbon intensive good consumption, but not the subsistence consumption component. By construction, urban households have a lower subsistence consumption than the average. Hence, an urban household anticipates that the tax and transfer scheme results in horizontal transfers from the more constrained rural households, which makes leftover disposable income increase with the tax level.

⁴ $y_i + T - qx_0^u$ can be rewritten as $q(1 - \alpha)(x_0^r - x_0^u) + y_i - \frac{1 + \frac{p}{\tau}}{\frac{1-\beta-\gamma}{1-\beta} \frac{1}{p} + \frac{1}{\tau}} \bar{x}_0 + \frac{\gamma}{(1-\beta-\gamma) + (1-\beta) \frac{p}{\tau}} \bar{y}$. With $y_i - \frac{1 + \frac{p}{\tau}}{\frac{1-\beta-\gamma}{1-\beta} \frac{1}{p} + \frac{1}{\tau}} \bar{x}_0 + \frac{\gamma}{(1-\beta-\gamma) + (1-\beta) \frac{p}{\tau}} \bar{y} \xrightarrow{\tau \rightarrow +\infty} y_i + \frac{\gamma \bar{y} - (1-\beta)p \bar{x}_0}{1-\beta-\gamma}$, and $x_0^r > x_0^u$, it can then be shown that $y_i + T - qx_0^u \xrightarrow{\tau \rightarrow +\infty} +\infty$.

Because tax payments cannot exceed income in this setting, I set an upper bound for the tax rate such that the rural household with the lowest income can afford to pay the subsistence consumption, τ^{max} such that $y_i^- + T(\tau^{max}) + (p + \tau^{max})x_0^r = 0$.

With fully anticipated lump-sum transfers, the indirect utility of an urban household $V^u(q, y_i + T, x_0^u)$ is not necessary single-peaked (see Appendix A.7). As detailed in Appendix A.7, under some conditions the preferred tax rate of an urban household can then be either the highest possible tax rate τ^{max} or, $\tau^u(y_i)$ defined implicitly by

$$\tau^u(y_i) = \frac{\beta \varepsilon_{E,\tau}}{\frac{\gamma}{(p + \tau^u(y_i))} + (1 - \beta) \frac{x_0^h - \frac{\partial T}{\partial \tau}}{y_i + T - (p + \tau^u(y_i))x_0^h}}.$$

If $\forall y_i \in [y^-, y^+]$, $\frac{\partial}{\partial \tau} V^u(p + \tau^{max}, y_i + T, x_0^u) > 0$, then all urban households prefer the highest tax rate τ^{max} . The majority voting tax rate in the urban population will be also the highest possible, i.e. $\tau^u(\tilde{y}^u) = \tau^{max}$. Making the additional assumption that the preferences of rural households are single-peaked⁵, the majority voting tax rate in the whole population will be the maximum τ^{max} whenever there is a majority of urban households ($\alpha > \frac{1}{2}$). In this case, lump-sum transfers can result in strong increases in the majority voting carbon tax, but are also likely to increase the urban-rural divide in political support due to the response of urban households to the transfers.

Lump-sum transfers with myopia on the tax-transfer outcome

I turn to a second case, in which households do not anticipate the effect of the tax on the transfer amount they will individually receive; which implies that transfers are treated by households as additional income. This case is arguably more realistic than the previous case with full anticipation of transfers, which resulted in the anticipation of a “tax rent” paid by the rural to the urban households and in anticipation of large increases in income for the urban households. In this second case, the households are also myopic to the rebound effect of transfers on aggregate consumption of the carbon intensive good.

Transfers reduce the absolute cost of the tax for the households receiving them. However, they do not necessarily result in political support for higher carbon tax rates. Transfers can increase this political support only if the marginal income they bring translates into more demand for mitigation than for carbon-intensive consumption. This leads to the following condition:

Proposition 6. *Transfers to households increase the carbon tax rate which is supported by majority voting if $\varepsilon_{E,q} + \frac{1}{\left(\frac{qx_0^h}{y_i}\right)^{-1} - 1} \geq \frac{\gamma}{\beta}$ for all y_i .*

⁵The formal proof for the singled-peakedness of the indirect utility of rural households has not been derived. The numerical illustrations support this assumption, see Appendix A.7.

Proof: Transfers enter the household budget as additional income. Proposition 1 gives the condition for an increase in income to result in a higher preferred tax rate.

Because the tax chosen by majority voting can only be characterized implicitly, I perform numerical simulations to shed light on the magnitudes of the political support effects captured in the model. The next section illustrates the majority voting results and provides further insights into the potential of different transfer schemes to improve equity and political support for carbon taxation.

5 Calibration of the model to European countries

The model is calibrated with European data. I use fuels and domestic energy expenditures as a proxy for carbon-intensive consumption. These consumption categories correspond to the notion of a heterogeneous subsistence consumption, with consumers constrained in the short-term. In addition, price shifts due to a carbon tax tend to have a large pass-through (e.g., Harju et al., 2022 on gasoline) and be salient for these categories of goods. Because households and the social planner factor in the post-tax price only, I set the pre-tax relative price to 1 to make interpretation more straightforward.

5.1 Parameter calibration

I use the latest round of the Eurostat Household Budget Survey (Eurostat, 2015). Variables are harmonized across countries which facilitates cross country comparisons.

Income and share of urbans and rurals

The income distribution $F(\cdot)$ is calibrated for each country and separately for urbans and rurals, by assuming a truncated log-normal distribution $Lognormal(\mu_h, \sigma_h^2)$, with $\mu^h = \ln(\bar{y}^h)$ and $\sigma^2 = 2(\ln(\bar{y}^h) - \mu^h)$. Mean and median income \bar{y}^h and \tilde{y}^h are calibrated using total consumption expenditure⁶ per adult from the Household Budget Survey. For the minimum and maximum income, y^- and y^+ , I use the 1st and 99th percentile of the consumption expenditure distribution.

For the horizontal inequality, i.e. the urban-rural type, I use the population density level variable. It can take three values: Densely populated (at least 500 inhabitants/km²), Intermediate (between 100 and 499 inhabitants/km²) and Sparsely populated (less than 100 inhabitants/km²). I use the share of households living in densely populated areas as the share of urbans α , and the share in either intermediate or sparsely populated areas as the share of rurals $(1 - \alpha)$.

⁶Total consumption expenditure fits better to the notion of income used in this paper. The expenditure-elasticity of emissions is closer to 1 than the total income elasticity, due to different propensities to save across income groups.

Estimation of the demand for carbon-intensive goods

To calibrate the subsistence amount of the carbon-intensive good x_0^h , I estimate a demand system using the Household Budget Survey. I drop the countries for which the necessary data (fuels, energy expenditure and density of population) is not available or of bad quality.

The linear expenditure system (LES) (Pollak and Wales, 1969) is the demand system derived from a Stone-Geary specification. From the demand equation (3.1.1), expenditure can be rewritten as

$$qx_i = qx_0^h + \frac{\gamma}{1-\beta} (y_i - qx_0^h).$$

This results in an Engel curve for the carbon-intensive good which is linear in income with origin qx_0^h . As a preliminary check of whether this specification is a good enough fit to the data, I compute for each country the mean expenditure by quintile of total expenditure, for urban and rural. As shown in Figures A8 and A9 in Appendix B, a linear Engel curve for fuel and energy expenditure appears to be a reasonable approximation. Horizontal inequality, i.e. the difference in mean expenditure between urban and rural, appears to be large in some countries and negligible in others.

The assumption of linearity in estimating the Linear Expenditure System parameters involves estimating a system of equations for J goods such that

$$p_j x_j = p_j x_{0j} + \lambda_j \left(y_i - \sum_m p_m x_{0m} \right)$$

with $p_j x_j$ the overall expenditure on good j , $p_j x_{0j}$ the subsistence expenditure on good j , λ_j the marginal budget share of good j , and y_i total expenditure. I construct the polluting good expenditure by aggregating the COICOP categories “Electricity, gas and other fuels” under Housing and “Fuels and lubricants” under Transport.

The difference in subsistence consumption due to the urban-rural divide can be estimated either by estimating the demand system separately on the rural and the urban subpopulations, or by a translation procedure (Pollak and Wales, 1978). The translation procedure specifies that the subsistence amounts depends on the demographic variable. Finally, assuming no subsistence consumption for the rest of expenditure to avoid singularity, I estimate for each country

$$p_i x_i = (\chi_{0,1} + 1_{h=r} \chi_{0,2}) + \gamma y_i$$

with $p_i x_i$ the expenditure in good i , $\chi_{0,1} = p x_0^u$ the constrained expenditure of an urban, and $\chi_{0,2} = p x_0^r - p x_0^u$ the additional constrained consumption of a rural household with respect to that of an urban household.

Environment

I chose the environmental quality function to be

$$E(X) = 1 - \frac{X(q)}{X(p)}.$$

$E(X)$ is positive when emissions are reduced with respect to the baseline case without carbon taxation, and negative if they increase. The choice of pre-tax emissions $X(p)$ as the baseline and the CES type elasticity imply that a positive tax rate will always be chosen.

The parameter that determines preference over the environment, β , cannot be directly calibrated given the data. I find the value β which leads to a fixed and pre-defined optimal emissions reduction. This is as if an emission reduction target was fixed, which reveals the preference for mitigation of the social planner given the other model parameters. I choose a 10% emissions reduction in each country, i.e. $E(X) = 0.1$. This corresponds to a short-term and relatively strong reduction. For instance, the Fit for 55 package adopted by the European Commission in 2021 sets a target to reduce emissions by 55% by 2030, relative to 1990 emissions levels. Given that emissions have already decreased by around 25% between 1990 and 2020, an average reduction of around 5% per year between 2020 and 2030 is needed to reach the 55% reduction goal.

5.2 Results

The results of the empirical estimation are shown in Figures (A10) and (A11), with the detail in Table A11. I solve numerically for the tax rate which maximizes indirect utility of the household of type $h = \{u, r\}$ and income y_i . The median voter tax rate in the urban population only (resp. rural only) is the tax rate preferred by the urban (resp. rural) household with median income, $\tau^u(\tilde{y})$ (resp. $\tau^r(\tilde{y})$). The majority voting tax rate is the tax such that $\alpha F(y_{mv}^u(\tau_{mv})) + (1 - \alpha)F(y_{mv}^r(\tau_{mv})) = 0.5$, with $y^h \sim \text{Lognormal}(\mu^h, (\sigma^h)^2)$ on the support $[y^-, y^+]$. The optimal tax solves the social planner program, with equal weight on the urban and rural households, $\omega^r = \omega^u = 1$.

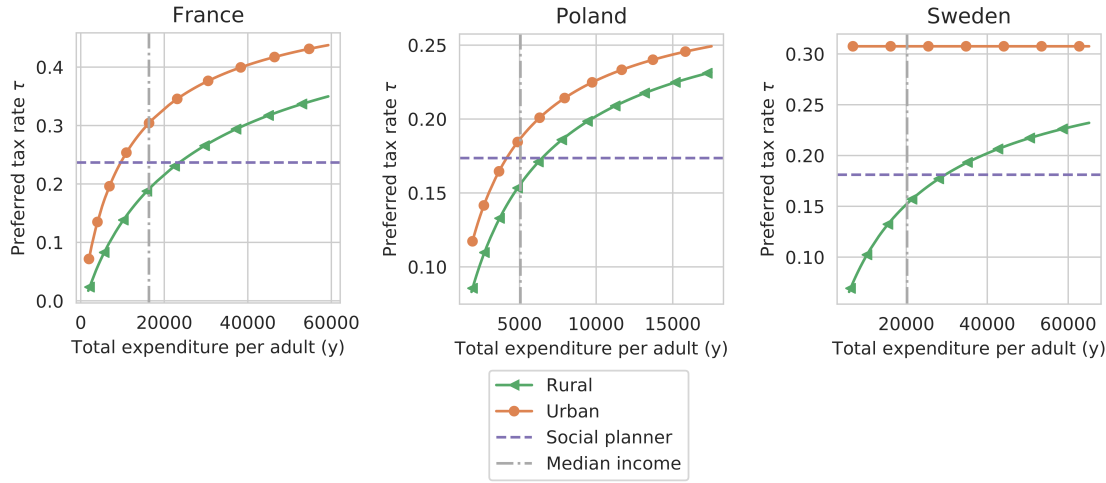
I analyze political support for carbon taxation, the role of urban-rural inequality and the distributive and support impacts of redistribution of the tax revenues. In what follows, I show graphical representation of the calibration results for selected countries. The graphs for all countries can be found in Appendix (B.3).

Impact of income and urban-rural type on political support

For all the calibrated countries, I find a (weakly) positive effect of income and preferred tax rate. For Finland, Hungary and Sweden (cf. Figure (A12)) the effect of income on the preferred tax rate of the urbans is null. This is because the estimate of subsistence

expenditure for the urban was non-significant or slightly negative, which results in no subsistence expenditure for the urban households in these case. The effect of income on the level of preferred tax rates is larger at lower levels of income. In addition, the gap between the preferred tax rate of urban and rural households with the same level of income decreases with income. This concavity reflects the loosening of the constraint from subsistence consumption of the carbon-intensive good. These findings are illustrated in Figure A5 for France, Poland and Sweden.

Figure A5: Effect of income and urban-rural type on calibrated preferred tax rates



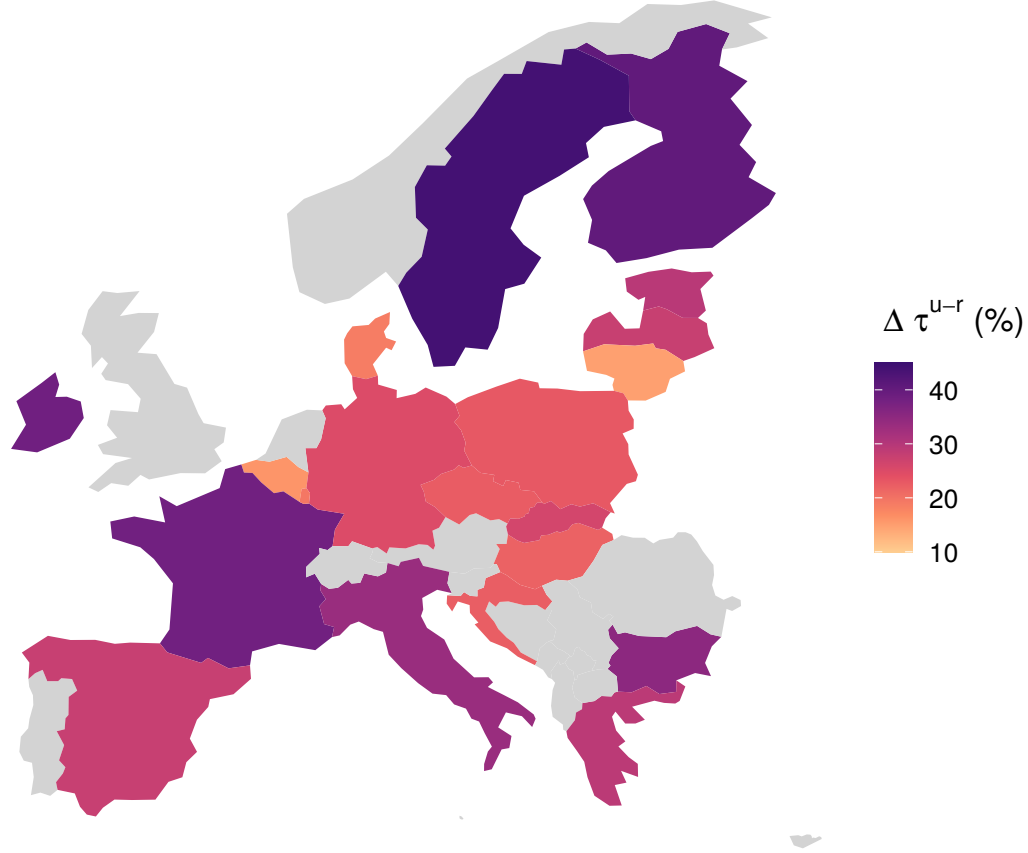
More precisely, the impact of the higher subsistence consumption of the carbon-intensive good of rurals on the political support for carbon taxation can be captured by comparing the tax rate of the median voter inside the urban and rural populations separately. I compare the tax preferred by an urban household earning the median income in the urban population, to the one preferred by a rural household earning the median income in the rural population, dividing by the urban's tax to capture the gap as a proportion :

$$\Delta\tau^{u-r}(\tilde{y}) = \frac{\tau^u(\tilde{y}^u) - \tau^r(\tilde{y}^r)}{\tau^u(\tilde{y}^u)}.$$

Figure A6 displays this gap for all the calibrated countries, in percentage. It shows that the tax rate of a household with the median income is between 10 and 40% lower for a rural than an urban household. Sweden, France, Finland and Ireland are found to be the countries with the larger gap.

Turning to the difference between the social planner tax rate τ_{sp} , with equal weights on rural and urban households, and the majority voting tax rate τ_{mv} , I find that the majority voting tax rate is lower than the social planner's in every country. As shown in Table A6, the difference is between 1 and 7.8 %. The gap is smaller

Figure A6: Gap between the median voter tax rates in the urban vs rural population, as a share of median voter tax rate in the urban population, in %



Note: $\Delta \tau^{u-r} = \frac{\tau^u(\bar{y}^u) - \tau^r(\bar{y}^r)}{\tau^u(\bar{y}^u)}$.

than between urban's and rural's median households tax rates. This indicates that although the optimal tax rate is close to achieving support from half of the population, this support is polarized along the urban-rural dimension. The optimal tax rate also takes into account the heterogeneity in tax burden and additional cost for the rurals. If social weights are skewed towards urban households' welfare, the gap between optimal and majority voting rates increases.

Distributional and political support impacts of lump-sum transfers

Next, I focus on the impact of redistributing the revenues generated by the carbon tax through transfers. I analyze three transfer options: lump-sum, targeted at households

Table A6: Calibration results, without transfers

Country	τ_{sp}	τ_{mv}	$\Delta\tau_{sp/mv}(\%)$	$\Delta\tau^{u/r}(\%)$
Belgium	0.425	0.397	6.7	16
Bulgaria	0.146	0.140	4.3	35.1
Czech Republic	0.226	0.221	2.1	22.6
Germany	0.249	0.238	4.2	25
Denmark	0.189	0.182	3.9	18.8
Estonia	0.207	0.193	6.8	29.5
Greece	0.203	0.192	5.2	29.3
Spain	0.168	0.166	1	27.8
Finland	0.166	0.153	7.7	40.4
France	0.237	0.228	3.7	38.4
Croatia	0.147	0.143	3	22.5
Hungary	0.131	0.124	5.7	22
Ireland	0.215	0.213	1.1	38.5
Italy	0.188	0.180	4.3	33.5
Lithuania	0.128	0.126	1.5	14.9
Luxembourg	0.258	0.246	4.9	19.5
Latvia	0.162	0.155	4.5	27.7
Poland	0.174	0.166	4.5	23
Sweden	0.181	0.167	7.8	43.9
Slovakia	0.257	0.245	4.4	26.2

with income below the median and targeted at rural households.

The transfer amount is computed from the majority voting tax rate in the absence of transfers, i.e.,

$$T = \frac{\tau_{mv}}{n \left((1 - \beta) - \gamma \frac{\tau_{mv}}{p + \tau_{mv}} \right)} \left[\frac{\gamma}{p + \tau_{mv}} \bar{y} + (1 - \gamma - \beta) \bar{x}_0 \right],$$

with $n = 1$ if transfers are lump-sum, $n = \alpha F^u(\tilde{y}) + (1 - \alpha) F^r(\tilde{y})$ if transfers are income-based and $n = (1 - \alpha)$ if transfers are targeted to the rural households.

Before redistribution, carbon taxation is regressive due to subsistence consumption. Regressivity is stronger inside the rural population, due to the larger amount of subsistence consumption. Lump-sum transfers render the tax and rebate scheme progressive overall, but leaves the urban households better than the rural households. Carbon tax and lump-sum transfers thus result in horizontal distributional effects, between rural and urban households. Income-based transfers result in even stronger progressivity of revenue recycling, but only below the median income. Finally, rural

targeted transfers reverse the regressivity of the tax carbon, but for rural households only. Focusing on the first income quintile in each country, Figure (A14) demonstrates that urban households benefit the most from income-based transfers. Urban households gain up to 5% of their income in net from the carbon tax and rebate scheme. As shown in Figure (A13), rural households in the first quintile benefit the most from either income-based or rural-only transfers, depending on the country. In many countries, income-based transfers tend to have a better incidence at the bottom of the distribution than income-based transfers, with rural households in the first quintile gaining up to 6% of their income in net.

I analyze the effect of redistribution on political support and urban-rural support polarization, looking at the induced change in the majority voting tax rate. Figure (A16) shows that transfers targeted at households below the median income or targeted at rural households tend to result in a larger decrease in the urban-rural gap in political support, compared to lump-sum transfers. However, this is not the case for countries where the rural population is richer on average than the urban population (Belgium, Germany, Finland, and Luxembourg, c.f. Table (A11)). Additionally, income-based transfers tend to reduce urban-rural polarization more than transfers targeted at rural households in eastern European countries such as Poland, the Czech Republic, or Estonia. These countries tend to have a high marginal propensity to consume carbon-intensive goods and a spatial income distribution in which poor households live in rural areas.

Lastly, Figure (A15) displays the impact of transfers on the majority voting carbon tax, compared with the benchmark social planner tax. The social planner tax increases by 5%-18%, in part due to the rebound effect in greenhouse gas emissions that the households do not consider. Transfers increase the majority voting tax rate by a small percentage. This increase can be interpreted as the “pure” effect of changes in the tax incidence, without factoring in the rebound effect nor the relationship between the tax rate and transfer amount, and when households have the same preferences for the environment as the social planner. As Figure (A15) shows, no transfer type stands out in terms of its effect on political support. Transfers directed at rural households do not appear to improve carbon tax acceptability more than lump-sum transfers. These transfers, which pose informational and efficiency issues, are thus not justified on grounds of acceptability.

Robustness checks

I test the robustness of the results to the level of the emission reduction target. I set the emissions reduction target at 5% instead of 10%. As shown by comparing Figures (A17)-(A20) in Appendix B.4 to Figures (A13)-(A16) in Appendix B.3, a less stringent climate target changes the magnitude but not the direction and overall pattern of the results.

6 Discussion

I integrate the issue of acceptability to the equity-efficiency trade-off described in optimal carbon taxation models. This results in a framework in which the opinion of households over the carbon tax is driven by selfish motives (private costs and benefits) and environmental preference. Further work could explore other determinants of public support, integrating insights from the behavioral and political science literature.

Reviewing evidence on public preferences over carbon pricing, [Klenert et al. \(2018\)](#) highlight two insights from the political science literature. The first is the role of trust. They underline how salient lump-sum transfers could limit political distrust. This insight could be integrated through modeling the level of trust in the efficiency of the carbon tax, or in the credibility of transfers. The second insight relates to the Olsonian argument that concentrating benefits and diffusing costs is likely to help enact a given policy. This paper explores the acceptability issues that could arise from concentration of the costs on more carbon constrained households. Alternative frameworks could include other distributional dimensions, such as loss of employment in carbon intensive industries.

[Klenert et al. \(2018\)](#) also put forth the role of behavioral effects on beliefs and decision-making in driving public attitudes to carbon taxation. Political and economic beliefs could be included in a static majority voting framework through additional parameters in household preferences. Other approaches have also focused on the dynamics of changing preferences over climate policies (e.g. [Konc et al. \(2021\)](#), [Besley and Persson \(2023\)](#)).

Finally, public support for carbon taxation needs to be translated through political institutions in order to be implemented. The type of institution and quality of governance matter for successful implementation of climate policy, in particular because it affects the likelihood of solving distributive conflicts or managing vested interests ([Levi, 2021](#)). This type of issue is studied in the political economy literature through a variety of models, such as probabilistic voting or political competition. An interesting avenue of research could be to study the consequences of horizontal distributional impacts across voters within such frameworks.

7 Concluding remarks

I have analyzed political support for carbon taxation and the impact of horizontal distributive effects. Political support is captured through a majority voting model in which households differ with respect to the minimum amount of emission-intensive good they are constrained to consume, as well as the income they earn. According to the theoretical model, income can have a positive or negative effect on household's preferred tax rate, depending on the relationship between the price-elasticity of en-

vironmental quality, the preference over carbon-intensive consumption and mitigation, and the level of expenditure for subsistence carbon-intensive goods. Income and urban-rural inequalities jointly determine the majority voting tax rate and the corresponding median voter.

I then calibrate the model to twenty European countries and a ten percent emission reduction. I find that the political support of households increases with income and for urban households with respect to rural households. That is to say, political support increase when the budget constraint from the subsistence consumption of the carbon-intensive good slackens. The results show that the majority voting tax is 1-8% lower than the optimal carbon tax. However, the gap in accepted carbon tax between the median urban household and the median rural household is larger, with the median rural household's preferred tax up to 16-44% lower than the median urban household's preferred tax. I find that redistributing the revenues of the carbon tax as a lump-sum transfer renders the regressive tax scheme progressive. However, lump-sum redistribution does not correct for the horizontal inequality and has limited, albeit positive, impact on political support.

These results yield mixed policy implications. Recycling the revenues generated by a carbon tax has the potential to greatly improve its distributional impact and fairness. However, lump-sum redistribution of tax revenues might not be sufficient to significantly improve political feasibility, especially if a large portion of households remains dependent on carbon-intensive consumption.

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A Proofs

A.1 Social planner

The social planner's welfare function can be re-written as

$$W = \left(\theta \int_{y^-}^{y^+} v(q, y_i, x_0^h) dF(y_i) + (1 - \theta) \int_{y^-}^{y^+} v(q, y_i, x_0^h) dF(y_i) \right) E(X)^\beta,$$

which leads to the following first-order condition

$$\begin{aligned} \frac{\partial W}{\partial \tau} = & \left(\theta \int_{y^-}^{y^+} \frac{\partial}{\partial \tau} v(q, y_i, x_0^h) dF(y_i) + \theta \omega^r \int_{y^-}^{y^+} \frac{\partial}{\partial \tau} v(q, y_i, x_0^h) dF(y_i) \right) E(X)^\beta \\ & + \left(\theta \int_{y^-}^{y^+} v(q, y_i, x_0^h) dF(y_i) + (1 - \theta) \omega^r \int_{y^-}^{y^+} v(q, y_i, x_0^h) dF(y_i) \right) \frac{\partial E(X)^\beta}{\partial \tau} = 0. \end{aligned} \quad (\text{A.1.1})$$

Plugging in the indirect utilities and their derivatives with respect to the tax and using LOTUS:

$$\begin{aligned} \frac{\partial W}{\partial \tau} = & -\frac{\gamma}{q} \left(\theta \mathbb{E}[(y_i - qx_0^u)^{(1-\beta)}] + (1 - \theta) \mathbb{E}[(y_i - qx_0^r)^{(1-\beta)}] \right) E(X)^\beta \\ & - (1 - \beta) \left(\theta x_0^u \mathbb{E}[(y_i - qx_0^u)^{-\beta}] + (1 - \theta) x_0^r \mathbb{E}[(y_i - qx_0^r)^{-\beta}] \right) E(X)^\beta \\ & + \left(\theta \mathbb{E}[(y_i - qx_0^u)^{(1-\beta)}] + (1 - \theta) \mathbb{E}[(y_i - qx_0^r)^{(1-\beta)}] \right) \beta E(X)^{\beta-1} \frac{\partial E}{\partial \tau} = 0. \end{aligned}$$

Re-ordering finally results in equation 3.2.1.

A.2 Local concavity of household's indirect utility

Denote $v(\tau) := \frac{a}{q^\gamma} (y_i - qx_0^h)^{(1-\beta)}$ and $h(\tau) := (E(X(q)))^\beta$, such that $V(\tau) = v(\tau)h(\tau)$. Let $\tau^* = \tau^h(y_i)$ such that $\frac{\partial V(\tau^*)}{\partial \tau} = 0$. The goal is to determine the sign of $\frac{\partial^2 V(\tau^*)}{\partial \tau^2} := V''(\tau^*)$. Dropping τ^* for convenience,

$$V' = v'h + vh' = 0$$

(by the first order condition), and

$$V'' = v''h + 2v'h' + vh''.$$

Next, rewrite

$$\begin{aligned} v' &= -\frac{a}{q^* \gamma} (y_i - q^* x_0^h)^{(1-\beta)} \left(\frac{\gamma}{q^*} + (1 - \beta) x_0^h (y_i - q^* x_0^h)^{-1} \right) \\ &= -vg \end{aligned}$$

with $q^* := p + \tau^*$ and $g := \frac{\gamma}{q^*} + (1 - \beta)x_0^h(y_i - q^*x_0^h)^{-1}$. Hence,

$$\begin{aligned} V'' &= (v'g + vg')h + 2(-vg)h' + vh'' \\ &= -gV' - vg'h - vgh' + vh''. \end{aligned}$$

Using the first order condition, i.e. $V' = 0$, results in

$$V'' = -v(g'h + gh' - h'').$$

So $\frac{\partial^2 V(\tau^*)}{\partial \tau^2} < 0$ if $g'h + gh' - h'' > 0$, i.e.

$$\beta(1 - \beta)\varepsilon_{E,q}^2 + (2 + \gamma)\beta\varepsilon_{E,q} - \gamma + (1 - \beta)\frac{q^*x_0^h}{y_i - q^*x_0^h} \left(\beta\varepsilon_{E,q} + \frac{q^*x_0^h}{y_i - q^*x_0^h} \right) > 0.$$

In the special case without subsistence consumption of the carbon-intensive good ($x_0^h = 0$), ($g'h + gh' - h'' > 0$) reduces to $\beta(1 - \beta)\varepsilon_{E,q}^2 + (2 + \gamma)\beta\varepsilon_{E,q} - \gamma > 0$. A sufficient condition for local concavity when $x_0^h = 0$ is for the environmental quality function $E()$ to be such that

$$\varepsilon_{E,q} > \frac{\left((1 + \frac{\gamma}{2})^2 + \frac{1-\beta}{\beta}\gamma \right)^{\frac{1}{2}} - (1 + \frac{\gamma}{2})}{(1 - \beta)}.$$

In addition, for $x_0^h > 0$, ($g'h + gh' - h'' > 0$) also holds when $\beta(1 - \beta)\varepsilon_{E,q}^2 + (2 + \gamma)\beta\varepsilon_{E,q} - \gamma > 0$. Hence, $\varepsilon_{E,q} > \frac{\left((1 + \frac{\gamma}{2})^2 + \frac{1-\beta}{\beta}\gamma \right)^{\frac{1}{2}} - (1 + \frac{\gamma}{2})}{(1 - \beta)}$ is a sufficient condition for local concavity $\forall x_0^h$.

A second sufficient condition for local concavity when $x_0^h > 0$, for any environmental function such that $E > 0$ for $\tau \geq 0$ and $\frac{\partial E}{\partial \tau} > 0$ is that the budget share of subsistence consumption is sufficiently large, i.e.

$$\frac{q^*x_0^h}{y_i} > \frac{1}{1 + \left(\frac{1-\beta}{\gamma} \right)^{\frac{1}{2}}}.$$

A.3 Single-peakedness of indirect utility

Suppose that the environmental function $E()$ is such that $\frac{\partial^2 V(\tau^*)}{\partial \tau^2} < 0 \forall \tau^*$ such that $V(\tau^*) = 0$ (Appendix A.2). Under this condition, all optima are local maxima. Given that the program is continuous on the domain and the maximization is on one variable only, the absence of any local minimum implies that there is only one optimum. Thus the optimum τ^* is a global maximum.

Next, consider \hat{q} in the neighborhood of q^* , with $\hat{q} > q^*$. By local strict concavity, $\frac{\partial V(\hat{q})}{\partial \hat{q}} < 0$, i.e.

$$\beta(y_i - \hat{q}x_0^h)\varepsilon_{E,q}(\hat{q}) < \gamma y_i + (1 - \gamma - \beta)\hat{q}x_0^h.$$

Now consider \hat{q} arbitrarily far from \hat{q} (i.e. not necessarily in the neighborhood) such that $\hat{q} > \hat{q}$. Then

$$\gamma y_i + (1 - \gamma - \beta)\hat{q}x_0^h > \gamma y_i + (1 - \gamma - \beta)\hat{q}x_0^h$$

and

$$\beta(y_i - \hat{q}x_0^h)\varepsilon_{E,q}(\hat{q}) < \beta(y_i - \hat{q}x_0^h)\varepsilon_{E,q}(\hat{q})$$

under the condition that $\frac{\partial}{\partial q}\varepsilon_{E,q}(q) \leq 0$, which reflects the fact that an increase in the tax has a stronger impact on environmental quality at lower than higher initial prices. Finally, $\hat{q} > \hat{q}$ implies

$$\beta(y_i - \hat{q}x_0^h)\varepsilon_{E,q}(\hat{q}) < \beta(y_i - \hat{q}x_0^h)\varepsilon_{E,q}(\hat{q}) < \gamma y_i + (1 - \gamma - \beta)\hat{q}x_0^h < \gamma y_i + (1 - \gamma - \beta)\hat{q}x_0^h,$$

i.e. $\frac{\partial V(\hat{q})}{\partial \hat{q}} < 0$. Thus, for all $q > q^*$, the indirect utility function $V()$ is strictly decreasing.

Symmetrically, it can be shown that for all $q < q^*$, $V()$ is strictly increase if $\frac{\partial}{\partial q}\varepsilon_{E,q}(q) \leq 0$. Hence, $V()$ is strictly quasi-concave under the condition for local concavity (Appendix A.2) and $\frac{\partial}{\partial q}\varepsilon_{E,q}(q) \leq 0$.

A.4 Effect of income on preferred tax rate

The sign of $A = \left(-\frac{\partial v}{\partial y_i} \frac{\partial x_i^*}{\partial y_i} E^\beta - \frac{\partial^2 v}{\partial y_i^2} x_i^* E^\beta + \frac{\partial v}{\partial y_i} \frac{\partial E^\beta}{\partial \tau} \right)$ needs to be determined. Developing each term yields

$$\begin{aligned} A &= \frac{a}{q^\gamma} (y_i - qx_0^h)^{-\beta-1} E^\beta \left(-\frac{\gamma}{q} (y_i - qx_0^h) + \beta \left(\frac{\gamma}{q} y_i + (1 - \gamma - \beta)x_0^h \right) - (1 - \beta)(y_i - qx_0^h) \beta \frac{\partial E}{\partial \tau} \right) \\ &= \frac{a}{q^\gamma} (1 - \beta)(y_i - qx_0^h)^{-\beta-1} E^\beta \left(-\left(\frac{\gamma}{q} - \beta \frac{\partial E}{\partial \tau} \right) y_i + \left(\gamma + \beta \left(1 - \frac{\partial E}{\partial \tau} \right) \right) x_0^h \right) \end{aligned}$$

Using the fact $\frac{\partial E}{\partial \tau} = \frac{\partial E}{\partial q}$ for $q = p + \tau$ with p fixed,

$$A = \frac{a}{q^{1+\gamma}} (1 - \beta)(y_i - qx_0^h)^{-\beta-1} E^\beta \left(-(\gamma - \beta\varepsilon_{E,q}) y_i + (\gamma + \beta(1 - \varepsilon_{E,q})) qx_0^h \right)$$

with $\varepsilon_{E,q}$ the price elasticity of environmental quality. Hence, a necessary and sufficient condition for $A \geq 0$, i.e. preferred tax weakly increase with income, is

$$(\gamma + \beta(1 - \varepsilon_{E,q})) qx_0^h \geq (\gamma - \beta\varepsilon_{E,q}) y_i.$$

When $0 < x_0^h < y_i$, the condition can be rewritten as

$$\varepsilon_{E,q} + \frac{1}{\left(\frac{qx_0^h}{y_i}\right)^{-1} - 1} \geq \frac{\gamma}{\beta}.$$

In the case with no carbon-intensive subsistence consumption, $x_0^h = 0$, the condition reduces to $\beta\varepsilon_{E,q} > \gamma$. Finally, when $qx_0^h = y_i$, the condition boils down to $\beta \geq 0$ which is true by assumption.

A.5 Effect of rural-urban type on preferred tax

The sign of $\left(\frac{\partial}{\partial \tau} V_i^r(\tau_u, y)\right|_y$, is

$$\text{sign}\left(-\left(\frac{\partial v_r(\tau_u)}{\partial y_i} x_{ir}^*(\tau_u) - \frac{\partial v_u(\tau_u)}{\partial y_i} x_{iu}^*(\tau_u)\right) E((\tau_u))^\beta + (v_r(\tau_u) - v_u(\tau_u)) \frac{\partial E((\tau_u))^\beta}{\partial \tau}\right).$$

Starting with the first term, $B = -\left(\frac{\partial v_r(\tau_u)}{\partial y_i} x_{ir}^*(\tau_u) - \frac{\partial v_u(\tau_u)}{\partial y_i} x_{iu}^*(\tau_u)\right) E((\tau_u))^\beta$, it can be rewritten as

$$B = -\frac{a}{q(\tau_u)^\gamma} \left(\frac{\frac{\gamma}{q(\tau_u)} y_i + (1 - \gamma - \beta) x_0^r}{(y_i - q(\tau_u) x_0^r)^\beta} - \frac{\frac{\gamma}{q(\tau_u)} y_i + (1 - \gamma - \beta) x_0^u}{(y_i - q(\tau_u) x_0^u)^\beta} \right) E((\tau_u))^\beta.$$

Given that $x_0^r > x_0^u$, it can be shown that

$$\frac{\gamma}{q(\tau_u)} y_i + (1 - \gamma - \beta) x_0^r > \frac{\gamma}{q(\tau_u)} y_i + (1 - \gamma - \beta) x_0^u$$

and

$$(y_i - q(\tau_u) x_0^r)^{-\beta} > (y_i - q(\tau_u) x_0^u)^{-\beta}.$$

Hence,

$$\frac{\frac{\gamma}{q(\tau_u)} y_i + (1 - \gamma - \beta) x_0^r}{(y_i - q(\tau_u) x_0^r)^\beta} - \frac{\frac{\gamma}{q(\tau_u)} y_i + (1 - \gamma - \beta) x_0^u}{(y_i - q(\tau_u) x_0^u)^\beta} > 0$$

and $B < 0$.

Next, the second term $C = (v_r(\tau_u) - v_u(\tau_u)) \frac{\partial E((\tau_u))^\beta}{\partial \tau}$ can be rewritten as

$$C = \frac{a}{q(\tau_u)^\gamma} \left((y_i - q(\tau_u) x_0^r)^{(1-\beta)} - (y_i - q(\tau_u) x_0^u)^{(1-\beta)} \right) \frac{\partial E((\tau_u))^\beta}{\partial \tau}.$$

Using once again the fact that $x_0^r > x_0^u$, it can be shown that

$$(y_i - q(\tau_u) x_0^r)^{(1-\beta)} - (y_i - q(\tau_u) x_0^u)^{(1-\beta)} < 0$$

and as a result, $C < 0$.

Finally

$$\left. \frac{\partial}{\partial \tau} V_i^r(\tau_u, y) \right|_y = B + C < 0.$$

A.6 Comparison of majority voting and social planner tax rate

Subtracting the median voter first order condition to the social planner first order condition evaluated at the majority voting tax rate, $\frac{\partial}{\partial \tau} W(\tilde{\tau}) - \frac{\partial}{\partial \tau} V(\tilde{\tau}, y_{mv}^h)$, yields

$$\begin{aligned} & \frac{a}{\tilde{q}^{\gamma+1}} \left[-\gamma \sum_{j=\{u,r\}} \left(\theta^j \mathbb{E} \left[(y_i - \tilde{q} x_0^j)^{1-\beta} \right] \right) - (1-\beta) \sum_{j=\{u,r\}} \left(\theta^j \frac{\tilde{q} x_0^j}{\mathbb{E} \left[(y_i - \tilde{q} x_0^j)^\beta \right]} \right) \right. \\ & \left. + \sum_{j=\{u,r\}} \left(\theta^j \mathbb{E} \left[(y_i - \tilde{q} x_0^j)^{1-\beta} \right] \right) \beta \varepsilon_{E,q} \right] E(X(\tilde{q}))^\beta \\ & - \frac{a}{\tilde{q}^{\gamma+1}} \left[-\gamma (y_{mv}^h - \tilde{q} x_0^h)^{1-\beta} - (1-\beta) \tilde{q} x_0^h (y_{mv}^h - \tilde{q} x_0^h)^{-\beta} + (y_{mv}^h - x_0^h)^{(1-\beta)} \beta \varepsilon_{E,q} \right] E(X(\tilde{q}))^\beta \end{aligned}$$

with $\theta^u = \theta = \frac{\alpha \omega^u}{\alpha \omega^u + (1-\alpha) \omega^r}$ and $\theta^r = 1 - \theta$. Re-ordering the terms,

$$\frac{\partial}{\partial \tau} W(\tilde{\tau}) - \frac{\partial}{\partial \tau} V(\tilde{\tau}, y_{mv}^h) > 0$$

is equivalent to

$$\begin{aligned} & \frac{a}{\tilde{q}^{\gamma+1}} E(X(\tilde{q}))^\beta \left[(\beta \varepsilon_{E,q} - \gamma) \left(\sum_{j=\{u,r\}} \left(\theta^j \mathbb{E} \left[(y_i - \tilde{q} x_0^j)^{1-\beta} \right] \right) - (y_{mv}^h - \tilde{q} x_0^h)^{1-\beta} \right) \right. \\ & \left. - (1-\beta) \left(\sum_{j=\{u,r\}} \left(\theta^j \frac{\tilde{q} x_0^j}{\mathbb{E} \left[(y_i - \tilde{q} x_0^j)^\beta \right]} \right) - \frac{\tilde{q} x_0^h}{(y_{mv}^h - \tilde{q} x_0^h)^\beta} \right) \right] > 0, \end{aligned}$$

resulting in equation (4.2.1).

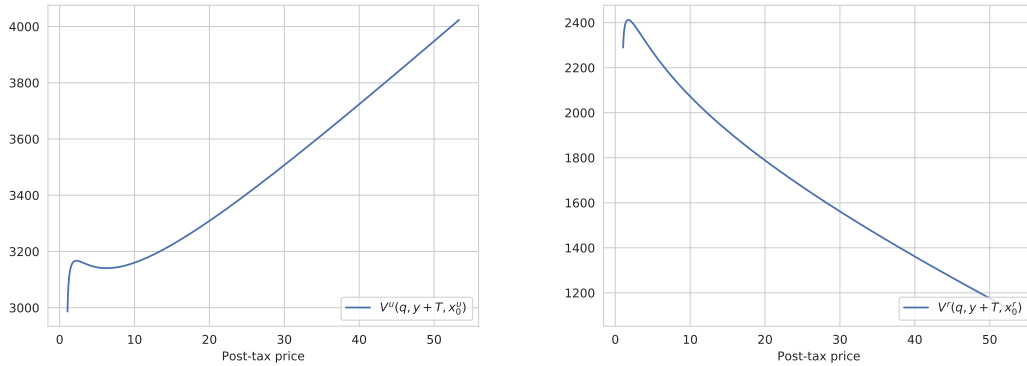
A.7 Indirect utility of urban households with fully anticipated lump-sum transfers

With fully anticipated lump-sum transfers, the indirect utility of an urban household writes

$$\begin{aligned}
V^u(q, y_i + T, x_0^u) &= \frac{a}{q^\gamma} (y_i + T - q\chi_h)^{(1-\beta)} E(X(q, T))^\beta \\
&= \frac{a}{q^\gamma} \left(y_i + \frac{\tau}{(1-\beta) - \gamma \frac{\tau}{q}} \left(\frac{\gamma}{q} \bar{y} + (1-\gamma-\beta) \bar{x} \right) - qx_0^u \right)^{(1-\beta)} E(X(q, T))^\beta \\
&= \frac{a}{q^\gamma} \left(y_i + q\alpha(x_0^r - x_0^u) + \frac{\gamma \bar{y} - (1-\beta)p(1 + \frac{p}{\tau}) \bar{x}_0}{(1-\beta-\gamma) + (1-\beta)\frac{p}{\tau}} \right)^{(1-\beta)} E(X(q, T))^\beta.
\end{aligned}$$

An example calibration illustrates that $V^u(\cdot)$ is not always singled-peaked. Figure A7 plots $V^u(q, y_i + T, x_0^u)$ with y_i the median urban income (left) and $V^r(q, y_i + T, x_0^r)$ with y_i the median rural income (right), calibrated on Poland. The indirect utility of the urban features a first peak at low values of q , but then increases with q to a second maximum at $p + \tau^{max}$. That is not the case for the indirect utility of the rural household, which features a unique maximum.

Figure A7: Illustration of indirect utility with fully anticipated transfers over post-tax price $q \in [p, p + \tau^{max}]$



Note: The left figure shows indirect utility of an urban household, and the right figure the indirect utility of a rural household. The indirect utility is shown for a household with the median income, and calibrated with the data for Poland.

Next, I turn to the conditions under which the preferred tax rate of an urban household is not the maximum rate τ^{max} . As can be noted in the example provided in Figure A7, the indirect utility of an urban household can be quasi-concave on a first interval of tax rates $[0, \hat{\tau}]$, and then monotonically increase at higher tax levels. If the range of admissible tax rates $[0, \tau^{max}]$ is restricted so that the maximum tax rate is within the first interval, i.e. $\tau^{max} < \hat{\tau}$, then indirect utility will be single peaked on $[0, \tau^{max}]$.

That is to say, if $V^u(q, y_i + T, x_0^u)$ has a local maximum at $\tau^u(y_i) < \tau^{max}$, and $\frac{\partial}{\partial \tau} V^u(p + \tau^{max}, y_i + T, x_0^u) < 0$, then the preferred tax rate of the urban household will be characterized by the first order condition

$$\frac{\partial}{\partial \tau} V^u(q, y_i + T, x_0^u) = 0.$$

Solving for the first order condition then results in the implicit tax rate $\tau^u(y_i)$ such that

$$\tau^u(y_i) = \frac{\beta \varepsilon_{E,\tau}}{\frac{\gamma}{(p + \tau^u(y_i))} + (1 - \beta) \frac{x_0^h - \frac{\partial T}{\partial \tau}}{y_i + T - (p + \tau^u(y_i))x_0^h}}.$$

On the contrary, if $\frac{\partial}{\partial \tau} V^u(p + \tau^{max}, y_i + T, x_0^u) > 0$, then the preferred rate of an urban household with income y_i will be the maximum tax rate τ^{max} . Hence, a sufficient condition for τ^{max} to be the preferred tax rate of all households is that $\forall y_i \in [y^-, y^+]$, $\frac{\partial}{\partial \tau} V^u(p + \tau^{max}, y_i + T, x_0^u) > 0$.

B Calibration

B.1 Engel curves

Figure A8: Mean per adult energy expenditure, by expenditure quintile and density, 2015

Group of countries with higher mean expenditure

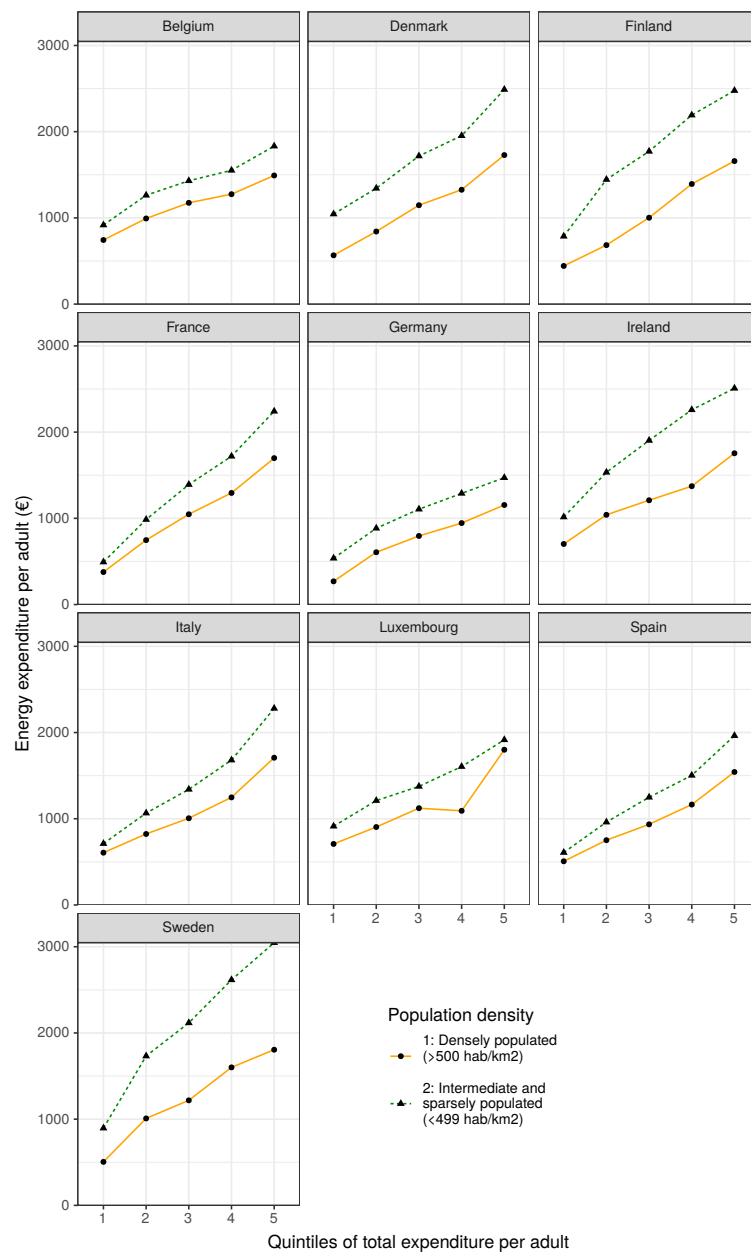
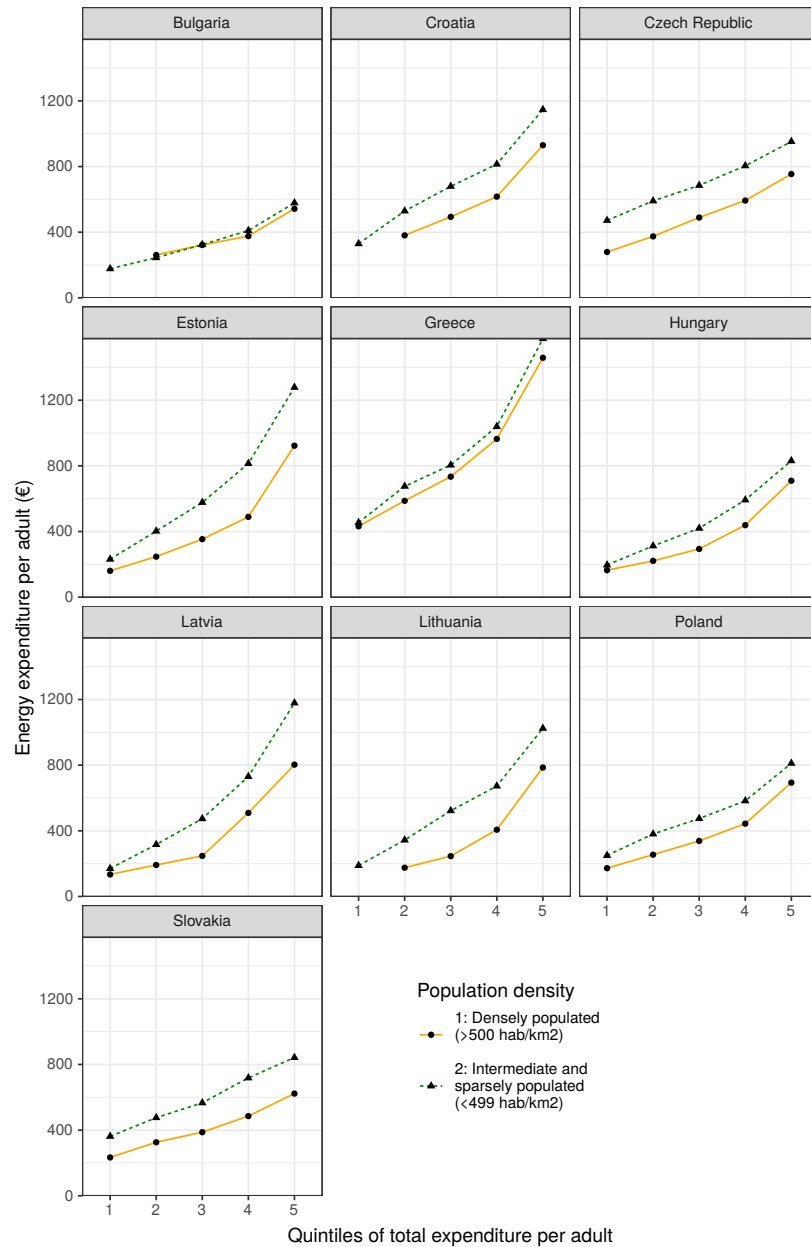


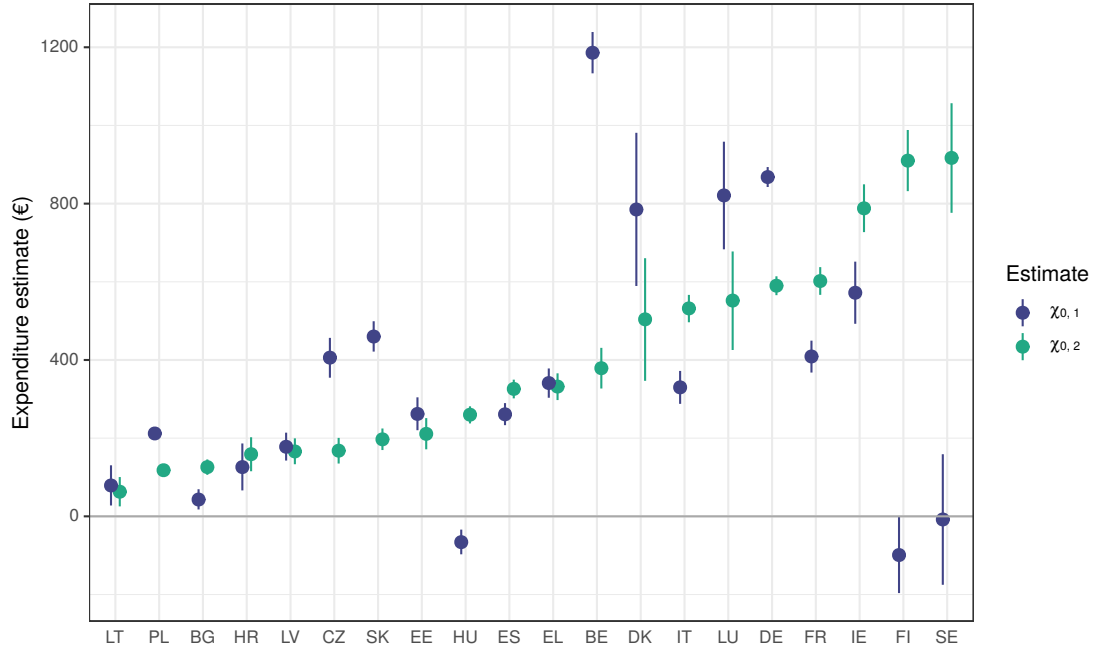
Figure A9: Mean per adult energy expenditure, by expenditure quintile and density, 2015

Group of countries with lower mean expenditure



B.2 Estimation results

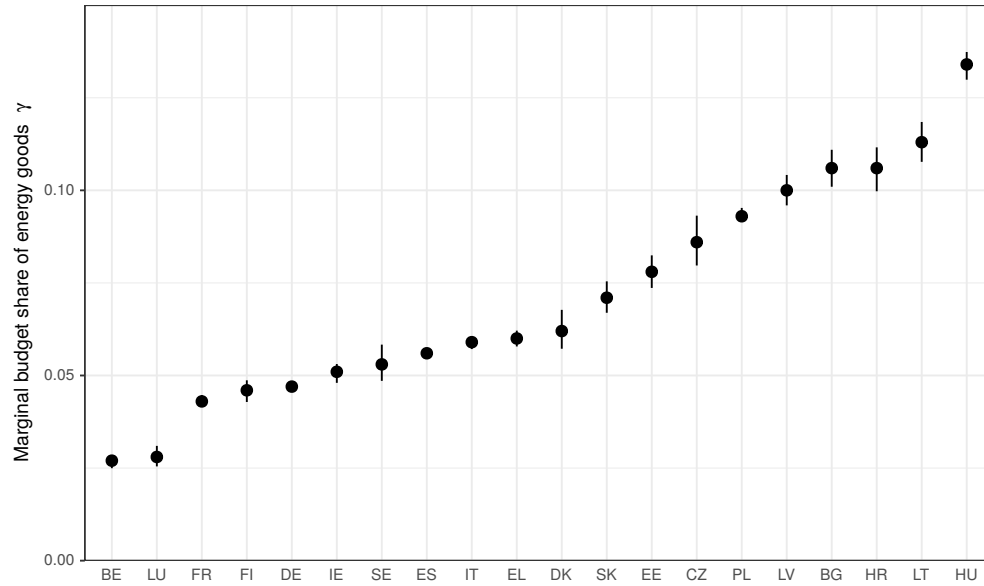
Figure A10: Estimates of subsistence expenditure of energy and fuels



Note: Coefficients with 95%CI for the intercept in the regression of energy and fuels expenditure on total expenditure, $p_i x_i = (\chi_{0,1} + 1_{h=r} \chi_{0,2}) + \gamma y_i$. $\chi_{0,2}$ is the estimated additional expenditure of rurals (households in intermediate and less populated areas, with less than 499 hab/km²).

BE: Belgium, BG: Bulgaria, CZ: Czech Republic, DE: Germany, EE: Estonia, EL: Greece, ES: Spain, FI: Finland, FR: France, HU: Hungary, HR: Croatia, IE: Ireland, IT: Italy, LU: Luxembourg, LT: Lithuania, LV: Latvia, PL: Poland, SE: Sweden, SK: Slovakia.

Figure A11: Estimates of marginal budget share for fuel and energy



*Note: Coefficients with 95%CI for total expenditure in the regression of energy and fuels expenditure on total expenditure, $p_i x_i = (\chi_{0,1} + 1_{h=r} \chi_{0,2}) + \gamma y_i$.
 BE: Belgium, BG: Bulgaria, CZ: Czech Republic, DE: Germany, EE: Estonia, EL: Greece, ES: Spain, FI: Finland, FR: France, HU: Hungary, HR: Croatia, IE: Ireland, IT: Italy, LU: Luxembourg, LT: Lithuania, LV: Latvia, PL: Poland, SE: Sweden, SK: Slovakia.*

Table A11: Linear Expenditure System estimation for fuel and energy expenditures, 2015

Country	$\chi_{0,1}$	$\chi_{0,2}$	γ
Belgium	1186*** (27)	379*** (26.5)	0.027*** (0.001)
Bulgaria	43*** (13.2)	126*** (10)	0.106*** (0.003)
Czech Republic	406*** (26)	168*** (16.7)	0.086*** (0.003)
Germany	868*** (13)	590*** (12.3)	0.047*** (0)
Denmark	785*** (99.9)	504*** (80)	0.062*** (0.003)
Estonia	262*** (21.4)	211*** (20.4)	0.078*** (0.002)
Greece	341*** (19.1)	332*** (17.4)	0.06*** (0.001)
Spain	261*** (14.4)	326*** (12.2)	0.056*** (0.001)
Finland	-99** (49.8)	910*** (39.9)	0.046*** (0.001)
France	409*** (20.8)	602*** (18.1)	0.043*** (0.001)
Croatia	126*** (30.6)	159*** (22.2)	0.106*** (0.003)
Hungary	-66*** (16.1)	260*** (11.2)	0.134*** (0.002)
Ireland	572*** (40.5)	788*** (31.2)	0.051*** (0.001)
Italy	330*** (21.5)	532*** (17.9)	0.059*** (0.001)
Lithuania	79** (26.2)	63*** (19.1)	0.113*** (0.003)
Luxembourg	821*** (70.2)	552*** (64.3)	0.028*** (0.001)
Latvia	178*** (18.2)	166*** (16.9)	0.1*** (0.002)
Poland	212*** (8.2)	118*** (6.8)	0.093*** (0.001)
Sweden	-8 (85.2)	917*** (71.5)	0.053*** (0.002)
Slovakia	460*** (19.8)	197*** (14.1)	0.071*** (0.002)

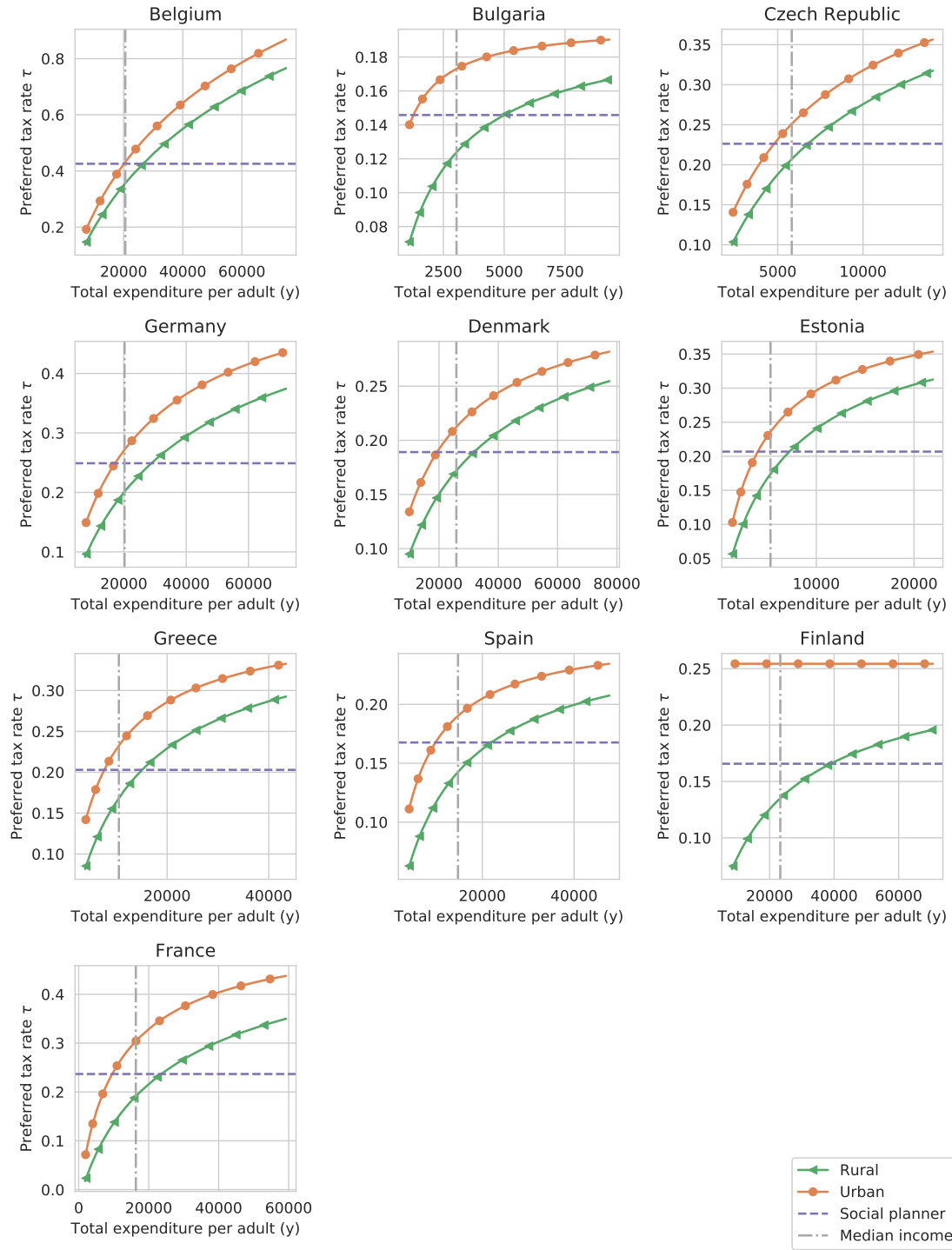
*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

B.3 Calibration results for all countries

Table A11: Calibrated parameter values

Country	α	γ	β	x_0^u	x_0^r	y^-	y^+	\tilde{y}^u	\tilde{y}^r	\bar{y}^u	\bar{y}^r
Belgium	0.55	0.03	0.05	1186	1565	6938	74946	20149	20687	23117	23770
Bulgaria	0.44	0.11	0.02	43	169	1065	9325	3886	2539	4294	2777
Czech Republic	0.33	0.09	0.04	406	574	2310	14093	6297	5572	6644	5995
Germany	0.54	0.05	0.03	868	1458	7564	72031	19746	20260	22455	22748
Denmark	0.27	0.06	0.02	785	1289	9690	77483	25479	25767	29475	28600
Estonia	0.33	0.08	0.03	262	473	1360	21918	5696	5137	6992	6168
Greece	0.39	0.06	0.02	341	673	3862	43394	10554	9995	12716	11761
Spain	0.47	0.06	0.01	261	587	3882	47717	15598	13993	17509	15810
Finland	0.34	0.05	0.01	0	811	8291	70589	24136	22829	27252	25462
France	0.39	0.04	0.02	409	1011	1809	59250	16861	16096	19267	17979
Croatia	0.28	0.11	0.02	126	285	1948	18575	7404	5896	8142	6529
Hungary	0.27	0.13	0.02	0	194	1700	13432	6377	4662	6891	5010
Ireland	0.44	0.05	0.02	572	1360	5869	64594	23891	20499	25990	22458
Italy	0.29	0.06	0.02	330	862	4262	58059	17392	15981	20183	18496
Lithuania	0.40	0.11	0.02	79	142	1911	18015	7425	4625	8129	5242
Luxembourg	0.38	0.03	0.02	821	1373	10122	108766	30430	34750	35249	39143
Latvia	0.50	0.10	0.03	178	344	1471	20943	5178	4274	6408	5104
Poland	0.34	0.09	0.03	212	330	1865	17528	5847	4617	6703	5250
Sweden	0.25	0.05	0.02	0	909	5863	65152	21124	19877	23205	22372
Slovakia	0.40	0.07	0.05	460	657	2212	18871	6861	5921	7564	6429

Figure A12: Effect of income and urban-rural type on calibrated preferred tax rates



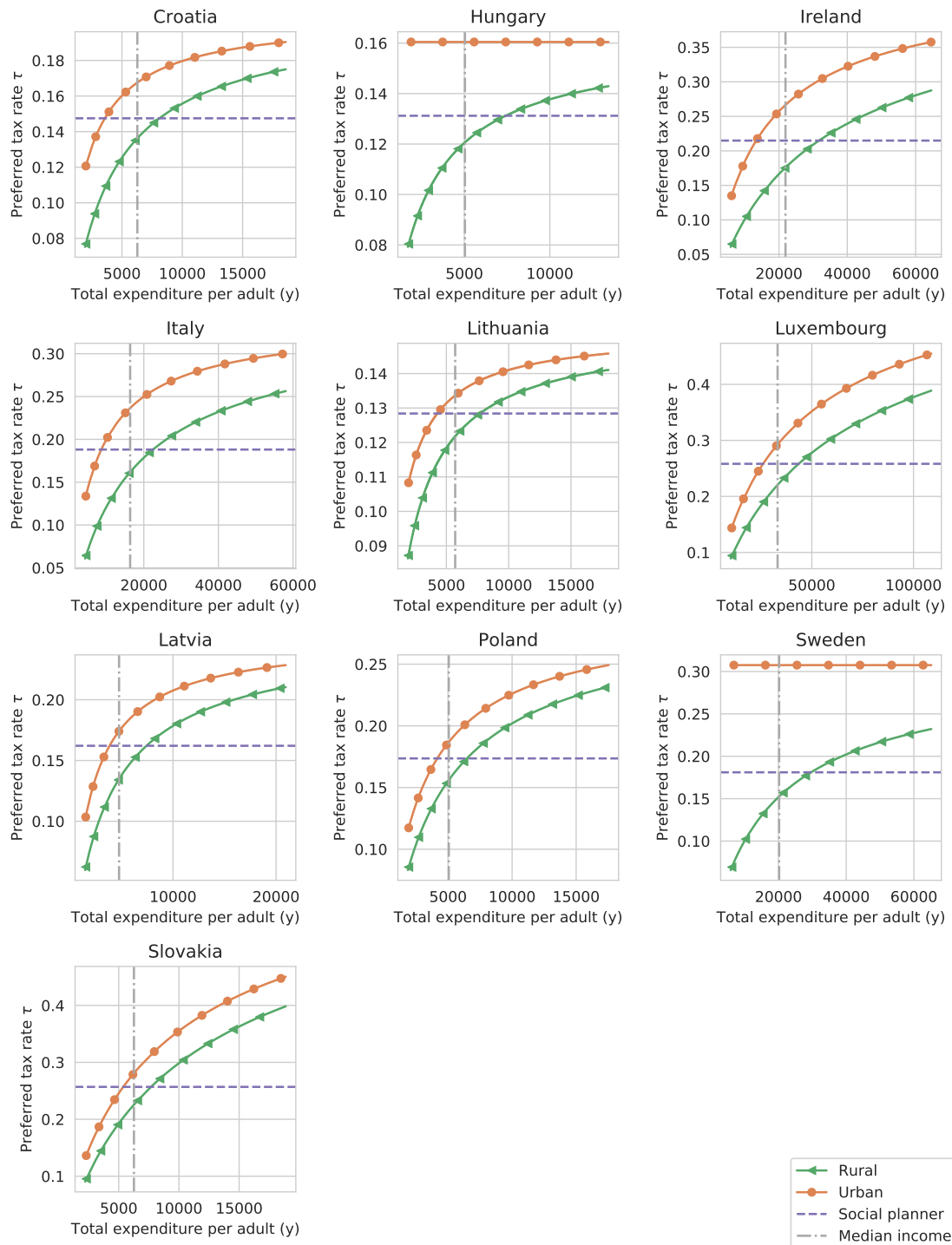
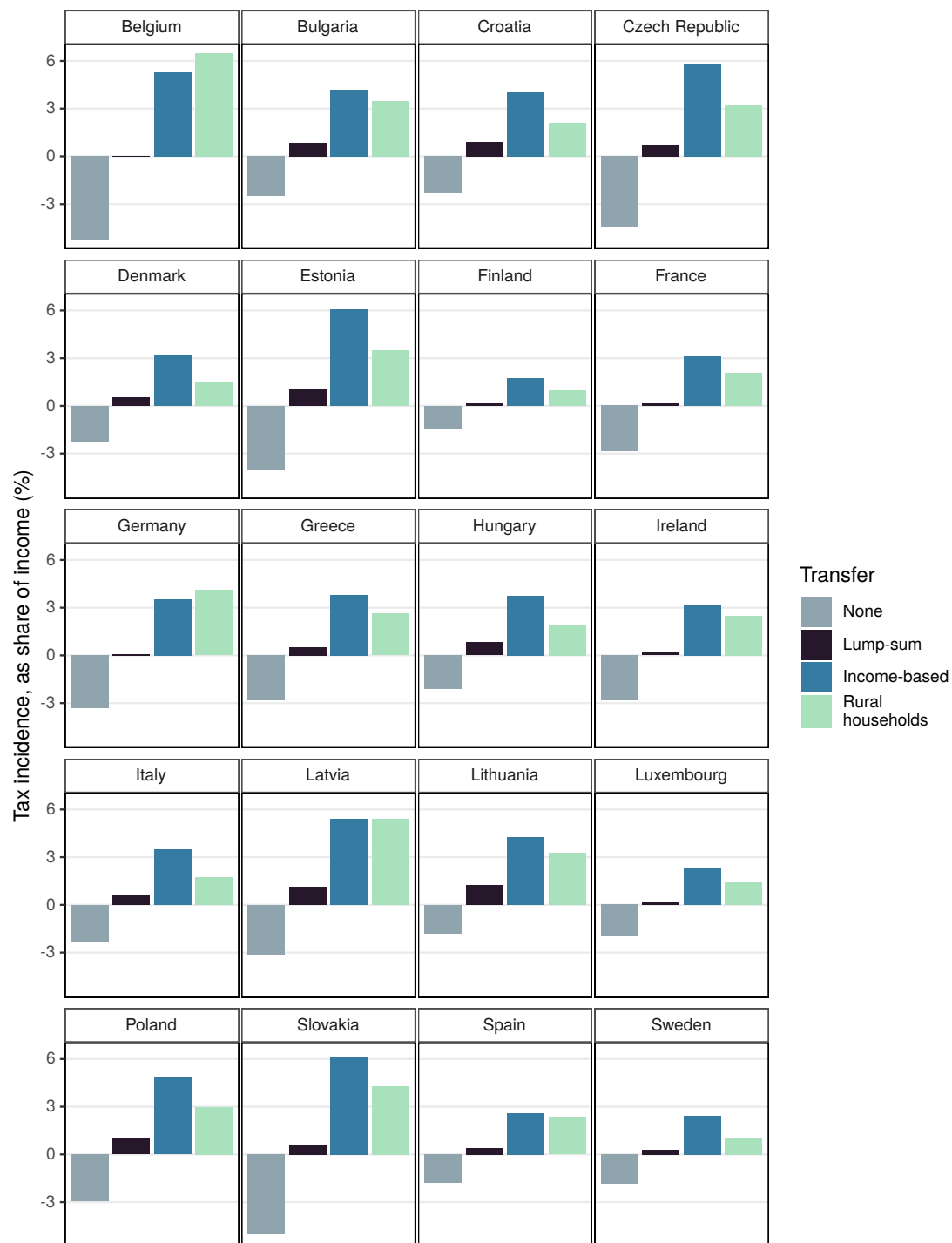
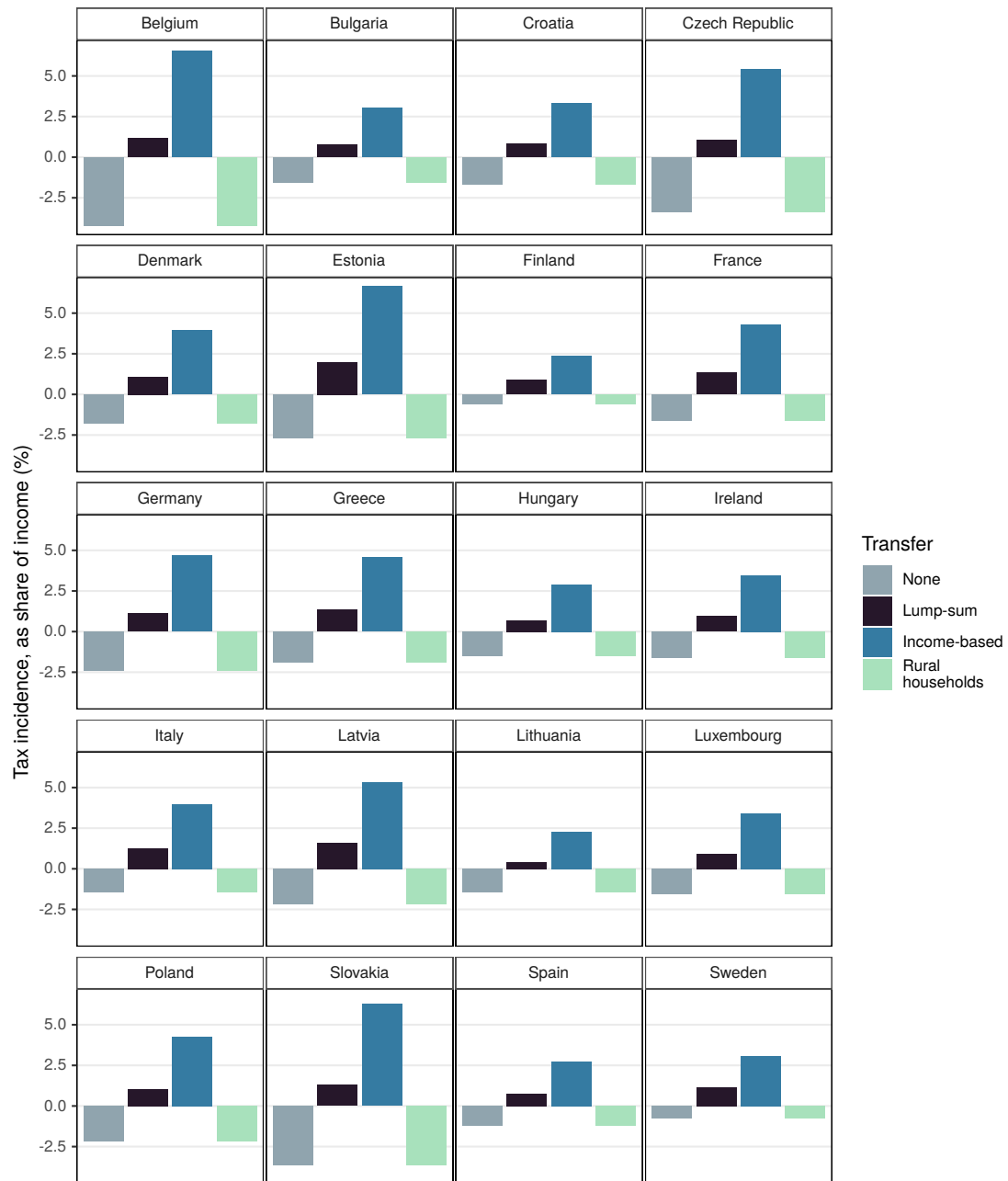


Figure A13: Tax incidence for rural households in the first quintile, as proportion of income (%)



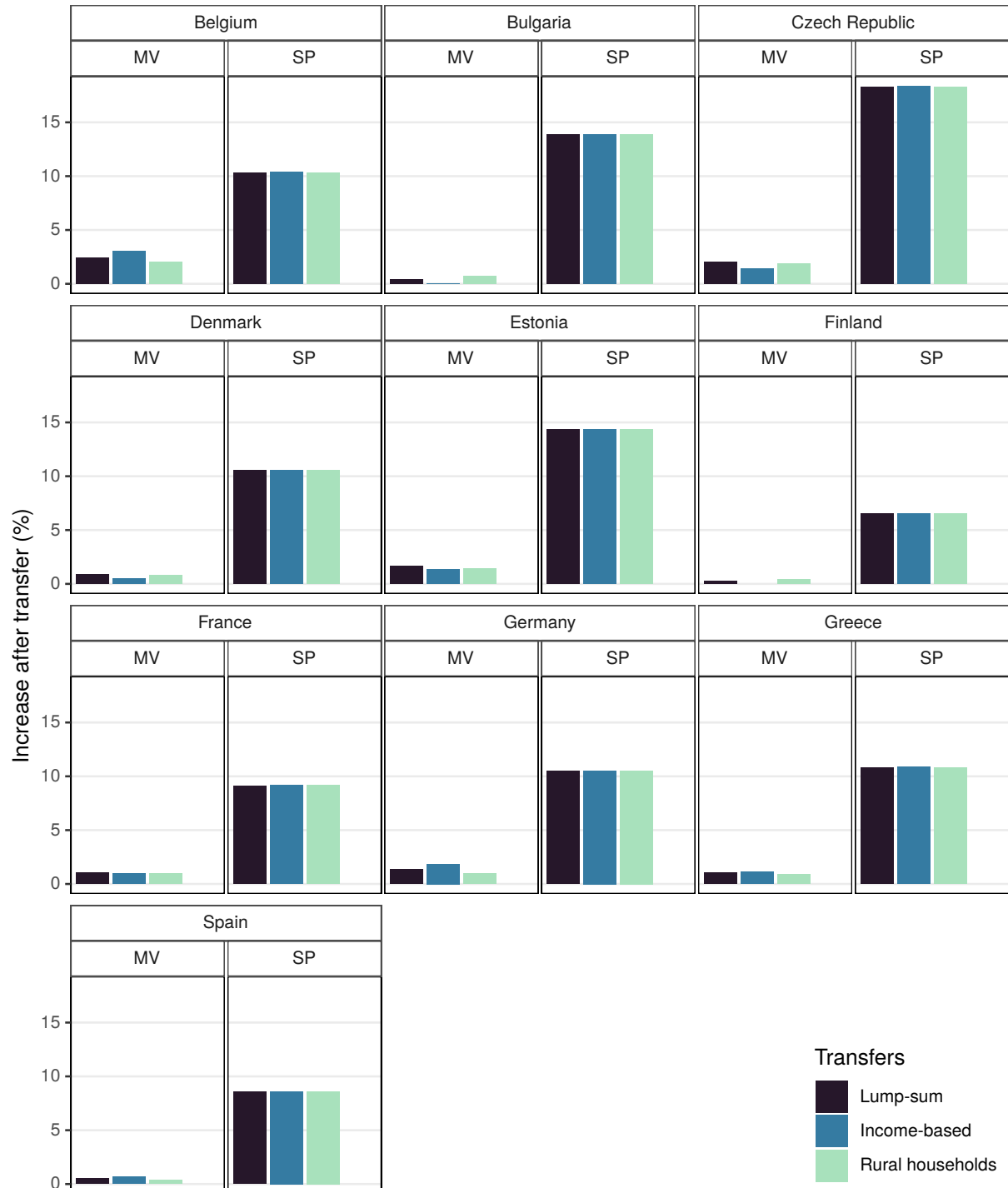
Note: negative values indicate net tax payments, positive values net tax rebates.

Figure A14: Tax incidence for urban households in the first quintile, as proportion of income (%)



Note: negative values indicate net tax payments, positive values net tax rebates.

Figure A15: Change in the median voter (mv) and the social planner (sp) carbon tax rates, (%)



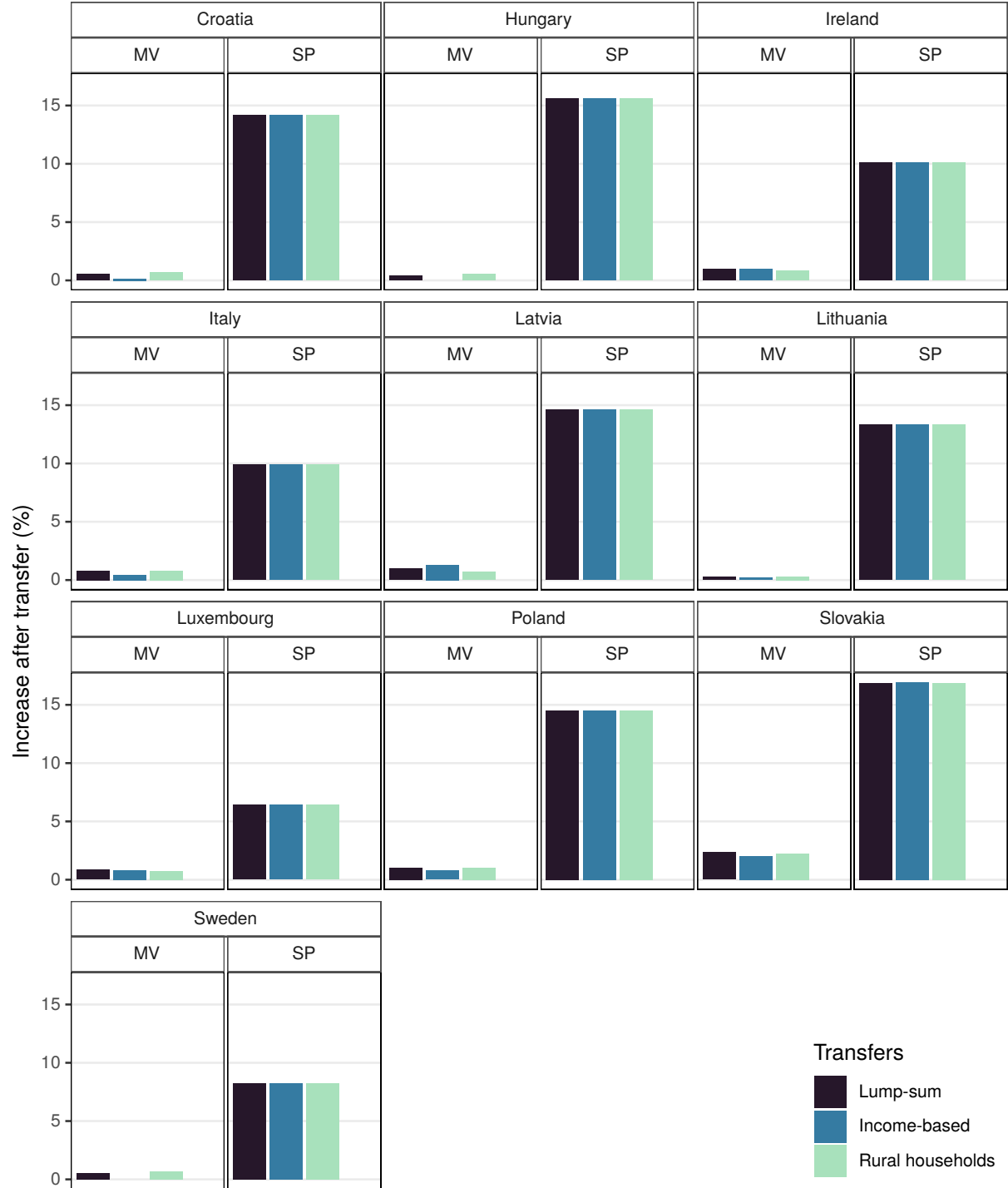
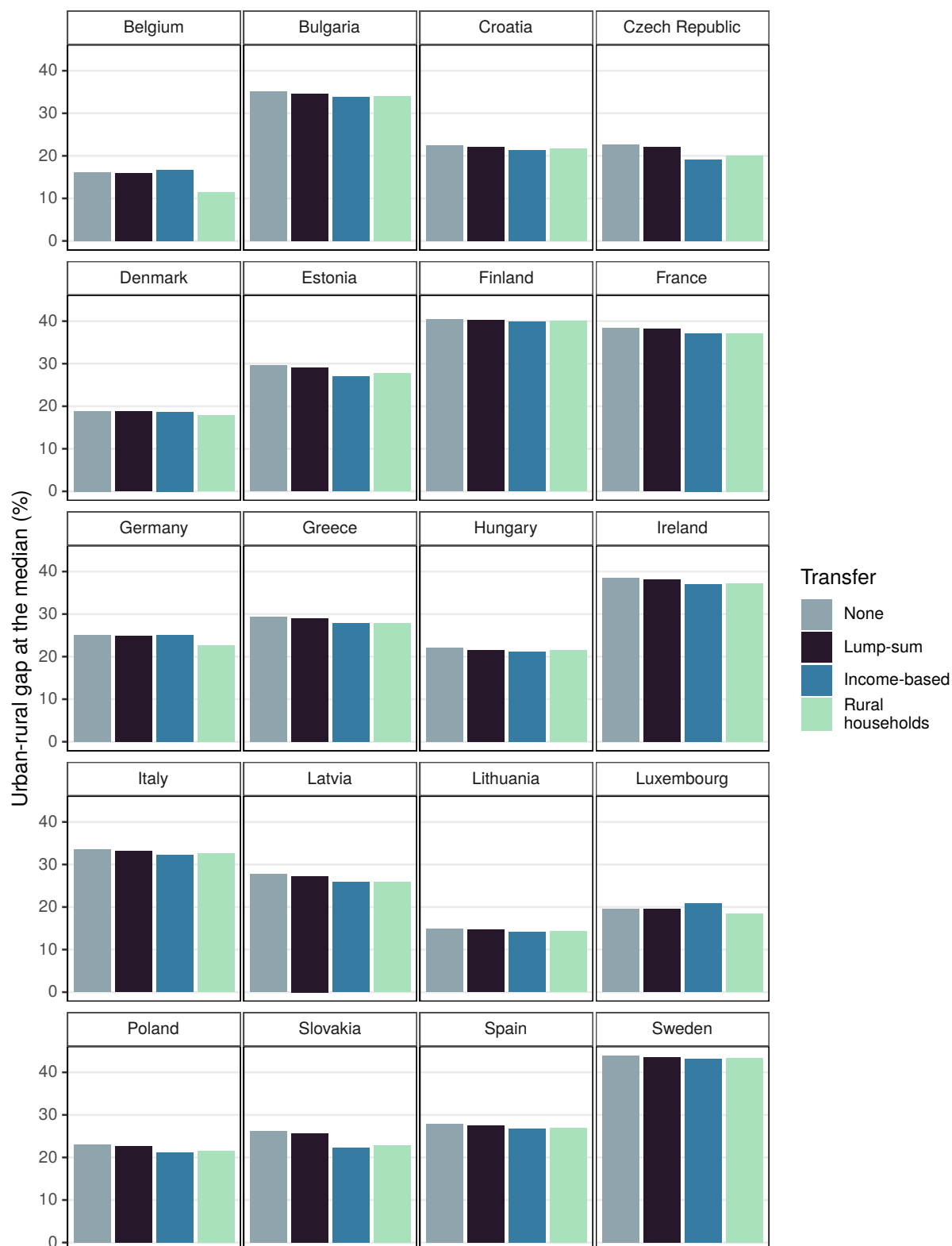


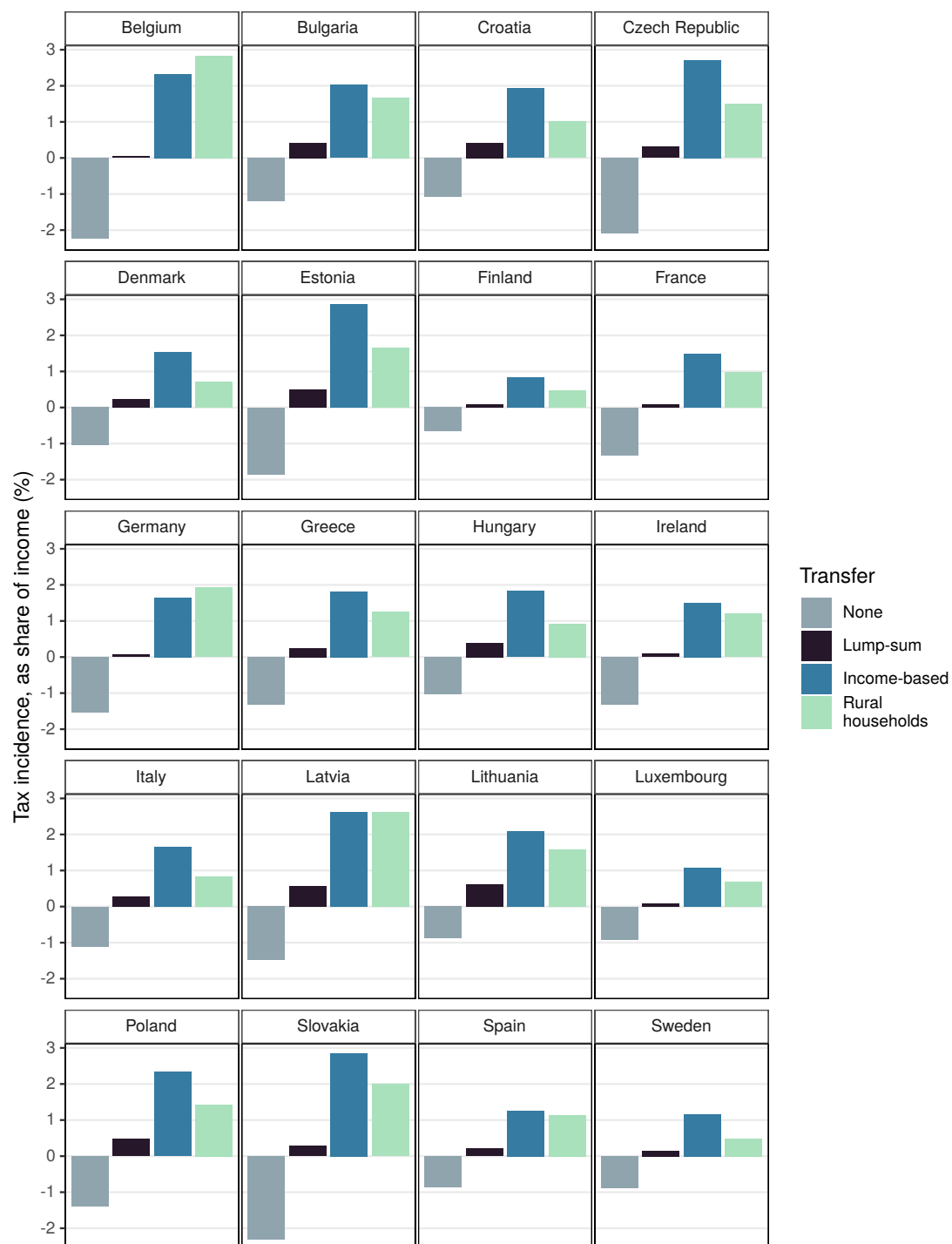
Figure A16: Gap between the median voter tax rates in the urban vs rural population, as a share of median voter tax rate in the urban population (%), for different transfer schemes.



B.4 Robustness checks

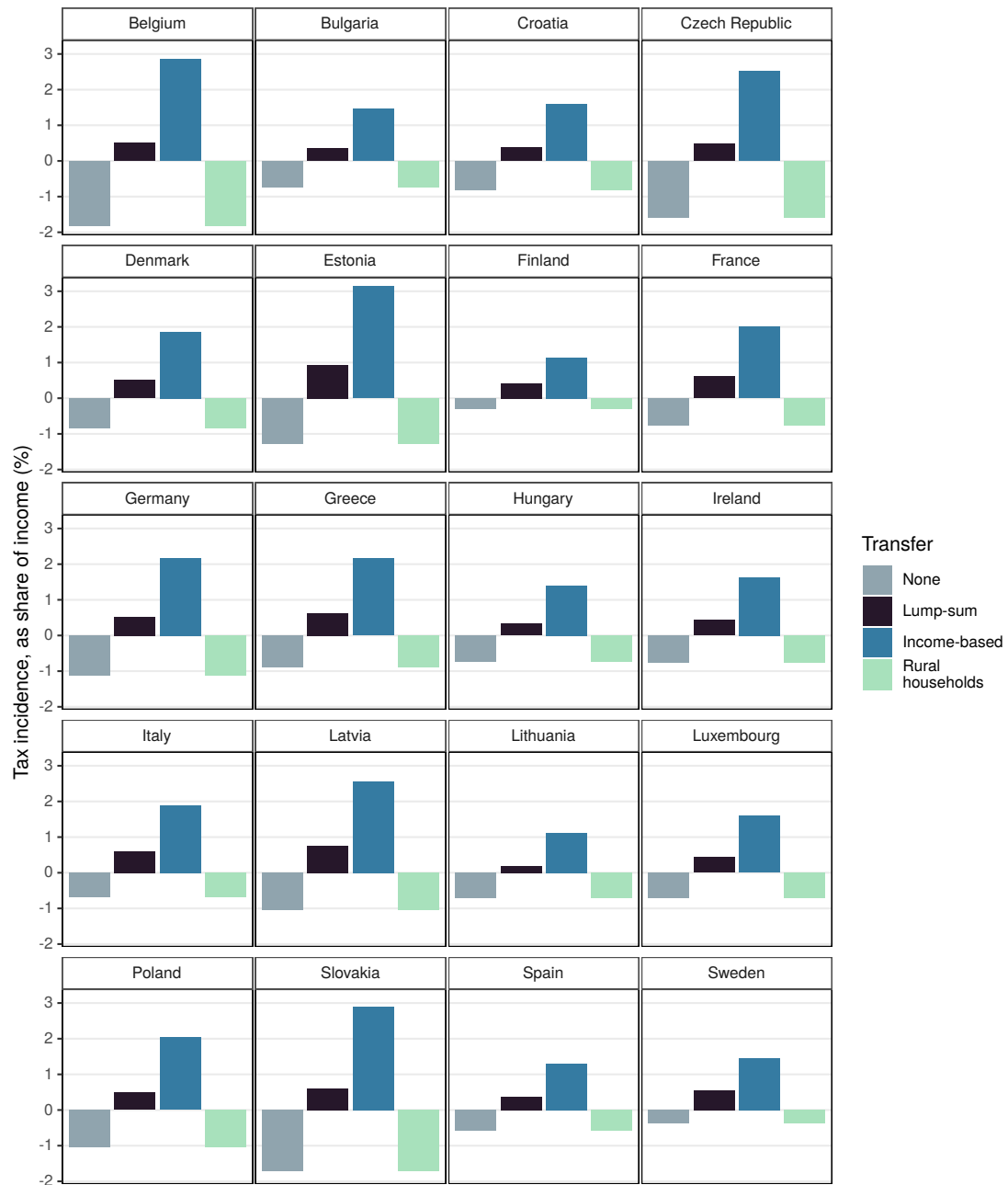
Emissions reduction target to 5%

Figure A17: Tax incidence for rural households in the first quintile, as proportion of income (%)



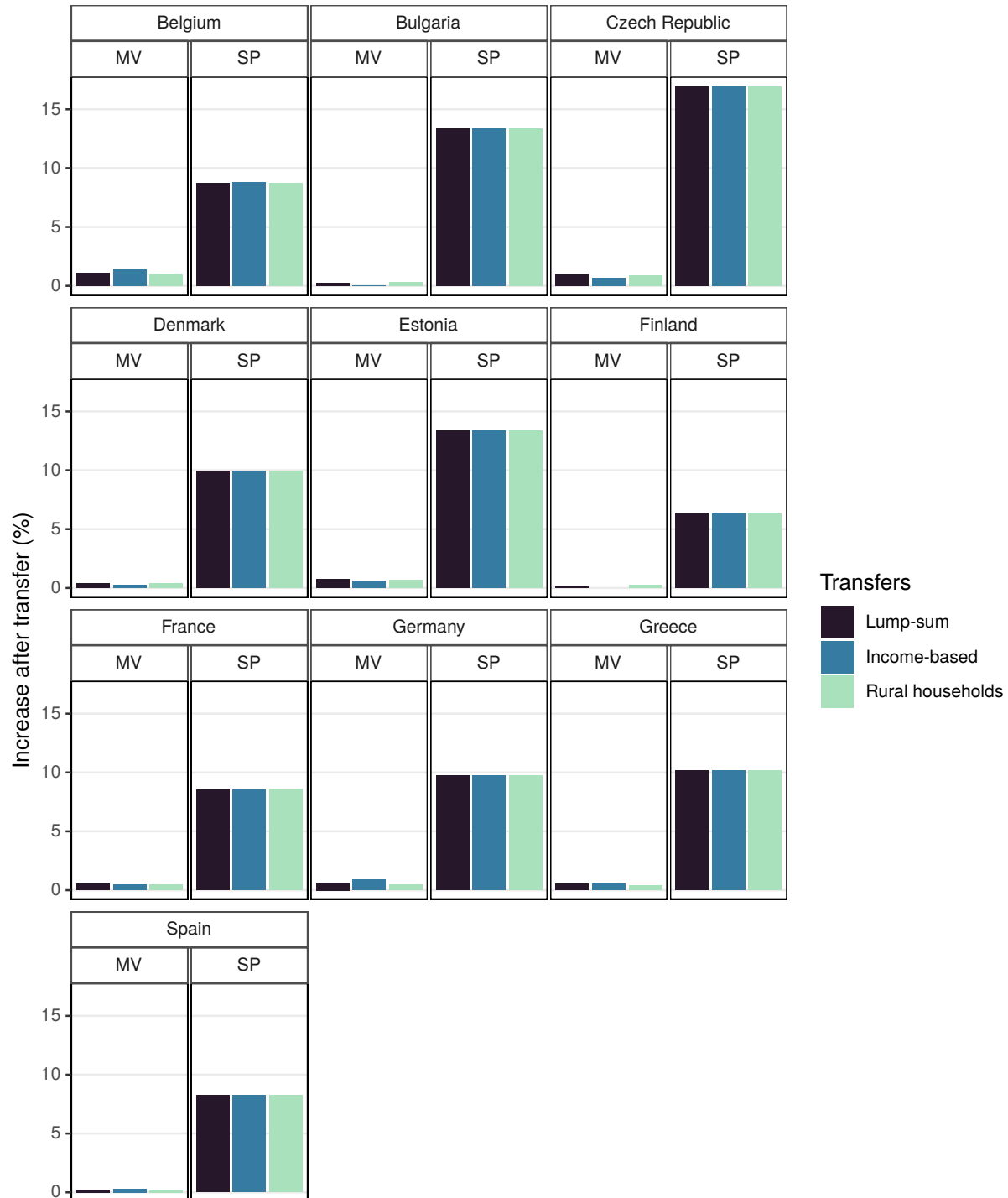
Note: negative values indicate net tax payments, positive values net tax rebates. Emissions reduction target of 5%

Figure A18: Tax incidence for urban households in the first quintile, as proportion of income (%)



Note: negative values indicate net tax payments, positive values net tax rebates. Emissions reduction target of 5%

Figure A19: Change in the median voter (mv) and the social planner (sp) carbon tax rates, (%)



Note: Emissions reduction target of 5%.

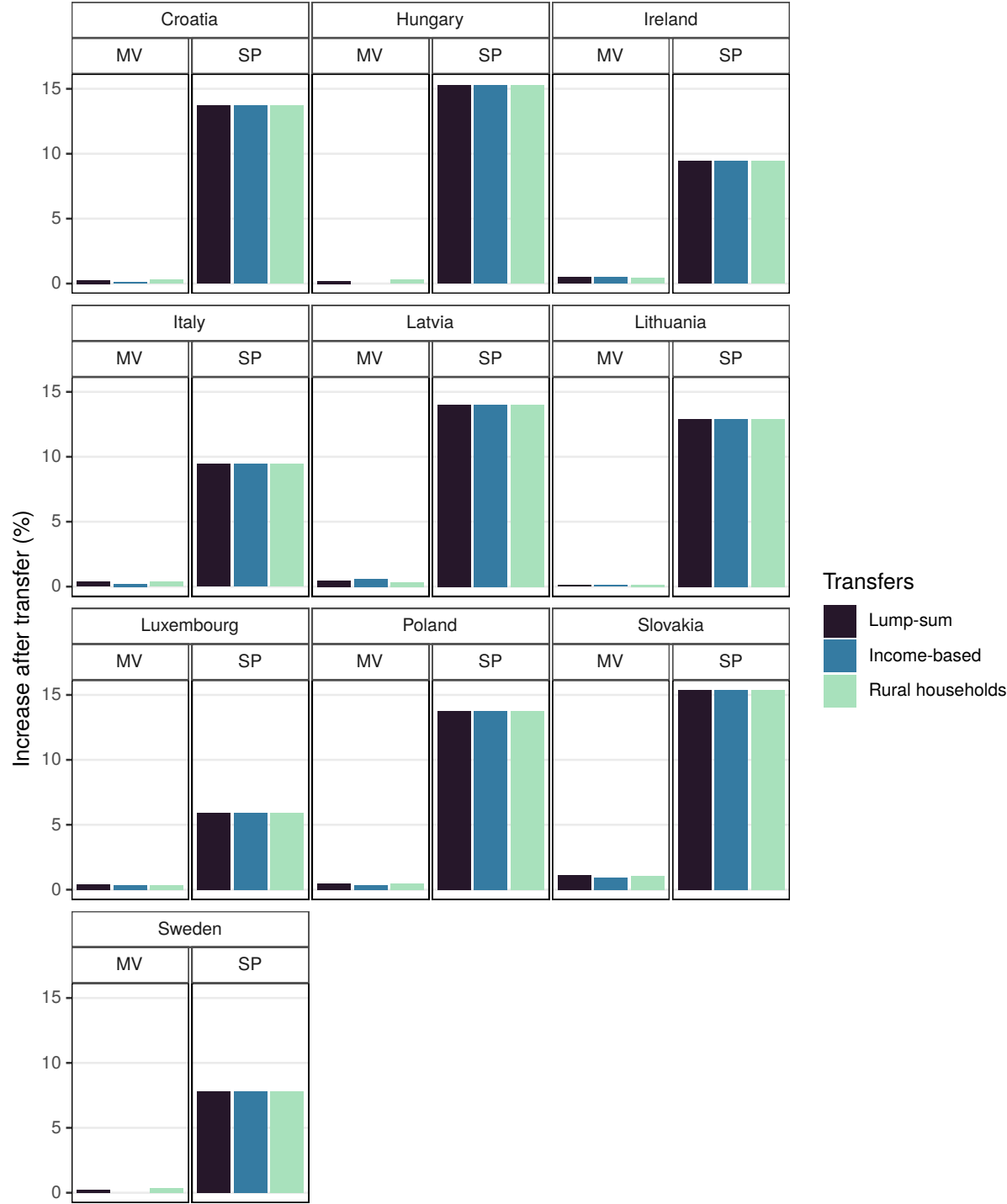
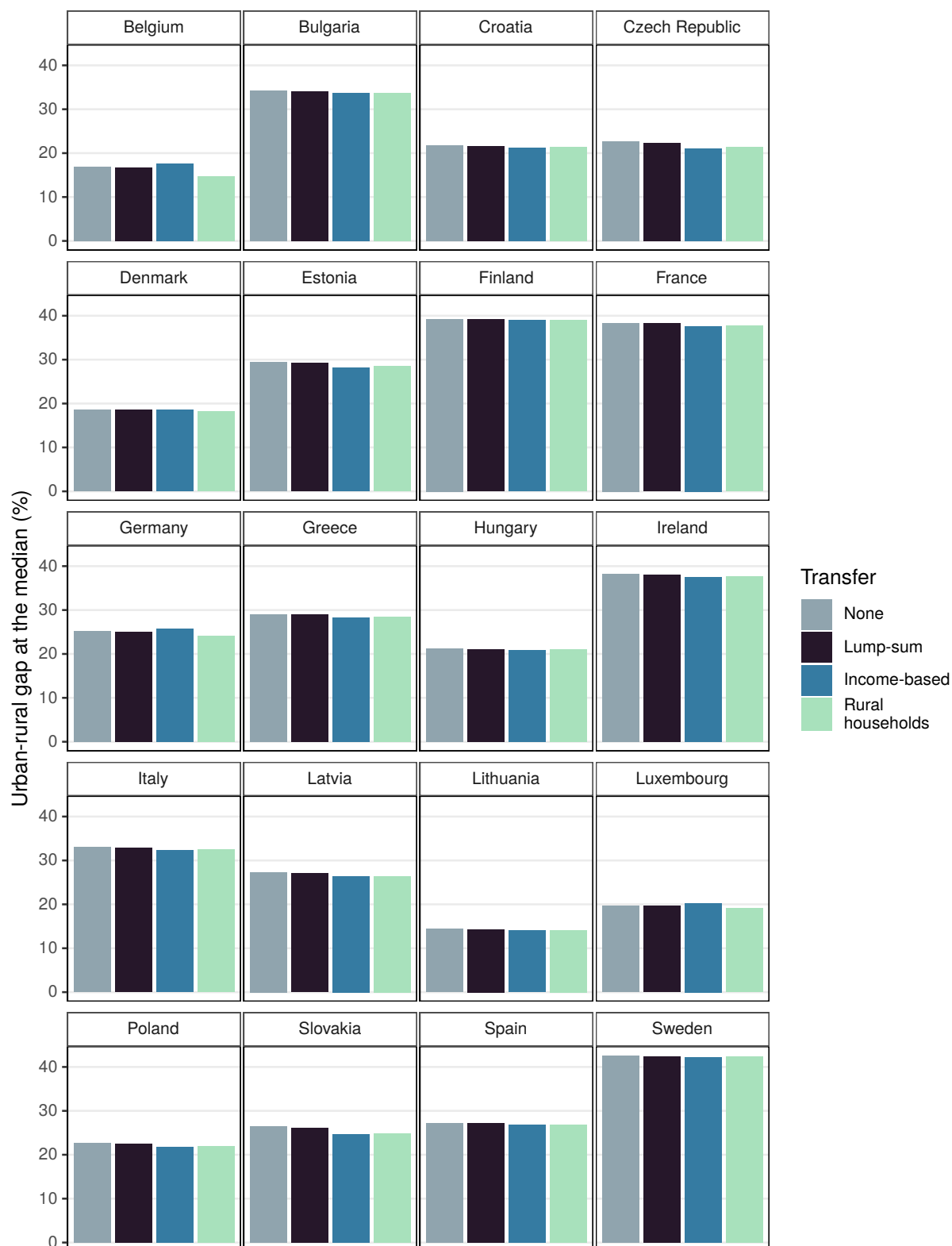


Figure A20: Gap between the median voter tax rates in the urban vs rural population, as a share of median voter tax rate in the urban population (%), for different transfer schemes.



Note: Emissions reduction target of 5%.