Climate risks beyond borders : towards an assessment of national supply chain exposure

Adrien Delahais

▶ **To cite this version:**

Adrien Delahais. Climate risks beyond borders : towards an assessment of national supply chain exposure. Economics and Finance. École des Ponts ParisTech, 2026. English. ⟨NNT : 2026ENPC0001⟩. ⟨tel-05603241⟩

HAL Id: tel-05603241

https://theses.hal.science/tel-05603241v1

Submitted on 27 Apr 2026

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

HAL Authorization

ÉCOLE NATIONALE DES PONTS ET CHAUSSÉES

IP PARIS

THÈSE DE DOCTORAT

de l'École nationale des ponts et chaussées

Climate risks beyond borders: towards an assessment of national supply chain exposure

École doctorale N°528, Ville, Transports, Territoires (VTT)

Sciences économiques

Thèse préparée au CIRED, UMR 8683

Thèse soutenue le 16 janvier 2026, par

Adrien DELAHAIS

Composition du jury:

Aude POMMERET Professeure, Université Savoie Mont Blanc	*Rapportrice,* *Présidente du jury*
Birgit BEDNAR-FRIEDL Prof. associée, Université de Graz	*Rapportrice*
Fanny HENRIET Directrice de recherche, Université d'Aix-Marseille	*Examinatrice*
David BRESCH Professeur, ETH Zurich	*Examinateur*
Vincent VIGUIÉ Chercheur, École nationale des ponts et chaussées	*Directeur de thèse*

Remerciements

Difficile de résumer en quelques paragraphes un morceau de ma vie qui aura duré trois ans, rempli de hauts et de bas. Dans ces quelques lignes, je voudrais surtout remercier toutes les personnes sans lesquelles cette thèse n'aurait pas abouti, mais également toutes celles et ceux qui ont rendu ces années beaucoup plus divertissantes !

Ce travail trouve son origine dans mon passage à France Stratégie, que je remercie sincèrement de m'avoir permis de découvrir les questions d'adaptation au changement climatique. Je pense évidemment à Claire et Alice, avec qui j'ai d'abord travaillé mais qui sont surtout ensuite devenues des amies. Sans ce stage cette thèse n'aurait sans doute pas existé sous cette forme.

Est venu ensuite le CIRED. C'est d'abord Vincent qui me vient à l'esprit, car il m'a fait confiance dès le départ, et n'a jamais été avare de son temps, pour m'accompagner à travers toutes les étapes du travail de chercheur. Surtout, Vincent a toujours eu à cœur de me laisser le privilège d'explorer les sujets qui m'intéressaient réellement : je suis pas sûr de connaître à nouveau avant quelques années cette même situation de liberté. Je pense ensuite aux membres de mon comité de thèse, Julie et Céline, que je remercie pour leurs conseils et leur rôle important dans le cadrage de la thèse. Mais plus largement, je pense à l'ensemble des membres du CIRED : pour leur accueil, leur aide, leurs conversations, leurs conseils ! Une mention particulière aux occupants successifs de l'open space : merci de m'avoir supporté trois ans, avec mon besoin récurrent de conversations (et notamment Auriane, qui en a spécifiquement fait les frais).

La thèse ne s'est évidemment pas vécue uniquement au CIRED. Merci à tous mes amis, anciens et plus récents, qui ont partagé avec moi ces années. Ils ont souvent trouvé les mots justes pour me faire relativiser tout ce que j'ai pu être amené à penser de cette thèse, à un moment ou à un autre. De même, je pense à ma famille, et tout particulièrement mes parents : après tout, cette thèse aura été à la fois l'aboutissement de mon parcours scolaire, et le début des choses sérieuses !

Merci à vous tous, du fond du coeur.

Résumé court

Le changement climatique exerce déjà des effets tangibles sur les sociétés et les économies, impacts qui devraient s'intensifier au cours des prochaines décennies. Concevoir des politiques d'adaptation efficaces suppose non seulement de comprendre la nature des impacts futurs, mais aussi d'en quantifier les coûts économiques, or ces connaissances demeurent incomplètes. Cette thèse examine dans quelle mesure la compréhension quantitative actuelle des impacts du changement climatique, y compris dans leurs dimensions transfrontalières, permet d'éclairer les stratégies d'adaptation.

La première partie (**Chapitre 1**) s'intéresse au coût économique des impacts climatiques en France. L'estimation de ces coûts est essentielle pour guider les décisions d'investissement en matière d'adaptation : elle aide à hiérarchiser les actions, à arbitrer entre adaptation et autres objectifs de politique publique, et à évaluer les implications macroéconomiques à long terme. Le Chapitre 1 passe en revue les estimations quantitatives figurant dans les documents de politique d'adaptation français. Malgré l'abondance du matériau institutionnel, de nombreuses catégories d'impacts restent partiellement quantifiées et rarement monétisées. Agrégées, les estimations disponibles produisent un ordre de grandeur cohérent avec la littérature macroéconomique, mais nettement inférieur aux évaluations économétriques mondiales récentes. Cet écart révèle des limites méthodologiques et informationnelles — notamment l'absence de prise en compte des risques transfrontaliers, pourtant susceptibles de contribuer significativement aux coûts totaux des impacts climatiques.

La deuxième partie (Chapitres 2 et 3) aborde ces risques climatiques transfrontaliers transmis par le commerce international. Ils surviennent lorsque des chocs climatiques à l'étranger se propagent à d'autres pays via les chaînes d'approvisionnement, les échanges, les migrations ou les flux financiers. Dans une économie mondialisée, ces effets indirects peuvent représenter une part importante du coût total du changement climatique. Pourtant, peu de pays intègrent systématiquement ces dimensions dans leurs évaluations nationales des risques.

Le **Chapitre 2** développe un cadre quantitatif pour mesurer l'exposition des pays aux risques climatiques transfrontaliers liés au commerce. Il combine des tableaux input–output multirégionaux avec des indices de risque climatique (ND-GAIN, INFORM CC) afin d'évaluer l'exposition indirecte de chaque pays à travers les secteurs. Les résultats révèlent une forte hétérogénéité : les économies développées sont en général moins exposées via leurs importations, tandis que de nombreux pays en développement ou les moins avancés sont doublement vulnérables — directement aux impacts locaux et indirectement du fait de leur dépendance à des partenaires plus exposés. Cette double vulnérabilité met en évidence une inégalité mondiale

face aux impacts directs et transfrontaliers du changement climatique, soulignant la nécessité d'un financement international de l'adaptation et de stratégies de diversification commerciale.

Le **Chapitre 3** examine dans quelle mesure l'ajustement du degré d'intégration commerciale peut constituer une stratégie d'adaptation face aux événements extrêmes. En mobilisant une base de données mondiale d'inondations, un modèle de propagation input–output (ARIO) et un algorithme de projection des scénarios de commerce (SPIN), il analyse les arbitrages entre ouverture et protectionnisme dans un contexte d'extrêmes croissants. Les résultats montrent que l'ouverture commerciale aide les pays touchés à lisser leur consommation et à réduire les pertes de bien-être. Malgré cette redistribution, le bien-être mondial s'améliore : les gains des pays les plus touchés compensent les pertes ailleurs. À l'inverse, isoler les économies très exposées aggraverait leur situation, suggérant que le repli commercial pourrait constituer une forme de maladaptation à l'échelle globale.

Mots clés : Impacts du changement climatique ; France ; Risques climatiques transfrontaliers ; Commerce international ; Événements météorologiques extrêmes ; Modélisation input–output.

Short abstract

Climate change already exerts tangible effects on societies and economies, and these impacts will intensify in the coming decades. Designing effective adaptation policies requires not only understanding the nature of future impacts but also quantifying their economic costs—yet such knowledge remains incomplete. This thesis examines whether the current quantitative understanding of climate change impacts, including their cross-border dimensions, is sufficient to inform adaptation strategies.

The first part (**Chapter 1**) focuses on the economic cost of climate change impacts in France. Estimating these costs is essential to guide decisions on where and how much to invest in adaptation: cost assessments help prioritize actions, balance adaptation with other policy goals, and evaluate long-term macroeconomic implications. Chapter 1 reviews the quantitative estimates contained in France's adaptation policy documents. Despite abundant institutional material, many impact categories remain only partially quantified and rarely monetized. When aggregated, available estimates yield a total magnitude consistent with macroeconomic literature but markedly below recent global econometric assessments. This gap points to methodological and informational limits—particularly concerning cross-border risks, largely absent from national assessments though potentially significant contributors to overall costs.

Building on this finding, the second part (Chapters 2 and 3) addresses cross-border climate risks transmitted through international trade. Such risks arise when climate shocks abroad propagate through supply chains, trade, migration, or financial linkages. In a globalized economy, these indirect effects can represent a substantial share of total climate costs. Recent events, such as droughts disrupting food markets or water shortages constraining the Panama Canal, illustrate trade as a major transmission channel. Yet few countries systematically include these dimensions in national risk assessments.

Chapter 2 develops a quantitative framework to measure countries' exposure to trade-related cross-border climate risks. It combines multi-regional input–output tables with climate risk indices (ND-GAIN, INFORM CC), using publicly available data to evaluate each country's indirect exposure across all sectors. Results show strong heterogeneity: developed economies are generally less exposed through imports, while many developing and least developed countries are doubly vulnerable—both directly to local impacts and indirectly via dependence on risk-prone partners. This dual exposure highlights global inequality in vulnerability to both direct and cross-border impacts, stressing the need for international adaptation finance and trade diversification.

Chapter 3 examines whether adjusting trade integration can itself serve as an adaptation

strategy to extreme weather. Using a global flood database, an input–output propagation model (ARIO), and a projection algorithm for trade scenarios (SPIN), it explores the trade-offs between openness and protectionism under intensifying extremes. Results indicate that trade openness helps flood-affected countries smooth consumption and reduce welfare losses by decoupling them from local production. However, it also raises exposure elsewhere, as partners become dependent on affected economies. Despite this redistribution, global welfare improves overall: the gains of heavily impacted countries outweigh the losses of others. Conversely, isolating highly exposed economies would worsen their situation, suggesting that trade retrenchment may amount to global maladaptation.

Keywords : Climate change impacts; France; Cross-border climate risks; International trade; Extreme weather events; Input–output modeling.

Contents

Remerciements **i**

Résumé court **ii**

Short abstract **iv**

Introduction **1**
1 Context and research questions 1
2 Assessing the cost of climate change impacts 6
3 Cross-border risks: when climate change hits beyond borders 8
4 Dissertation outline and contributions 14
5 References 15

1 When the costs of climate change impacts do not add up: do local policy assessments align with global macroeconomic insights? A case study of France **24**
1 Introduction 25
2 Data and methods 26
3 Results 28
4 Discussion and conclusion 35
5 References 37

Appendices
A Studies reviewed 45
B Additional figures 50
C Quantification and monetization 53

2 Countries' unequal exposure to climate change impacts through international trade **54**
1 Introduction 55
2 Methods 57
3 Results 59
4 Discussion and conclusion 67
5 References 68

Appendices
A Measuring cross-border climate exposure 73
B Distribution of exposure and its decomposition 80
C Descriptive results for all four exposure measures 86

D Exposure by product among developed countries . . . 106
E Sensitivity analysis on risk classification . . . 117
F Robustness of the spatial distribution of local climate risk . . . 127

3 Trading for resilience: assessing the impact of extreme events in the context of climate change across various trade scenarios 130
1 Introduction . . . 131
2 Methods . . . 133
3 Results . . . 136
4 Discussion and conclusion . . . 146
5 References . . . 149

Appendices
A Supplementary Methods . . . 153

Conclusion 161
1 Key findings . . . 161
2 Policy recommandations . . . 162
3 Limitations and avenues for further research . . . 163

Introduction

Contents

1 Context and research questions **1**
1.1 Adaptation is needed, but lagging 1
1.2 Adaptation in France 2
1.3 The state of knowledge on climate impacts, at country scale 3
1.4 Research questions 5
2 Assessing the cost of climate change impacts **6**
2.1 Conceptual framework 6
2.2 These assessments are controversial 7
2.3 The role of the costs assessments 8
3 Cross-border risks: when climate change hits beyond borders **8**
3.1 Definition and types of cross-border risks 9
3.2 Trade can mitigate or amplify climate risks 9
3.3 How to quantitatively investigate such risks ? 10
3.4 Knowledge gaps 12
4 Dissertation outline and contributions **14**
5 References **15**

1 Context and research questions

1.1 Adaptation is needed, but lagging

Climate change is an ongoing phenomenon: the planet has already warmed by approximately 1.1°C compared to pre-industrial levels, according to the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2023). This warming is not merely a physical process; it has profound implications for human well-being, including effects on health, quality of life, and economic activity. While future greenhouse gas emissions will determine the level of warming by the end of the century—leading to very different possible futures—the near term is already largely set. Due to past emissions, significant climate impacts are unavoidable by mid-century, regardless of the mitigation actions taken today (IPCC, 2021).

Adaptation to climate change is therefore necessary (Fankhauser, 2017), and it raises a wide range of challenges across sectors and time horizons. To highlight a few examples, in the short term, it is essential to cope with the consequences of climate change that are already

visible and expected to intensify rapidly. Sectors such as agriculture and tourism, which rely heavily on specific meteorological conditions, will face significant challenges and will need to adjust their practices accordingly (Ortiz-Bobea, 2021; Steiger et al., 2019). Infrastructure will need to become more resilient in order to adapt to extreme events—such as floods, droughts or tropical cyclones—which are expected to become more frequent and intense due to climate change (Hallegatte, Rentschler, et al., 2019; IPCC, 2023). More generally, this also involves adapting lifestyles to higher temperatures, including working conditions (Romanello et al., 2024). In the long term, infrastructure and assets with long operational lifespans—such as nuclear plants or coastal cities—must be planned with particular care, given that they will be exposed to a range of evolving and uncertain climate conditions over the next century (Hallegatte, Hourcade, et al., 2007; Lecocq et al., 2011).

However, efforts undertaken to adapt to climate change remain insufficient given the scale of the challenges ahead. At the global level, several dimensions require improvement: adaptation planning often lacks clearly defined actions and robust mechanisms for evaluation; progress in adaptation—as measured by the number of projects and financial volumes—remains slow; and international public funding, which reached, according to the United Nations Environment Programme (UNEP), only $28 billion in 2022, remains well below estimated adaptation needs, ranging from €215 to €387 billion in 2023 (United Nations Environment Programme et al., 2024). Even in high-income countries, assessments indicate that adaptation efforts are not being implemented at the appropriate scale—as evidenced recently in the United Kingdom (Climate Change Committee, 2025), in the United States (GAO, 2024), and in the European Union (European Environment Agency, 2024a). Several systemic barriers to adaptation have been identified by the IPCC, such as funding, knowledge, and practice gaps, including lack of climate literacy and data.

1.2 Adaptation in France

In particular, we delve into the case of France, which will serve as a guiding thread throughout this dissertation. France has had an official framework for climate change adaptation in place for several years. A national climate change adaptation strategy was adopted in 2006 (Onerc, 2006), followed by two successive national adaptation plans for 2011–2015 and 2018–2022 (Ministère de la Transition Écologique et Solidaire, 2018; Ministère de l'Ecologie, du Développement Durable, des Transports et du Logement, 2011). Numerous studies have been conducted to assess the vulnerability of key national sectors to projected climate change, and adaptation actions have been implemented (Ministère de la Transition Écologique, 2022). However, recent official assessments consistently emphasize that the country is not adequately prepared to cope with the challenges ahead. This concern is notably echoed in the annual reports of the Haut Conseil pour le climat, which emphasize that the gap is widening between implemented adaptation measures and actual needs, as climate impacts are accelerating faster than the responses deployed to address them (Haut Conseil pour le climat, 2025).

The preparation of the third national climate change adaptation plan provided renewed

political momentum for addressing this issue (Ministère de la Transition Écologique, 2025). For instance, additional public funds were allocated to support adaptation projects (Ministère de la Transition écologique et de la Cohésion des territoires, 2024), and efforts were made to quantify adaptation costs and establish priorities (Dépoues, Dolques, and Nicol, 2024; Dépoues and Dolques, 2025).

1.3 The state of knowledge on climate impacts, at country scale

Among the barriers to adaptation identified by the IPCC, barriers related to knowledge include, among other things, understanding the impacts of climate change. While some countries—such as the United Kingdom, through its Climate Change Risk Assessment (see Climate Change Committee, 2021), and the United States, through its National Climate Assessment (see USGCRP et al., 2023)—have institutionalized regular, synthetic, and systematic assessments of climate change impacts, it appears that no such comprehensive synthesis exists at the national level in France. However, such syntheses are a key input of adaptation planning, which is necessary to ensure effective adaptation.

Adaptation requires planning

Adaptation to climate change indeed requires long term planning for several reasons. First, it involves anticipating future conditions and implementing actions today whose benefits will materialize only in the medium or long term. Second, adaptation measures often require the coordination of multiple stakeholders—including private actors, local authorities, and the state—as well as collaboration across different economic sectors (Füssel, 2007; Mullan et al., 2013; Yan, 2024). Such planning is particularly relevant at the national level, as it is the most effective scale for generating political momentum, mobilizing financial resources, and adapting the legal and regulatory framework (M. Garschagen et al., 2021). This does not preclude the value of locally driven initiatives or subnational adaptations, which also play a crucial role (Araos et al., 2016; Pietrapertosa et al., 2023).

As a consequence, the Parties to the UNFCCC agreed under the Cancun Framework (2010) that adaptation should be planned, leading to the development of National Adaptation Plans (NAPs). While this process was initially designed with a strong focus on developing countries, it remains relevant for high-income countries as well. The NAP process is flexible and non-prescriptive, but it is supported by methodological guidance and recommendations (UNFCCC et al., 2012). High-income countries have also engaged in adaptation planning; several OECD countries began adopting national adaptation plans as early as 2005 (Mullan et al., 2013). Today, more than 17 European countries have established a NAP (European Environment Agency, 2024b).

Methodological guidances highlight the role of national climate risk assessments

In all cases considered above, methodological guidance consistently recommends including a national climate risk assessment as part of the adaptation planning process, although the level of detail may vary (European Environment Agency, 2018). However, no single standardized

methodology exists. Most approaches draw on general guidance from the IPCC as well as adaptation-related standards such as ISO 31000:2018 and ISO 14091. Some countries have developed their own national methodologies. For instance, Australia (DCCEEW, 2023), the United Kingdom (Watkiss et al., 2021), and the United States (USGCRP et al., 2023) have each established distinct approaches. At the European level, an initiative is currently underway to propose a harmonized methodology (CLIMAAX, 2023).

The academic literature assessing National Adaptation Plans (NAPs) and their associated national climate risk assessments remains relatively scarce. Morgan et al. (2019) analyze 54 NAPs and assign them scores based on criteria derived from a reading of the Paris Agreement. While the presence of a risk assessment is among the evaluation criteria, the study does not differentiate between types or levels of analysis. M. Garschagen et al. (2021) review 73 NAPs and related documents and find that these plans often fail to account for future changes in vulnerability and exposure. Woodruff et al. (2019) highlight wide variation in the quality of NAPs across countries, identifying multi-agency coordination as the strongest determinant of quality. Finally, Warren et al. (2018), in their analysis of the UK's second Climate Change Risk Assessment (CCRA2), observe the heterogeneity of available impact data and emphasize the need for more systematic development of impact indicators.

What type of information is necessary to inform climate change adaptation?

The diversity of methodologies across countries—and ultimately, the nature of the information available to each country—leads to highly heterogeneous descriptions of climate risks. A first step is to obtain direct climate models outputs—physical variables from global circulation models, such as average local temperature, precipitation etc.—that indicate what the local climate would be under a +2°C or +4°C global warming scenario. These data are available, at a certain resolution, for all countries worldwide[1]. However, such figures remain abstract, as they do not capture the full range of socio-economic and welfare consequences associated with this change. This limitation in how climate change is communicated is well known (Strydhorst, 2025); even researchers in the field still wonder what a +4°C world would truly look like. To inform climate change adaptation, more information is therefore required.

More specific indicators, sometimes derived from specialized models, such as the number of tropical nights in cities, the duration of heatwaves, or hydrological projections like river flows and precipitation patterns, can provide a more detailed understanding of future conditions. Yet, these indicators remain indirect measures of how climate change affects people's lives. Expressing impacts through socio-economic indicators—such as health (mortality and morbidity) or economic activity—provides a clearer and more concrete understanding of the challenges to which societies must adapt. It is therefore essential to reach this level of analysis to inform effective adaptation planning (Warren et al., 2018). A further level of analysis involves expressing impacts in monetary terms. This approach allows for comparisons of impacts across different sectors and makes it possible to aggregate the costs of climate change, thereby helping to sit-

[1]For example, in France, the DRIAS portal provides access to climate projections, see: https://www.drias-climat.fr.

uate adaptation challenges within broader policy debates. It also enables cost–benefit analyses of adaptation options (see in particular Section 2.3).

1.4 Research questions

The starting point of this dissertation lies in wondering if the state of information available in France is sufficient to guide national adaptation. As mentioned above, climate model projections are available, but more detailed indicators may not exist for different types of impacts. We therefore ask the following research question:

To what extent is current quantitative knowledge of climate change impacts in France comprehensive enough to inform adaptation?

To answer this question—as will be explained in Chapter 1—we first conducted a review of the quantified information on climate change impacts found in French institutional documents, developed in the context of adaptation policymaking. It appears that, although the available data is relatively rich, it does not allow for a comprehensive quantification — let alone monetization — of climate change impacts at the national level. We then asked how the elements already monetized in this review compare with macroeconomic assessments of climate change impacts in France. Indeed, an abundant literature estimates the cost of climate change at the global level, often providing country-level breakdowns (e.g. Burke et al., 2019; Dellink et al., 2019; Kalkuhl et al., 2020; Kotz et al., 2024). It emerged that there is considerable uncertainty surrounding the estimated aggregate costs of climate change for France in this global macroeconomic literature, and that the total figures derived from sectoral assessments in French national documents fall within the range of this uncertainty. However, a growing discrepancy can be observed between local policy assessments and the latest macroeconomic studies, which point to significant costs of climate change impacts for France—often above 5% of GDP.

This implies either that the national policy literature underestimates the costs of climate change for France, or that recent macroeconomic assessments overestimate them. In the former case, this would mean that major categories of impacts are not accounted for in the national sectoral literature, or that some sectoral estimates are flawed. Indeed, it appeared that cross-border risks—climate impacts occurring in other countries but with consequences for France—are scarcely documented in these institutional sources. It also emerged that such cross-border risks are among the key reasons why recent econometric estimates are so high. This highlights the importance of quantitatively documenting cross-border risks as a crucial step in designing effective adaptation policies. As a result, the remainder of the thesis focuses on the following sub-question:

What quantitative tools can support the planning of adaptation to cross-border climate risks arising from trade?

The remainder of this introduction is structured as follows. **Section 2** provides contextual elements on the assessment of climate change costs, in order to situate Chapter 1 within a broader perspective. **Section 3** introduces the concept of cross-border climate risks, with a

particular focus on a specific sub-category: climate risks affecting international supply chains. We then identify two key knowledge gaps in the quantitative understanding of trade-related cross-border climate risks and present how Chapters 2 and 3 contribute to addressing them. Finally, **Section 4** takes a step back to summarise the overall contributions of the thesis by restating the two main research questions and outlining how Chapters 1 to 3 collectively respond to them.

2 Assessing the cost of climate change impacts

As noted earlier, estimating the cost of climate change impacts is a key concern, and Chapter 1 explores this question in the specific context of France. Section 2 aims to place this analysis within a broader perspective. What is meant by the expression 'cost of climate change'?" What are the main methodological approaches used to estimate it (Section 2.1)? What are the main controversies surrounding these estimations (Section 2.2)? And what is the value of such estimates for policy and decision-making (Section 2.3)?

2.1 Conceptual framework

The assessment of the costs of climate change impacts has long been a key concern. Initially, these estimates were intended to inform decisions about mitigation, by weighing the benefits of avoiding climate impacts against the costs of reducing greenhouse gas emissions (Nordhaus, 1991; Stern, 2006). The notion of the cost of climate change aims to encompass the full range of impacts—both detrimental and beneficial to populations—associated with global temperature increases.

From an economic perspective, climate change can affect individuals through multiple channels: destruction of physical capital, productivity losses (e.g., labor or agricultural), and reductions in labor supply (Piontek, Kalkuhl, et al., 2019). These different channels may affect both current production levels and long-term economic growth. Including the spontaneous adaptation of economic agents in the analysis—whereby activity shifts toward sectors and regions less exposed to climate change—can lead to lower estimated costs, but it assumes a high degree of flexibility. In that case, the cost may stem less from direct damages than from those induced by transitioning from one strategy to another—for example, through the displacement of cities with strong agglomeration economies (Desmet et al., 2021). Besides, this raises the issue of additional costs associated with building an economy that is resilient to a changing climate (Hallegatte, Hourcade, et al., 2007). Moreover, economic impacts are not limited to direct effects. They can propagate across supply chains (Barrot et al., 2016; Hallegatte, 2019) and across borders, calling for a macroeconomic framework of analysis. As a result, in practice, climate risks are highly complex and may cascade across sectors and borders (Simpson et al., 2021; Carter et al., 2021).

In practice, the estimation of climate damages has followed two main types of approaches (IPCC, 2022; Piontek, Drouet, et al., 2021). The bottom-up approach uses a range of sec-

toral models to estimate impacts across different parts of the economy, which are then aggregated—either directly or through integration into a macroeconomic model. This method has the advantage of being highly transparent about the nature of the impacts considered, but it accumulates uncertainties at each stage of modeling and may fail to capture all relevant transmission channels. The top-down approach, by contrast, establishes direct statistical relationships between temperature changes—global or local—and aggregate economic activity (Auffhammer, 2018). While this method allows for empirical estimation at scale, it has been criticized for its "black-box" nature, and there are concerns about whether the observed historical effects of warming can be reliably extrapolated to future climate conditions (Morris et al., 2025).

Beyond measurable economic losses, climate change also affects non-market dimensions of well-being, including quality of life, health (Adger et al., 2022), or the intrinsic value of biodiversity. While efforts have been made to monetize these effects, this remains highly challenging. Yet ignoring them can bias cost-benefit assessments, which should account for any reduction in agents' well-being.

2.2 These assessments are controversial

Fundamental criticisms have been raised against the very idea of estimating the costs of climate change, due to the intrinsic complexity and deep uncertainty surrounding such assessments. First, a wide range of climate impacts are not captured in conventional monetary evaluations—notably effects on human well-being, ecosystem services, and large-scale social phenomena such as migration (Rising, Tedesco, et al., 2022). Moreover, even the impacts that are included may be substantially underestimated, as current models struggle to capture the full cascade of indirect and interacting effects triggered by climate disruptions (Rising, Taylor, et al., 2022). Most estimates rely on climate scenarios developed by the IPCC, which may overlook low-probability, high-impact events such as tipping points — events that could generate catastrophic consequences but are poorly represented in integrated assessment models (Kemp et al., 2022; Morris et al., 2025; Weitzman, 2011). Finally, as Morris et al. (2025) emphasize, the wide divergence between top-down (econometric/statistical) and bottom-up (structural/process-based) approaches to estimating climate damages creates fundamental difficulties in producing policy-relevant guidance.

In fact, the IPCC has emphasized that aggregate economic costs are only one of several reasons to reduce greenhouse gas emissions. Even if overall economic losses were relatively limited, other "Reasons for Concern" are put forward—such as the threat to unique and irreplaceable systems (such as certain ecosystems or cultures), the highly unequal distribution of climate impacts across populations and regions, or the possibility of low-probability but high-impact events. Besides, with the adoption of the Paris Agreement, the rationale for mitigation no longer relies primarily on estimating the costs of climate change. Mitigation is now framed around the objective of limiting global warming to well below 2°C, and ideally to 1.5°C. In this context, the question is no longer whether to reduce emissions, but how to do so effectively and equitably (Koomey, 2013).

2.3 The role of the costs assessments

However, in contrast to mitigation policies, adaptation strategies can still benefit significantly from estimating the costs of climate change. At the macro level, cost estimates help to quantify the long-term effects of climate change on the economy and society. This is particularly relevant for sectors and institutions that require long-term foresight — for example, pension systems, infrastructure planning, or fiscal sustainability frameworks. Moreover, macroeconomic estimates enable policymakers to weigh the expected impacts of climate change against other public policy priorities. At the micro level, cost estimates are essential for determining appropriate levels of adaptation investment. Adaptation requires making choices: responses are often costly, and for a given climate hazard, multiple technical and policy options may be available (Lecocq et al., 2011). For instance, in the case of coastal erosion, possible responses include managed retreat, hard-engineering protection, or nature-based solutions (Bachner et al., 2022). Similarly, adaptation to increasing heat in cities can involve green infrastructure, building retrofits, or behavioral adjustments (Viguié et al., 2020). Economic analysis helps to rationalize these choices by comparing the expected costs and benefits of each option, with flexibility components accounted for when needed: in the case of climate change adaptation, expected benefits are precisely the costs of climate change impacts (Haasnoot et al., 2020; IMF, 2022; Verschuur et al., 2025).

Since costs of climate change impacts can be used to guide adaptation decisions, it is important to have monetized impact assessments by sector—this is precisely what we aim to examine in Chapter 1. Moreover, considering the aggregate sum—that is across all impacts and sectors—of climate change costs as reported in national adaptation policy documents is also a meaningful exercise. Such a result offers insight into how national stakeholders perceive the significance of climate impacts. Confronting this perspective with the global macroeconomic literature allows us to assess whether this perceived level of importance is of the right order of magnitude compared to other lines of evidence. That is also what we do in Chapter 1.

3 Cross-border risks: when climate change hits beyond borders

Chapter 1 reveals that institutional sources provide limited information on cross-border climate risks in France—that is, impacts occurring abroad but affecting France. Yet, these risks appear to be a major factor behind the high values observed in recent econometric estimates. This suggests that improving the quantitative understanding of cross-border effects could help inform more effective adaptation policies. Chapters 2 and 3 focus on cross-border climate risks transmitted through international trade, with Chapter 3 specifically addressing the consequences of extreme weather events. In Section 3, we situate this particular risk within the broader category of cross-border impacts and explain how these chapters contribute to filling two gaps in the existing literature.

3.1 Definition and types of cross-border risks

Cross-border risks are defined as "*consequences of climate change that occur remotely from the location of their initial impact*", that is "*a risk in a region of interest that is remote from the location of the initial impact*" (Carter et al., 2021). Cross-border risks may arise either from the physical impacts of climate change or from human responses to those impacts. A striking instance is India's July 2023 ban on exports of non-basmati white rice, implemented to restrain surging domestic prices following a heatwave-induced crop stress. This decision reduced global rice supply and helped trigger a sharp increase in global rice prices—up to 20% year-on-year within just one month (Glauber et al., 2024; Jadhav et al., 2023). It is worth noting that accounting for cross-border risks changes the nature of adaptation, which has traditionally been viewed as a predominantly local issue, but can in fact involve externalities—much like mitigation (Benzie et al., 2019; Khan et al., 2021).

The concept of *cross-border risks* covers a wide range of concrete manifestations. For instance, Benzie et al. (2019) identify several transboundary pathways through which climate change impacts may propagate: migration, which can be induced by climate-related shocks; financial flows, which may decline as a result of climate-induced instability; physical flows, such as droughts affecting downstream regions; and international trade. In the latter case, climate shocks can disrupt both supply and demand, with cascading effects throughout global value chains — for example, a flood in a key manufacturing hub can halt production and affect consumers and firms worldwide. **In this thesis, we focus on the latter propagation channel, and restrict our analysis to cross-border risks related to international trade, also referred to as global supply chains**.

Recent examples of cross-border propagation of extreme events show that this issue is already highly relevant. For instance, the 2020-2023 global chip shortage has been partly attributed to the 2021 drought in Taiwan. Similarly, the significant rise in global food prices since 2022 has been linked to the fact that the last few years ranked, globally, among the driest in the recent past. More recently still, drought conditions in the Panama Canal have resulted in noticeable delays and rerouting in international trade flows from July 2023 to February 2024. In a more systematic approach, Wang et al. (2025) evaluates the cross-border trade impacts of past extreme events and finds that almost half of the costs stem from indirect effects due to cross-border propagation. As climate risks are expected to increase in the future, climate-related disruptions to supply chains are also likely to become more frequent and severe.

3.2 Trade can mitigate or amplify climate risks

Research on cross-border risks through trade is a rapidly expanding field, as evidenced by a recent literature review by Wenz and Willner (2022). Climate impacts are typically divided into two categories: slow-onset impacts, which develop gradually over time (e.g., sea level rise, desertification), and fast-onset impacts, which occur suddenly and cause immediate disruption (e.g., floods, heatwaves) (Carter et al., 2021). Trade is perceived as both an opportunity and an amplifying mechanism when it comes to climate impacts.

On the one hand, the integration of countries into international trade allows them to better face both slow- and fast-onset impacts (Janssens et al., 2021). In the short term, when affected by a climate-change-related extreme event, countries can compensate for local production losses through imports, thereby smoothing consumption. In the long term, trade networks may reconfigure to shift production toward regions with a comparative advantage — whether in terms of productivity or climate resilience. For instance, Gouel et al. (2021) show that changing crop types and trade partners constitutes an important long-term adaptation strategy to secure food supply. Similarly, Janssens et al. (2020) find that such trade adjustments could significantly reduce the number of people affected by malnutrition.

On the other hand, trade integration also exposes economies to external shocks (Wenz and Levermann, 2016), particularly to foreign fast-onset events, which are often impossible to anticipate and can have devastating local impacts. Economically, extreme events cause production interruptions and capital destruction for firms located in affected areas. As a consequence, their clients are not supplied, their suppliers face reduced demand, and their employees may experience income losses (Botzen et al., 2019). These effects may result either from supply shortages or from price increases. Such consequences are referred to as indirect effects, or higher-order effects, and they extend the impact of a geographically localized event across sectors and even across borders.

3.3 How to quantitatively investigate such risks ?

As a consequence, accounting for the role of international trade in either amplifying or mitigating climate risks is essential for all economies. This is all the more important as recent studies highlight the quantitative significance of cross-border risks, which represent a substantial share of the total costs of climate change (Neal et al., 2025; Zappalà, 2023). However, only a few countries so far have integrated cross-border risks into their climate change risk assessments (Adams et al., 2020; IPCC, 2023), and institutions tended to document qualitatively these climate impacts (Adaptation Without Borders, 2023).

The main research question of Chapter 2 and 3 of this thesis is precisely: what quantitative tools can support the planning of adaptation to cross-border risks from trade?

A first approach to this general question is to ask what types of data would allow for a quantitative assessment of these risks. Necessarily, any quantitative assessment of cross-border climate risks requires both trade data and climate risk data.

Trade data

Regarding trade data, two main types of sources can be used. First, bilateral customs data—which may be produced by countries themselves through their national statistical agencies—can also be accessed through harmonized global databases such as UN Comtrade (https://comtradeplus.un.org) or the BACI database (Gaulier et al., 2010). These datasets provide detailed information on trade flows between countries, typically disaggregated by product and

year. These data are useful for identifying direct trade relationships and assessing direct exposure to partner countries' shocks. In particular, the highly detailed product-level analysis helps identify risks of import or export concentration in a few specific countries, and has been used to assess geopolitical risks in supply chains (for an in-depth discussion of this approach, see Mejean et al., 2024). Second, Multi-Regional Input-Output Tables (MRIOT)— such as ICIO (OECD, 2023), EXIOBASE (Stadler et al., 2018) or Eora (Lenzen et al., 2012)— allow for a more comprehensive analysis of global supply chains by tracing the interdependencies between sectors and countries. MRIOT data capture not only direct trade but also indirect linkages across the global economy, making them especially relevant for evaluating higher-order effects of climate shocks through complex production networks. There is a trade-off between these two types of data. On the one hand, bilateral customs data offer a very fine sectoral breakdown—around 5,000 products in the case of BACI—while MRIOTs only detail trade flows between country-sector pairs at a much coarser resolution, typically limited to a few dozen sectors. On the other hand, bilateral customs data do not allow for assessing the importance of imports (respectively exports) relative to national consumption (respectively production). For instance, customs data can indicate, for a given product, the share of imports coming from a specific country relative to total imports of that product, but not their weight in national consumption.

Slow-onset impacts

Regarding climate risks, it is important to distinguish between long-term trends and extreme events. The effects of long-term climate trends—such as declines in agricultural yields or reductions in labor productivity due to heat—can be assessed using sectoral impact models (for instance, see the ISIMIP database : https://www.isimip.org/). The outputs of these models are then used as inputs in Computable General Equilibrium (CGE) models or quantitative spatial models to evaluate how economic agents adjust optimally to shifts in comparative advantage, potentially leading to a reconfiguration of trade networks (Cruz et al., 2024; Dellink et al., 2019; Gouel et al., 2021; Schenker, 2013).

Extreme weather events

However, this type of climate risk data is not well adapted to model the short-term consequences of climate change-related extreme weather events. In the short term, extreme weather events—such as floods, hurricanes, or heatwaves—can cause abrupt and localized disruptions to production, infrastructure, and trade flows. If these disruptions were treated as long-term productivity losses, their short-term amplification mechanisms—such as those related to reconstruction dynamics and input complementarities—would largely be overlooked (Carvalho et al., 2019; Hallegatte, 2014; Wenz and Willner, 2022). As a result, their effects would appear smoothed out, and their underlying dynamics, including cross-border spillovers, would differ significantly (Koks, Bočkarjova, et al., 2015). As a consequence, event-based databases have been developed for various types of extreme events. For instance, Alfieri et al. (2017) combined seven General Circulation Models with flood impact models to construct a global database of flood events—covering several thousand events worldwide—over the period 1970 to 2130 under the Representative Concentration Pathway (RCP) 8.5 climate scenario. Each event

is geographically localized and associated with an estimate of direct capital losses. Another example of such a dataset is CLIMADA, which provides probabilistic projections of individual extreme events—including tropical cyclones, river floods, droughts, heatwaves, wildfires, and winter storms (Aznar-Siguan et al., 2019; Bresch et al., 2021).

Climate risk indices

Finally, several country climate risk indices have been developed by public institutions to help decision makers pinpoint countries most at risk from actual and future climate change (Feldmeyer et al., 2021; Feldmeyer et al., 2021; Matthias Garschagen et al., 2021). Each country is given a climate risk score that accounts for hazard, exposure and vulnerability. For instance, ND-GAIN—a climate risk index developed by the University of Notre Dame—captures a wide range of climate impacts, both slow- and fast-onset, including dimensions such as food production, water availability, health, and infrastructure (University of Notre Dame Adaptation Initiative, 2023). INFORM Climate Change—developed by the Joint Research Centre of the European Commission—focuses more specifically on future population exposure to fast-onset climate impacts, such as floods, droughts, and epidemics (European Commission. Joint Research Centre., 2022).

3.4 Knowledge gaps

A simple systematic cross-country comparison

Several studies have sought to make use of existing data on climate risk and trade. One body of literature explores the effect of climate change on supply chains by focusing on a specific industry, which allows for a deeper understanding of sector-specific characteristics (Fleming et al., 2014; Gouel et al., 2021; Hedlund, Carlsen, et al., 2022; Langholtz et al., 2014; Nakano, 2017; Parajuli et al., 2019). Other studies estimate the supply chain consequences of climate risks across all industries, using economic models based on MRIOTs. This literature can be divided into two strands. On the one hand, some papers examine how trade networks evolve over the long term in response to slow-onset climate impacts. On the other hand, other studies analyze the short-term disruptions caused by extreme weather events, often relying on Input-Output models such as Acclimate (Kuhla et al., 2021; Otto et al., 2017; Wenz and Levermann, 2016; Willner et al., 2018), MRIA (Koks, Thissen, et al., 2019; Koks and Mark Thissen, 2016), or ARIO (Hallegatte, 2014; Sun et al., 2024). However, these approaches focus on specific economic sectors or particular types of hazards. Moreover, using complex impact-propagation models to assess the cross-border effects of climate change is computationally intensive, and the results are subject to an additional layer of uncertainty stemming from the propagation mechanism itself. In particular, we note that there is no straightforward method to provide a global view of countries' exposure to climate risks through international trade, one that considers all economic sectors and a broad range of climate hazards using publicly available data.

In the context of recent geopolitical tensions—such as geo-fragmentation or the Russia-Ukraine war (Aiyar et al., 2023)—approaches have been developed to assess dependence-related

risks by directly leveraging MRIO tables, without relying on propagation models. Indeed, it is possible to account for indirect dependencies using only Input-Output tables, through what is known as the Leontief inverse (Miller et al., 2009). The fact that this method relies exclusively on trade data, which is generally considered relatively robust, makes it a solid starting point for assessing dependence-related vulnerabilities. Baldwin et al. (2023b) show how to construct ratios based on Input-Output tables to identify a country's dependence on others, both at the aggregate and sectoral levels. They show, for example, that the dependence of the U.S. manufacturing sector on Chinese inputs is very strong when indirect dependence is taken into account (Baldwin et al., 2023a). Similarly, an OECD publication uses ratios based on input-output tables to compare how dependent different countries are on imports and exports relative to their domestic production (OECD, 2023). It finds that differences in dependence can be explained by the size of countries or their position in the global value chain—whether they are located upstream or downstream in the production process.

However, these studies define risk as 'being dependent on foreign countries' or 'importing products from a limited number of countries', with no consideration of climate change. Yet, as climate risk is heterogeneously distributed across the globe, depending on climate-riskier countries might be more of a concern than depending on unspecified foreign countries, since they would be more frequently or severely affected by climate impacts, which constitute the concrete manifestations of climate risks. In fact, it appears that this approach has not been applied when it comes to systematically measuring climate cross-border risks through trade. Cahen-Fourot et al. (2021) use Leontief matrices to measure the exposure of different countries to stranded assets caused by decarbonization. Hedlund, Fick, et al. (2018) propose indicators to assess cross-border climate risks across multiple dimensions (e.g., transboundary water dependency, remittance flows, openness to asylum), with trade being one channel. However, they measure exposure through trade solely by a country's openness to commerce, without distinguishing between trade partners of different risk levels. Nakano (2021) proposes a framework to assess cross-border risk by combining MRIOTs with historical natural disaster risk data, and applies it to analyze the cross-border exposure of the motor industry in four countries (see also Nakano, 2017). **In Chapter 2, we extend this framework by introducing new measures of exposure. We then apply it by combining future climate risk projections with MRIOT data to systematically assess the cross-border climate exposure of all countries**.

Reshoring or not: that is the question

Describing dependencies using MRIOTs is valuable, as it helps to map countries' vulnerability to climate-related cross-border trade risks, to highlight the level of exposure, and to compare countries globally or within a regional context. However, when strong dependencies on countries facing high climate risk are identified, adaptation strategies—beyond international cooperation through financing adaptation in the most vulnerable countries (Khan et al., 2021; Talebian et al., 2025)—could involve a set of measures related to remodeling international trade. In particular, reshoring has been discussed as a way to enhance the resilience of national supply chains in the context of increasing extreme weather events driven by climate change. While it

is clear that the increase in natural disasters has only a detrimental effect on the transportation of goods, the impact of international trade integration on the resilience of national value chains remains ambiguous, as previously discussed. By reshoring, countries become more exposed to local climate change impacts and less to foreign ones. As a result, reshoring has both beneficial and detrimental effects with regard to climate-related risks (Wenz and Willner, 2022). **In Chapter 3, we develop a quantitative framework to explore the cost-benefit trade-offs of reshoring in the context of increasing extreme weather events due to climate change, and we apply it to the analysis of continental floods.**

4 Dissertation outline and contributions

To sum up, this PhD thesis is guided by the following research question: **to what extent is current quantitative knowledge of climate change impacts in France comprehensive enough to inform adaptation?**

In the first part, we examine the current state of knowledge regarding the impacts of climate change in France, as reflected in national adaptation policy documents. Indeed, in **Chapter 1**, we review national institutional adaptation documents—produced by national public or private actors with the aim of informing adaptation policy—that provide at least one quantitative insight into the risks that climate change poses for France. We show that while the available data is rich—60 documents met the selection criteria—, it does not allow for a comprehensive quantification, and even less for a comprehensive monetization, of climate change impacts at the national level. Since the climate change costs reported in this institutional literature reflect the perceived significance of climate risks by national stakeholders, we aggregate all available monetized data and compare it with global macroeconomic studies that estimate the costs of climate change across countries and provide specific data for France. By reviewing these 21 macroeconomic studies, we find that the estimated cost of climate change for France has been significantly increasing over time, particularly since 2018. We also find that recent macroeconomic literature, especially econometric studies, produces much higher cost estimates than those that can be inferred from aggregating national policy assessments. This discrepancy can be attributed to methodological lag, limited sectoral coverage, lack of monetization, and the omission of cross-border effects. It raises concerns if one considers that adaptation investments should be calibrated based on an assessment of climate impacts within a cost–benefit framework. In the second part, we narrow down the initial question to focus on climate-related cross-border risks transmitted through trade, and position our work within the following research question: **what quantitative tools can support the planning of adaptation to cross-border risks from trade?**

In **Chapter 2**, we propose a simple and flexible framework to systematically assess the trade-related climate cross-border risks by combining input-output tables and country-scale climate risk indices. Using country-scale climate risk indices makes it possible to rely on publicly available data and to leverage a well-established stylized fact: the heterogeneity of climate risk levels across countries, regardless of the absolute magnitude of climate change impacts.

While this framework can be used to study a given country's dependence on regions facing the highest levels of climate risk—understood as the combination of hazard, exposure, and vulnerability—and to compare it with similar countries, it can also be used to investigate whether global stylized facts can be identified regarding trade-related climate cross-border risks. We find that this indirect exposure is highly heterogeneous between countries. While its geographical pattern generally differs from those of direct climate change impacts, several countries suffer a double exposure and are exposed to both risks, as a result of regional trade integration and geographic concentration of climate risks. In particular, when it comes to imports, developed countries are among the least exposed to cross-border climate risks, while the populations most exposed to such risks are often already among the most vulnerable to direct climate impacts. This pattern, however, does not hold when considering exports. Moreover, almost every country faces high exposure for at least one broad category of products.

The relation between trade integration and extreme weather events in the context of climate change is ambiguous. In **Chapter 3**, we propose a framework to assess quantitatively the effect of both trade openness and trade bloc formation to the resilience to extreme weather events, by combining an event-based extreme weather event database (from Alfieri et al., 2017), an input-output impact propagation model (ARIO) and a input-output tables projection algorithm (SPIN). We show that trade openness can help the most flood-affected countries smooth consumption by decoupling it from local production, but increases other countries' exposure to foreign shocks. Overall, while integration creates both winners and losers, global welfare improves, and isolating highly exposed economies would significantly worsen their situation. In a sense, trade retrenchment can thus be viewed as a form of maladaptation at the global level.

5 References

Adams, Kevin M., Katy Harris, Richard J. T. Klein, Frida Lager, and Magnus Benzie (2020). *Climate-Resilient Trade and Production: The Transboundary Effects of Climate Change and Their Implications for EU Member States*. Tech. rep. Stockholm Environment Institute. URL: https://www.cascades.eu/publication/climate-resilient-trade-and-production/ (visited on 12/21/2022).

Adaptation Without Borders (2023). *The Global Transboundary Climate Risk Report*. Tech. rep. URL: https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Rapport/the_global_transboundary_climate_risk_report.pdf.

Adger, W. Neil, Jon Barnett, Stacey Heath, and Sergio Jarillo (2022). "Climate change affects multiple dimensions of well-being through impacts, information and policy responses". *Nature Human Behaviour* 6.11, pp. 1465–1473. URL: https://www.nature.com/articles/s41562-022-01467-8 (visited on 05/29/2023).

Aiyar, Shekhar, Anna Ilyina, Jiaqian Chen, Alvar Kangur, Juan Trevino, Christian Ebeke, et al. (2023). "Geo-Economic Fragmentation and the Future of Multilateralism". *Staff Discussion Notes* 2023.001, p. 1. URL: https://elibrary.imf.org/openurl?genre=journal&issn=2617-6750&volume=2023&issue=001 (visited on 11/21/2024).

Alfieri, Lorenzo, Berny Bisselink, Francesco Dottori, Gustavo Naumann, Ad De Roo, Peter Salamon, et al. (2017). "Global projections of river flood risk in a warmer world". *Earth's Future* 5.2, pp. 171–182. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016EF000485 (visited on 09/06/2024).

Araos, Malcolm, Lea Berrang-Ford, James D. Ford, Stephanie E. Austin, Robbert Biesbroek, and Alexandra Lesnikowski (2016). "Climate change adaptation planning in large cities: A systematic global assessment". *Environmental Science & Policy* 66, pp. 375–382. URL: https://linkinghub.elsevier.com/retrieve/pii/S1462901116303148 (visited on 06/25/2025).

Auffhammer, Maximilian (2018). "Quantifying Economic Damages from Climate Change". *Journal of Economic Perspectives* 32.4, pp. 33–52. URL: https://pubs.aeaweb.org/doi/10.1257/jep.32.4.33 (visited on 11/25/2021).

Aznar-Siguan, Gabriela and David N. Bresch (2019). "CLIMADA v1: a global weather and climate risk assessment platform". *Geoscientific Model Development* 12.7, pp. 3085–3097. URL: https://gmd.copernicus.org/articles/12/3085/2019/ (visited on 05/19/2025).

Bachner, Gabriel, Daniel Lincke, and Jochen Hinkel (2022). "The macroeconomic effects of adapting to high-end sea-level rise via protection and migration". *Nature Communications* 13.1, p. 5705. URL: https://www.nature.com/articles/s41467-022-33043-z (visited on 06/12/2025).

Baldwin, Richard, Rebecca Freeman, and Angelos Theodorakopoulos (2023a). *Hidden Exposure : Measuring US Supply Chain Reliance*. Tech. rep. URL: http://www.nber.org/papers/w31820.pdf.

— (2023b). "Horses for Courses: Measuring Foreign Supply Chain Exposure". *SSRN Electronic Journal*. URL: https://www.ssrn.com/abstract=4335496 (visited on 05/20/2025).

Barrot, Jean-Noël and Julien Sauvagnat (2016). "Input Specificity and the Propagation of Idiosyncratic Shocks in Production Networks*". *The Quarterly Journal of Economics* 131.3, pp. 1543–1592. URL: https://academic.oup.com/qje/article/131/3/1543/2461213 (visited on 08/11/2023).

Benzie, Magnus, Timothy R. Carter, Henrik Carlsen, and Richard Taylor (2019). "Cross-border climate change impacts: implications for the European Union". *Regional Environmental Change* 19.3, pp. 763–776. URL: http://link.springer.com/10.1007/s10113-018-1436-1 (visited on 08/22/2023).

Botzen, W. J. Wouter, Olivier Deschenes, and Mark Sanders (2019). "The Economic Impacts of Natural Disasters: A Review of Models and Empirical Studies". *Review of Environmental Economics and Policy* 13.2, pp. 167–188. URL: https://www.journals.uchicago.edu/doi/10.1093/reep/rez004 (visited on 12/09/2022).

Bresch, David N. and Gabriela Aznar-Siguan (2021). "CLIMADA v1.4.1: towards a globally consistent adaptation options appraisal tool". *Geoscientific Model Development* 14.1, pp. 351–363. URL: https://gmd.copernicus.org/articles/14/351/2021/ (visited on 05/19/2025).

Burke, Marshall and Vincent Tanutama (2019). *Climatic Constraints on Aggregate Economic Output*. Tech. rep. w25779. Cambridge, MA: National Bureau of Economic Research, w25779. URL: http://www.nber.org/papers/w25779.pdf (visited on 01/06/2025).

Cahen-Fourot, Louison, Emanuele Campiglio, Antoine Godin, Eric Kemp-Benedict, and Stefan Trsek (2021). "Capital stranding cascades: The impact of decarbonisation on productive asset utilisation". *Energy Economics* 103, p. 105581. URL: https://linkinghub.elsevier.com/retrieve/pii/S0140988321004515 (visited on 11/23/2023).

Carter, Timothy R., Magnus Benzie, Emanuele Campiglio, Henrik Carlsen, Stefan Fronzek, Mikael Hildén, et al. (2021). "A conceptual framework for cross-border impacts of climate change". *Global Environmental Change* 69, p. 102307. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378021000868 (visited on 08/08/2023).

Carvalho, Vasco M. and Alireza Tahbaz-Salehi (2019). "Production Networks: A Primer". *Annual Review of Economics* 11.1, pp. 635–663. URL: https://www.annualreviews.org/doi/10.1146/annurev-economics-080218-030212 (visited on 08/14/2023).

CLIMAAX (2023). *Deliverable D1.2 - Desk review of existing CRA frameworks WP1 – Framework for local and regional climate risk assessment*. Tech. rep. URL: https://www.climaax.eu/wp-content/uploads/2023/07/CLIMAAX_D1.2_v1.2.0.pdf.

Climate Change Committee (2021). *Independent Assessment of UK Climate Risk. Advice to Government For the UK's third Climate Change Risk Assessment (CCRA3)*. Tech. rep. URL: https://www.theccc.org.uk/publication/independent-assessment-of-uk-climate-risk/.

— (2025). *Progress in adapting to climate change. 2025 report to Parliament*. Tech. rep. URL: https://www.theccc.org.uk/wp-content/uploads/2025/04/Progress-in-adapting-to-climate-change-2025-1.pdf.

Cruz, José-Luis and Esteban Rossi-Hansberg (2024). "The Economic Geography of Global Warming". *Review of Economic Studies* 91.2, pp. 899–939. URL: https://academic.oup.com/restud/article/91/2/899/7107009 (visited on 05/06/2025).

DCCEEW (2023). *National Climate Risk Assessment Methodology*. Tech. rep. Canberra: Department of Climate Change, Energy, the Environment and Water.

Dellink, Rob, Elisa Lanzi, and Jean Chateau (2019). "The Sectoral and Regional Economic Consequences of Climate Change to 2060". *Environmental and Resource Economics* 72.2, pp. 309–363. URL: http://link.springer.com/10.1007/s10640-017-0197-5 (visited on 08/22/2023).

Dépoues, Vivian and Guillaume Dolques (2025). *Le réflexe adaptation dans les investissements publics en pratique Pistes pour 2025 et perspectives*. Tech. rep. Paris. URL: https://www.i4ce.org/publication/reflexe-adaptation-investissements-publics-pratique-pistes-2025-perspectives-climat/.

Dépoues, Vivian, Guillaume Dolques, and Morgane Nicol (2024). *Anticiper les effets d'un réchauffement de +4 °C : quels coûts de l'adaptation ?* Tech. rep. Paris. URL: https://www.i4ce.org/publication/anticiper-effets-rechauffement-4-degres-adaptation-climat/.

Desmet, Klaus, Robert E. Kopp, Scott A. Kulp, Dávid Krisztián Nagy, Michael Oppenheimer, Esteban Rossi-Hansberg, et al. (2021). "Evaluating the Economic Cost of Coastal Flooding". *American Economic Journal: Macroeconomics* 13.2, pp. 444–486. URL: https://pubs.aeaweb.org/doi/10.1257/mac.20180366 (visited on 04/03/2023).

European Commission. Joint Research Centre. (2022). *INFORM Climate Change: quantifying the impacts of climate and socio economic trends on the risk of future humanitarian crises and disasters*. LU: Publications Office. URL: https://data.europa.eu/doi/10.2760/383939 (visited on 10/10/2023).

European Environment Agency (2018). *National climate change vulnerability and risk assessments in Europe, 2018*. LU: Publications Office. URL: https://data.europa.eu/doi/10.2800/348489 (visited on 11/06/2023).

— (2024a). *European Climate Risk Assessment*. LU: Publications Office. URL: https://data.europa.eu/doi/10.2800/8671471 (visited on 06/05/2025).

— (2024b). *Overview of national climate change adaptation strategies and plans in Europe*. Tech. rep. URL: https://www.eea.europa.eu/en/analysis/maps-and-charts/overview-of-national-and-sectoral-3.

Fankhauser, Sam (2017). "Adaptation to Climate Change". *Annual Review of Resource Economics* 9.1, pp. 209–230. URL: https://www.annualreviews.org/doi/10.1146/annurev-resource-100516-033554 (visited on 06/27/2025).

Feldmeyer, Daniel, Joern Birkmann, Joanna M. McMillan, Lindsay Stringer, Walter Leal Filho, Riyanti Djalante, et al. (2021). "Global vulnerability hotspots: differences and agreement between international indicator-based assessments". *Climatic Change* 169.1-2, p. 12. URL: https://link.springer.com/10.1007/s10584-021-03203-z (visited on 09/20/2023).

Fleming, A., A.J. Hobday, A. Farmery, E.I. Van Putten, G.T. Pecl, B.S. Green, et al. (2014). "Climate change risks and adaptation options across Australian seafood supply chains – A preliminary assessment". *Climate Risk Management* 1, pp. 39–50. URL: https://linkinghub.elsevier.com/retrieve/pii/S2212096313000065 (visited on 01/28/2024).

Füssel, H.-M. (2007). "Adaptation planning for climate change: concepts, assessment approaches, and key lessons". *Sustainability Science* 2.2, pp. 265–275. URL: http://link.springer.com/10.1007/s11625-007-0032-y (visited on 06/25/2025).

GAO (2024). *Climate Resilience. Congressional Action Needed to Enhance Climate Economics Information and to Limit Federal Fiscal Exposure*. Tech. rep. URL: https://www.gao.gov/assets/gao-24-106937.pdf.

Garschagen, M., D. Doshi, M. Moure, H. James, and H. Shekhar (2021). "The consideration of future risk trends in national adaptation planning: Conceptual gaps and empirical lessons". *Climate Risk Management* 34, p. 100357. URL: https://linkinghub.elsevier.com/retrieve/pii/S2212096321000863 (visited on 11/03/2023).

Garschagen, Matthias, Deepal Doshi, Jonathan Reith, and Michael Hagenlocher (2021). "Global patterns of disaster and climate risk—an analysis of the consistency of leading index-based assessments and their results". *Climatic Change* 169.1-2, p. 11. URL: https://link.springer.com/10.1007/s10584-021-03209-7 (visited on 09/20/2023).

Gaulier, Guillaume and Soledad Zignago (2010). "BACI: International Trade Database at the Product-Level (the 1994-2007 Version)". *SSRN Electronic Journal*. URL: http://www.ssrn.com/abstract=1994500 (visited on 07/01/2025).

Glauber, Joseph and Abdullah Mamun (2024). "India's export restrictions on rice continue to disrupt global markets, supplies, and prices". *IFPRI*. URL: https://www.ifpri.org/blog/indias-export-restrictions-rice-continue-disrupt-global-markets-supplies-and-prices/?utm_source=chatgpt.com.

Gouel, Christophe and David Laborde (2021). "The crucial role of domestic and international market-mediated adaptation to climate change". *Journal of Environmental Economics and Management* 106, p. 102408. URL: https://linkinghub.elsevier.com/retrieve/pii/S0095069620301315 (visited on 09/01/2022).

Haasnoot, Marjolijn, Maaike Van Aalst, Julie Rozenberg, Kathleen Dominique, John Matthews, Laurens M. Bouwer, et al. (2020). "Investments under non-stationarity: economic evaluation of adaptation pathways". *Climatic Change* 161.3, pp. 451–463. URL: http://link.springer.com/10.1007/s10584-019-02409-6 (visited on 04/21/2023).

Hallegatte, Stéphane (2014). "Modeling the Role of Inventories and Heterogeneity in the Assessment of the Economic Costs of Natural Disasters: Modeling the Role of Inventories and Heterogeneity". *Risk Analysis* 34.1, pp. 152–167. URL: https://onlinelibrary.wiley.com/doi/10.1111/risa.12090 (visited on 11/28/2022).

— (2019). "Disasters' impacts on supply chains". *Nature Sustainability* 2.9, pp. 791–792. URL: https://www.nature.com/articles/s41893-019-0380-5 (visited on 07/27/2023).

Hallegatte, Stéphane, Jean-Charles Hourcade, and Philippe Ambrosi (2007). "Using climate analogues for assessing climate change economic impacts in urban areas". *Climatic Change* 82.1-2, pp. 47–60. URL: http://link.springer.com/10.1007/s10584-006-9161-z (visited on 06/25/2025).

Hallegatte, Stéphane, Jun Rentschler, and Julie Rozenberg (2019). *Lifelines: The Resilient Infrastructure Opportunity*. The World Bank. URL: http://elibrary.worldbank.org/doi/book/10.1596/978-1-4648-1430-3 (visited on 05/26/2023).

Haut Conseil pour le climat (2025). "Avis sur le Plan National d'Adaptation au Changement Climatique (PNACC3): une première étape pour garantir la résilience et la protection des populations". URL: https://www.hautconseilclimat.fr/wp-content/uploads/2025/03/2025_HCC_auto_saisine_avis_PNACC3_VF.pdf.

Hedlund, Johanna, Henrik Carlsen, Simon Croft, Chris West, Örjan Bodin, Emilie Stokeld, et al. (2022). "Impacts of climate change on global food trade networks". *Environmental Research Letters* 17.12, p. 124040. URL: https://iopscience.iop.org/article/10.1088/1748-9326/aca68b (visited on 08/09/2023).

Hedlund, Johanna, Stephen Fick, Henrik Carlsen, and Magnus Benzie (2018). "Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk". *Global Environmental Change* 52, pp. 75–85. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378017312505 (visited on 02/29/2024).

IMF (2022). *Economic Principles for Integrating Adaptation to Climate Change into Fiscal Policy*. Tech. rep. URL: https://www.imf.org/-/media/Files/Publications/Staff-Climate-Notes/2022/English/CLNEA2022001.ashx.

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Tech. rep.

— (2022). *Climate Change 2022. Impacts, Adaptation and Vulnerability*. Tech. rep.

— (2023). *Climate Change 2023 – Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Tech. rep. Intergovernmental Panel on Climate Change (IPCC). URL: https://www.ipcc.ch/report/ar6/syr/ (visited on 06/27/2025).

Jadhav, Rajendra, Mayank Bhardwaj, and Shivam Patel (2023). "India imposes major rice export ban, triggering inflation fears". *Reuters*. URL: https://www.reuters.com/markets/commodities/india-prohibits-export-non-basmati-white-rice-notice-2023-07-20/?utm_source=chatgpt.com.

Janssens, Charlotte, Petr Havlík, Tamás Krisztin, Justin Baker, Stefan Frank, Tomoko Hasegawa, et al. (2020). "Global hunger and climate change adaptation through international trade". *Nature Climate Change* 10.9, pp. 829–835. URL: https://www.nature.com/articles/s41558-020-0847-4 (visited on 08/22/2023).

— (2021). "International trade is a key component of climate change adaptation". *Nature Climate Change* 11.11, pp. 915–916. URL: https://www.nature.com/articles/s41558-021-01201-8 (visited on 11/09/2022).

Kalkuhl, Matthias and Leonie Wenz (2020). "The impact of climate conditions on economic production. Evidence from a global panel of regions". *Journal of Environmental Economics and Management* 103, p. 102360. URL: https://linkinghub.elsevier.com/retrieve/pii/S0095069620300838 (visited on 01/10/2024).

Kemp, Luke, Chi Xu, Joanna Depledge, Kristie L. Ebi, Goodwin Gibbins, Timothy A. Kohler, et al. (2022). "Climate Endgame: Exploring catastrophic climate change scenarios". *Proceedings of the National Academy of Sciences* 119.34, e2108146119. URL: https://pnas.org/doi/full/10.1073/pnas.2108146119 (visited on 03/06/2023).

Khan, Mizan R. and Sirazoom Munira (2021). "Climate change adaptation as a global public good: implications for financing". *Climatic Change* 167.3-4, p. 50. URL: https://link.springer.com/10.1007/s10584-021-03195-w (visited on 08/10/2023).

Koks, Elco E., M. Bočkarjova, H. de Moel, and J. C. J. H. Aerts (2015). "Integrated Direct and Indirect Flood Risk Modeling: Development and Sensitivity Analysis: Integrated Direct and Indirect Flood Risk Modeling". *Risk Analysis* 35.5, pp. 882–900. URL: https://onlinelibrary.wiley.com/doi/10.1111/risa.12300 (visited on 02/01/2023).

Koks, Elco E., M Thissen, L Alfieri, H De Moel, L Feyen, B Jongman, et al. (2019). "The macroeconomic impacts of future river flooding in Europe". *Environmental Research Letters* 14.8, p. 084042. URL: https://iopscience.iop.org/article/10.1088/1748-9326/ab3306 (visited on 08/09/2023).

Koks, Elco E. and Mark Thissen (2016). "A Multiregional Impact Assessment Model for disaster analysis". *Economic Systems Research* 28.4, pp. 429–449. URL: https://www.tandfonline.com/doi/full/10.1080/09535314.2016.1232701 (visited on 08/23/2023).

Koomey, Jonathan (2013). "Moving beyond benefit–cost analysis of climate change". *Environmental Research Letters* 8.4, p. 041005. URL: https://iopscience.iop.org/article/10.1088/1748-9326/8/4/041005 (visited on 06/24/2025).

Kotz, Maximilian, Anders Levermann, and Leonie Wenz (2024). "The economic commitment of climate change". *Nature* 628.8008, pp. 551–557. URL: https://www.nature.com/articles/s41586-024-07219-0 (visited on 12/12/2024).

Kuhla, Kilian, Sven Norman Willner, Christian Otto, Tobias Geiger, and Anders Levermann (2021). "Ripple resonance amplifies economic welfare loss from weather extremes". *Environmental Research Letters* 16.11, p. 114010. URL: https://iopscience.iop.org/article/10.1088/1748-9326/ac2932 (visited on 11/07/2023).

Langholtz, Matthew, Erin Webb, Benjamin L. Preston, Anthony Turhollow, Norman Breuer, Laurence Eaton, et al. (2014). "Climate risk management for the U.S. cellulosic biofuels supply chain". *Climate Risk Management* 3, pp. 96–115. URL: https://linkinghub.elsevier.com/retrieve/pii/S2212096314000199 (visited on 01/28/2024).

Lecocq, Franck, Stéphane Hallegatte, and Christian De Perthuis (2011). *Designing climate change adaptation policies: An economic framework*. World Bank. URL: https://hdl.handle.net/10986/3335 (visited on 04/17/2025).

Lenzen, Manfred, Keiichiro Kanemoto, Daniel Moran, and Arne Geschke (2012). "Mapping the Structure of the World Economy". *Environmental Science & Technology* 46.15, pp. 8374–8381. URL: https://pubs.acs.org/doi/10.1021/es300171x (visited on 03/27/2024).

Mejean, Isabelle and Pierre Rousseaux (2024). "Identifying European trade dependencies". *Europe's economic security: in collaboration with Bruegel*. Paris report 2. London, UK: CEPR Press, pp. 49–99.

Miller, Ronald E and Peter D Blair (2009). "Input–Output Analysis: Foundations and Extensions, Second Edition".

Ministère de l'Ecologie, du Développement Durable, des Transports et du Logement (2011). *1er Plan national d'adaptation au changement climatique (2011-2015)*. Tech. rep. URL: https://www.ecologie.gouv.fr/sites/default/files/documents/ONERC_PNACC_1_complet.pdf.

Ministère de la Transition Écologique (2022). *Evaluation à mi-parcours du PNACC-2*. Tech. rep. URL: https://www.ecologie.gouv.fr/sites/default/files/documents/Evaluation%20%C3%A0%20mi-parcours%20du%20PNACC-2.pdf.

— (2025). *3e Plan national d'adaptation au changement climatique (2025-2029)*. Tech. rep. URL: https://www.ecologie.gouv.fr/sites/default/files/documents/PNACC3.pdf.

Ministère de la Transition écologique et de la Cohésion des territoires (2024). "Fonds vert, les collectivités s'adaptent au changement climatique". URL: https://www.ecologie.gouv.fr/presse/dossier-presse-fonds-vert-collectivites-sadaptent-changement-climatique.

Ministère de la Transition Écologique et Solidaire (2018). *2e Plan national d'adaptation au changement climatique (2018-2022)*. Tech. rep. URL: https://www.ecologie.gouv.fr/sites/default/files/documents/2018.12.20_PNACC2.pdf.

Morgan, Edward A., Johanna Nalau, and Brendan Mackey (2019). "Assessing the alignment of national-level adaptation plans to the Paris Agreement". *Environmental Science & Policy* 93, pp. 208–220. URL: https://linkinghub.elsevier.com/retrieve/pii/S1462901118306592 (visited on 09/17/2024).

Morris, Jennifer, Steven K. Rose, John Reilly, Angelo Gurgel, Sergey Paltsev, and C. Adam Schlosser (2025). "Reconciling widely varying estimates of the global economic impacts from climate change". *Nature Climate Change* 15.2, pp. 124–127. URL: https://www.nature.com/articles/s41558-024-02232-7 (visited on 03/06/2025).

Mullan, Michael, Nicholas Kingsmill, Arnoldo Matus Kramer, and Shardul Agrawala (2013). *National Adaptation Planning: Lessons from OECD Countries*. OECD Environment Working Papers 54. URL: https://www.oecd.org/en/publications/national-adaptation-planning_5k483jpfpsq1-en.html (visited on 06/25/2025).

Nakano, Katsuyuki (2017). "Screening of climatic impacts on a country's international supply chains: Japan as a case study". *Mitigation and Adaptation Strategies for Global Change* 22.4, pp. 651–667. URL: http://link.springer.com/10.1007/s11027-015-9692-6 (visited on 10/31/2023).

— (2021). "Risk assessment for adaptation to climate change in the international supply chain". *Journal of Cleaner Production* 319, p. 128785. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959652621029838 (visited on 09/28/2023).

Neal, Timothy, Ben R Newell, and Andy Pitman (2025). "Reconsidering the macroeconomic damage of severe warming". *Environmental Research Letters* 20.4, p. 044029. URL: https://iopscience.iop.org/article/10.1088/1748-9326/adbd58 (visited on 04/23/2025).

Nordhaus, William D. (1991). "To Slow or Not to Slow: The Economics of The Greenhouse Effect". *The Economic Journal* 101.407, p. 920. URL: https://academic.oup.com/ej/article/101/407/920-937/5188437 (visited on 06/24/2025).

OECD (2023). *Global value chain dependencies under the magnifying glass*. OECD Science, Technology and Industry Policy Papers 142. URL: https://www.oecd-ilibrary.org/science-and-technology/global-value-chain-dependencies-under-the-magnifying-glass_b2489065-en (visited on 11/01/2023).

Onerc (2006). *Stratégie nationale d'adaptation au changement climatique*. La Documentation française. URL: https://www.ecologie.gouv.fr/sites/default/files/documents/ONERC_Rapport_2006_Strategie_Nationale_WEB.pdf.

Ortiz-Bobea, Ariel (2021). "The empirical analysis of climate change impacts and adaptation in agriculture". *Handbook of Agricultural Economics*. Vol. 5. Elsevier, pp. 3981–4073. URL: https://linkinghub.elsevier.com/retrieve/pii/S1574007221000025 (visited on 06/27/2025).

Otto, C., S.N. Willner, L. Wenz, K. Frieler, and A. Levermann (2017). "Modeling loss-propagation in the global supply network: The dynamic agent-based model acclimate". *Journal of Economic Dynamics and Control* 83, pp. 232–269. URL: https://linkinghub.elsevier.com/retrieve/pii/S0165188917301744 (visited on 08/09/2023).

Parajuli, Ranjan, Greg Thoma, and Marty D. Matlock (2019). "Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: A review". *Science of The Total Environment* 650, pp. 2863–2879. URL: https://linkinghub.elsevier.com/retrieve/pii/S0048969718338920 (visited on 01/28/2024).

Pietrapertosa, Filomena, Marta Olazabal, Sofia G. Simoes, Monica Salvia, Paris A. Fokaides, Byron I. Ioannou, et al. (2023). "Adaptation to climate change in cities of Mediterranean Europe". *Cities* 140, p. 104452. URL: https://linkinghub.elsevier.com/retrieve/pii/S0264275123002640 (visited on 06/25/2025).

Piontek, Franziska, Laurent Drouet, Johannes Emmerling, Tom Kompas, Aurélie Méjean, Christian Otto, et al. (2021). "Integrated perspective on translating biophysical to economic impacts of climate change". *Nature Climate Change* 11.7, pp. 563–572. URL: http://www.nature.com/articles/s41558-021-01065-y (visited on 04/06/2022).

Piontek, Franziska, Matthias Kalkuhl, Elmar Kriegler, Anselm Schultes, Marian Leimbach, Ottmar Edenhofer, et al. (2019). "Economic Growth Effects of Alternative Climate Change Impact Channels in Economic Modeling". *Environmental and Resource Economics* 73.4, pp. 1357–1385. URL: http://link.springer.com/10.1007/s10640-018-00306-7 (visited on 06/25/2025).

Rising, James, Charlotte Taylor, Matthew C. Ives, and Robert E.T. Ward (2022). "Challenges and innovations in the economic evaluation of the risks of climate change". *Ecological Economics* 197, p. 107437. URL: https://linkinghub.elsevier.com/retrieve/pii/S0921800922000994 (visited on 03/22/2023).

Rising, James, Marco Tedesco, Franziska Piontek, and David A. Stainforth (2022). "The missing risks of climate change". *Nature* 610.7933, pp. 643–651. URL: https://www.nature.com/articles/s41586-022-05243-6 (visited on 04/17/2023).

Romanello, Marina, Maria Walawender, Shih-Che Hsu, Annalyse Moskeland, Yasna Palmeiro-Silva, Daniel Scamman, et al. (2024). "The 2024 report of the Lancet Countdown on health and climate change: facing record-breaking threats from delayed action". *The Lancet* 404.10465, pp. 1847–1896. URL: https://linkinghub.elsevier.com/retrieve/pii/S0140673624018221 (visited on 06/27/2025).

Schenker, Oliver (2013). "Exchanging Goods and Damages: The Role of Trade on the Distribution of Climate Change Costs". *Environmental and Resource Economics* 54.2, pp. 261–282. URL: http://link.springer.com/10.1007/s10640-012-9593-z (visited on 08/22/2023).

Simpson, Nicholas P., Katharine J. Mach, Andrew Constable, Jeremy Hess, Ryan Hogarth, Mark Howden, et al. (2021). "A framework for complex climate change risk assessment". *One Earth* 4.4, pp. 489–501. URL: https://linkinghub.elsevier.com/retrieve/pii/S2590332221001792 (visited on 08/08/2023).

Stadler, Konstantin, Richard Wood, Tatyana Bulavskaya, Carl-Johan Södersten, Moana Simas, Sarah Schmidt, et al. (2018). "EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables: EXIOBASE 3". *Journal of Industrial Ecology* 22.3, pp. 502–515. URL: https://onlinelibrary.wiley.com/doi/10.1111/jiec.12715 (visited on 05/08/2023).

Steiger, Robert, Daniel Scott, Bruno Abegg, Marc Pons, and Carlo Aall (2019). "A critical review of climate change risk for ski tourism". *Current Issues in Tourism* 22.11, pp. 1343–1379. URL: https://www.tandfonline.com/doi/full/10.1080/13683500.2017.1410110 (visited on 06/27/2025).

Stern, Nicholas (2006). "Stern Review: The economics of climate change".

Strydhorst, Natasha A. (2025). "A temperature check on climate communication: where are we?" *Humanities and Social Sciences Communications* 12.1, p. 276. URL: https://www.nature.com/articles/s41599-025-04585-6 (visited on 06/29/2025).

Sun, Yida, Shupeng Zhu, Daoping Wang, Jianping Duan, Hui Lu, Hao Yin, et al. (2024). "Global supply chains amplify economic costs of future extreme heat risk". *Nature*. URL: https://www.nature.com/articles/s41586-024-07147-z (visited on 03/21/2024).

Talebian, Sara, Magnus Benzie, Katy Harris, Łukasz Jarząbek, Piotr Magnuszewski, Timothy R. Carter, et al. (2025). "A conceptual framework for responding to cross-border climate change impacts". *Environmental Science & Policy* 163, p. 103949. URL: https://linkinghub.elsevier.com/retrieve/pii/S1462901124002831 (visited on 06/26/2025).

UNFCCC and LDC Expert Group (2012). *National Adaptation Plans. Technical guidelines for the national adaptation plan process*. Tech. rep. URL: https://unfccc.int/sites/default/files/resource/NAP_technical_guidelines_EN.pdf.

United Nations Environment Programme, Maria Del Pilar Bueno Rubial, Alexandre Magnan, Lars Christiansen, Henry Neufeldt, Anne Hammill, et al. (2024). *Adaptation Gap Report 2024: Come hell and high water - As fires and floods hit the poor hardest, it is time for the world to step up adaptation actions*. United Nations Environment Programme. URL: https://wedocs.unep.org/20.500.11822/46497 (visited on 06/05/2025).

University of Notre Dame Adaptation Initiative (2023). *Country Index Technical Report*. Tech. rep. URL: https://gain.nd.edu/assets/522870/nd_gain_countryindextechreport_2023_01.pdf.

USGCRP, Allison R. Crimmins, Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Brooke C. Stewart, et al. (2023). *Fifth National Climate Assessment*. Tech. rep. U.S. Global Change Research Program. URL: https://nca2023.globalchange.gov/ (visited on 06/20/2025).

Verschuur, Jasper, Nicola Ranger, and Jim. W. Hall (2025). "Climate adaptation finance: From paper commitments to climate risk reduction". *Science* 388.6754, pp. 1374–1377. URL: https://www.science.org/doi/10.1126/science.adx1950 (visited on 07/09/2025).

Viguié, Vincent, Aude Lemonsu, Stéphane Hallegatte, Anne-Lise Beaulant, Colette Marchadier, Valéry Masson, et al. (2020). "Early adaptation to heat waves and future reduction of air-conditioning energy use in Paris". *Environmental Research Letters* 15.7, p. 075006. URL: https://iopscience.iop.org/article/10.1088/1748-9326/ab6a24 (visited on 07/10/2025).

Wang, Bo-Wen, Yi He, Wen-Hao Wu, and Fei Teng (2025). "Quantifying indirect economic losses from extreme events to inform global and local adaptation strategies". *Advances in Climate Change Research* 16.4, pp. 674–687. URL: https://linkinghub.elsevier.com/retrieve/pii/S1674927825001509 (visited on 10/25/2025).

Warren, R. F., R. L. Wilby, K. Brown, P. Watkiss, Richard A. Betts, James M. Murphy, et al. (2018). "Advancing national climate change risk assessment to deliver national adaptation plans". *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376.2121, p. 20170295. URL: https://royalsocietypublishing.org/doi/10.1098/rsta.2017.0295 (visited on 11/06/2023).

Watkiss, Paul and Richard Betts (2021). *The Third UK Climate Change Risk Assessment Technical Report. Method*. Tech. rep. London: Climate Change Committee. URL: https://www.ukclimaterisk.org/publications/technical-report-ccra3-ia/chapter-2/.

Weitzman, Martin L. (2011). "Fat-Tailed Uncertainty in the Economics of Catastrophic Climate Change". *Review of Environmental Economics and Policy* 5.2, pp. 275–292. URL: https://www.journals.uchicago.edu/doi/10.1093/reep/rer006 (visited on 03/24/2023).

Wenz, Leonie and Anders Levermann (2016). "Enhanced economic connectivity to foster heat stress–related losses". *Science Advances* 2.6, e1501026. URL: https://www.science.org/doi/10.1126/sciadv.1501026 (visited on 09/29/2023).

Wenz, Leonie and Sven Norman Willner (2022). "Climate impacts and global supply chains: an overview". *Handbook on Trade Policy and Climate Change*. Edward Elgar Publishing. URL: https://www.elgaronline.com/view/edcoll/9781839103230/9781839103230.xml (visited on 06/26/2025).

Willner, Sven Norman, Christian Otto, and Anders Levermann (2018). "Global economic response to river floods". *Nature Climate Change* 8.7, pp. 594–598. URL: https://www.nature.com/articles/s41558-018-0173-2 (visited on 08/09/2023).

Woodruff, Sierra C. and Patrick Regan (2019). "Quality of national adaptation plans and opportunities for improvement". *Mitigation and Adaptation Strategies for Global Change* 24.1, pp. 53–71. URL: http://link.springer.com/10.1007/s11027-018-9794-z (visited on 11/03/2023).

Yan, Lingxiao (2024). "National adaptation plans". *Nature Climate Change* 14.9, pp. 896–896. URL: https://www.nature.com/articles/s41558-024-02124-w (visited on 06/25/2025).

Zappalà, Guglielmo (2023). "Sectoral Impact and Propagation of Weather Shocks". *IMF Working Papers* 2023.053, p. 1. URL: https://elibrary.imf.org/openurl?genre=journal&issn=1018-5941&volume=2023&issue=053 (visited on 06/16/2025).

Chapter 1

When the costs of climate change impacts do not add up: do local policy assessments align with global macroeconomic insights? A case study of France

In review at Environmnetal Research Letters.
Joint work with Vincent Viguié (CIRED).

Abstract

Climate change is expected to cause increasingly severe economic and social disruptions, making adaptation a key pillar of climate policy. Assessing the economic costs of climate impacts is essential to inform adaptation strategies, especially when these costs are used to calibrate the scale of adaptation investments and to weigh adaptation needs against other policy priorities. Yet, estimates of these costs vary widely across studies. Here we compare the estimated economic cost of climate change for France across two lines of evidence: international macroeconomic studies and national policy documents. We find that recent macroeconomic literature, especially econometric studies, produces much higher cost estimates than those that can be inferred from aggregating national policy assessments. This discrepancy can be attributed to methodological lag, limited sectoral coverage, lack of monetization, and the omission of cross-border effects. Besides, we also show that while the national institutional literature is extensive, many broad impact categories lack comprehensive quantification, and even fewer are monetized.

Keywords: Climate change impacts, Economic cost of climate change, Climate adaptation, National climate change risk assessment, France.

Contents

1 Introduction **25**
2 Data and methods **26**
2.1 Global macroeconomic studies 27
2.2 National institutional literature 27
3 Results **28**
3.1 Global macroeconomic studies 28
3.2 National institutional literature 30
4 Discussion and conclusion **35**
5 References **37**
A Studies reviewed **45**
A.1 Global macroeconomic studies 45
A.2 National institutionnal literature 47
B Additional figures **50**
C Quantification and monetization **53**

1 Introduction

Climate change is already underway and its impacts are expected to intensify, making adaptation measures essential (Forster et al., 2025; IPCC, 2023). In this context, the question of whether current adaptation efforts are sufficient is regularly raised. There is growing evidence of delays or gaps in adaptation (United Nations Environment Programme et al., 2024), even in high-income countries (European Environment Agency, 2024). One contributor to this adaptation gap is the persistent uncertainty surrounding the assessment of the economic and socio-economic costs of climate impacts. Indeed, these costs are often weighed against the investments and budgetary efforts required for adaptation (Bachner, Bednar-Friedl, et al., 2019; Haasnoot et al., 2020; IMF, 2022)—whether at the global (Bachner, Lincke, et al., 2022), continental (Dottori et al., 2023) or local scale (Avdeenko et al., 2025; Hyyrynen et al., 2025)—to help choose the best adaptation solutions. Underestimating climate impacts may lead to underinvestment in adaptation, whereas overestimating them could result in overinvestment in specific sectors. In fact, several of the barriers to adaptation identified by the IPCC are coherent with an underestimation of climate impacts, such as the limited involvement of the private sector and the general public, the lack of sustained political will or a low perceived sense of urgency (IPCC, 2023).

At the international level, the assessment of climate change impacts has given rise to a large macroeconomic literature, yielding highly contrasting results depending on the evaluation method used (econometric or process-based) (IPCC, 2023; Morris et al., 2025; Piontek, Drouet, et al., 2021). At the national level, numerous sectoral or macroeconomic assessments of the costs induced by climate change have been conducted. In France, for instance, these studies are carried out either by private actors (such as insurance companies, eg. France Assureurs, 2021) or by public institutions as part of the evaluation or design of national adaptation policies (e.g.

hydrological projections, Inrae et al., 2024). They may draw on data from the international literature or rely on ad hoc assessment exercises. The climate change costs reported in this institutional literature reflect the perceived significance of climate risk for national stakeholders. How do these cost estimates compare with those found in the broader macroeconomic literature discussed above?

Here, we focus on the case of France, a high-income country with a climate change adaptation strategy, in place for almost two decades, which led to a succession of three operational adaptation plans (Onerc, 2006; Ministère de l'Ecologie, du Développement Durable, des Transports et du Logement, 2011; Ministère de la Transition Écologique et Solidaire, 2018; Ministère de la Transition Écologique, 2025). During this process, several sectoral assessments of the costs of climate change impacts have been conducted (see Ministère de la Transition Écologique, 2022). We review the national institutional literature and examine how the aggregated cost estimates emerging from these studies compare with the evaluations of climate change impacts on France found in the global macroeconomic assessments.

We find that climate change costs for France, as assessed in the global macroeconomic literature, are characterized by a wide range of uncertainty. National institutional assessments fall within this range. We find however a substantial gap between national institutional assessments and the most recent macroeconomic studies. In particular, studies published after 2018 suggest, using econometric methods, that climate change could lead to substantial economic losses for France—sometimes above, or even well above, 5% of GDP. Such figures are not found in earlier work and are much higher than the estimates in the national institutional assessments. Several factors may explain this discrepancy: institutional assessments have been developed over a longer period and may be methodologically outdated; they do not monetize all impact channels; conversely, some econometric approaches may overestimate climate costs for France (see discussion in Morris et al., 2025). Understanding this gap is important, as it may help address the risk of underinvestment in climate adaptation.

Through this work, we contribute to the literature on the adaptation gap by analyzing how national stakeholders' perception of climate risk, as reflected in the estimation of impact costs presented in official documents, compare with that emerging from the international macroeconomic literature. We also contribute to the literature on the costs of climate change by showing that nationally produced documents—despite relying on more granular and context-specific data—do not necessarily help bridge the gap with recent econometric studies, which tend to produce the highest cost estimates.

2 Data and methods

We compare two types of estimates of the costs of climate change in France. On the one hand, we examine the values reported for France in global macroeconomic studies, which are primarily found in peer-reviewed international publications. On the other hand, we examine estimates from national institutional sources, meaning impact quantifications included in French sectoral

policy documents related to climate adaptation.

2.1 Global macroeconomic studies

Recent reviews of all the global macroeconomic studies on the costs of climate change impacts are available (IPCC, 2023; Piontek, Drouet, et al., 2021). Among all the studies reviewed, we selected those with results sufficiently disaggregated at the geographical level to include estimates for France or, at least, for Europe. We also conducted an additional search for relevant papers published after the reviews. In total, 21 studies were identified: 15 provide results specific to France, and 6 provide results at the European level. Each study may include multiple assessments—corresponding to different warming scenarios or to uncertainty analyses (e.g., across climate models). The studies span the period from 2012 to 2024 and cover projected additional warming above pre-industrial levels ranging from +1°C to +5°C (see Appendix A, Table 1.2 for a complete list).

2.2 National institutional literature

In the context of developing adaptation policies or solutions, documents quantifying future climate impacts are regularly produced. In particular, a substantial body of country-specific research has emerged for France, driven by the existence of a national adaptation plan since 2011 (Ministère de l'Ecologie, du Développement Durable, des Transports et du Logement, 2011). This body of work have been reviewed in 2009 (Onerc, 2009) and in 2023 (Delahais et al., 2023). This latest review examines the quantitative (monetized or not) assessments of climate risks available at the national level in France, as reported in adaptation planning and evaluation documents. As a result, it primarily draws on the "grey literature" produced by French public and private institutions. However, adaptation documents sometimes also refer to academic studies with a global scope but that provide specific estimates for France—such as Gasparrini et al. (2017) or Szewczyk et al. (2021). They have been included in the review as well.

Climate change impacts were classified into ten categories: water resources, agriculture, forestry, coastal risks, biodiversity, energy, infrastructure and networks, buildings, tourism and health. A total of 60 references were reviewed. To ensure comprehensiveness, the review was submitted for validation to an expert panel composed of representatives from the relevant ministries (see Appendix A, Table 1.3 for the full list of studies). Beyond these sectoral assessments, we identified one study that evaluates the multi-sectoral costs of climate change in France using a CGE model (Ademe, 2023). This study relies on global process-based impact assessments—some of which were also used in the 'global macroeconomic' category of studies—but employs an economic model with a particularly detailed representation of the French economy. Besides, the model was specifically adapted to more realistically capture the macroeconomic consequences of climate change impacts on the agricultural sector.

3 Results

3.1 Global macroeconomic studies

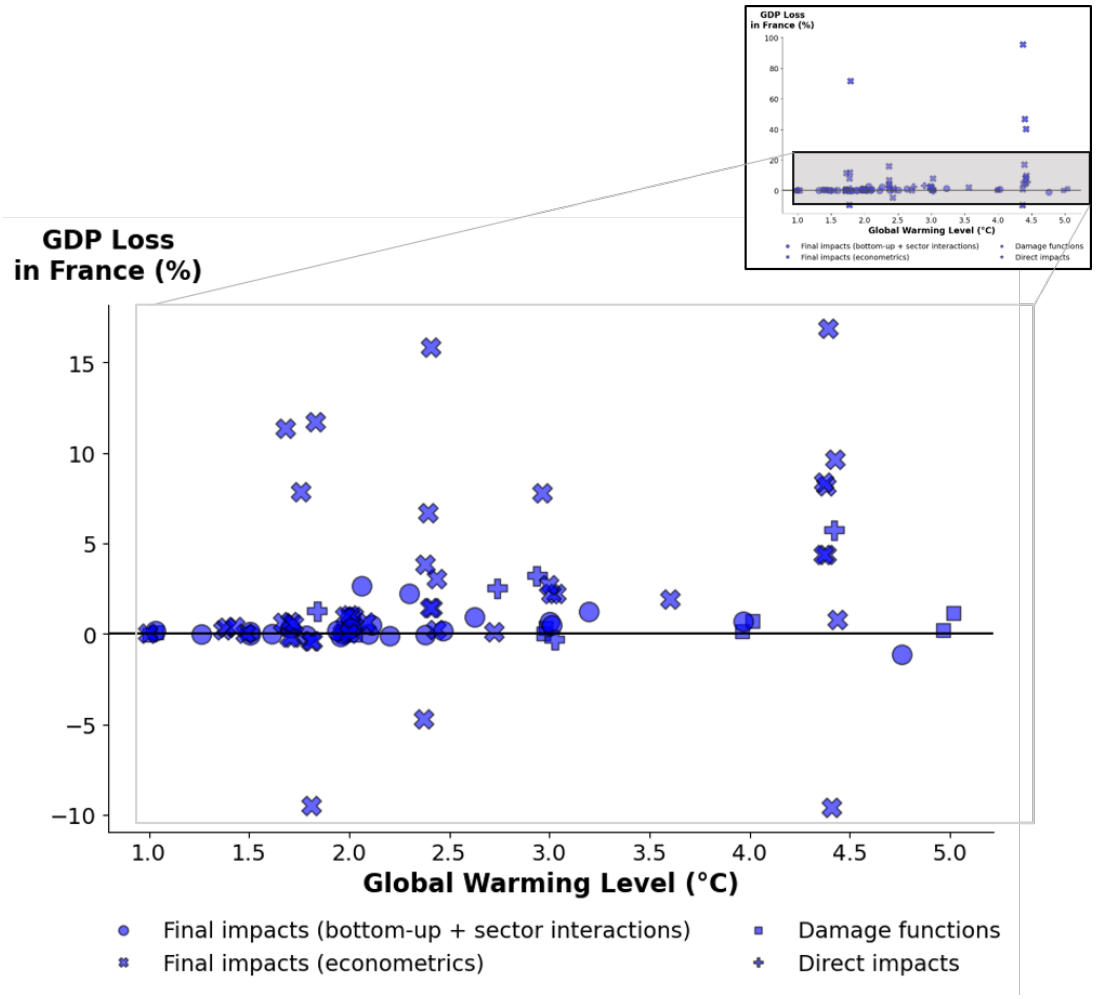
Global literature reviews on the global economic costs of climate change consistently find that, within a given study, higher levels of warming tend to result in higher estimated costs (IPCC, 2023). Figure 1.1 shows that this global pattern also applies if one focuses on the estimates for France: for instance, Kotz et al. (2024) find that the cost of climate change for France is 11% at +1.7°C and 46% at +4.4°C. Global literature reviews also reveal substantial variation across studies in the cost estimates for any given level of warming (Morris et al., 2025). The same is true at the French national level: at +4.4°C, corresponding to the median global warming level under SSP5-8.5 in 2100, estimates go from 0.8% (Mohaddes et al., 2024) to 95% (Neal et al., 2025). As with global estimates, the highest cost projections are derived from papers using a statistical approach (e.g. Kotz et al., 2024; Neal et al., 2025).

The publication years of the studies represented in Figure 1.1 range from 2012 to 2025. However, recent studies are likely to benefit from improved methodologies and data. Figure 1.2 illustrates how these estimates have changed over time. Prior to 2019, the estimated economic impact of climate change on France was typically small (less than 5% of GDP), or even suggested potential gains (e.g. Roson and Mensbrugghe, 2012). Since at least the Stern Report (2006), it has been recognized that the global costs of climate change could exceed 5% of GDP, although these impacts were initially expected to be concentrated primarily in low- and middle-income countries (Stern, 2006). France, as a high-latitude, high-income nation, was thought to be largely spared. However, as shown here, beginning around 2019, evidence emerged indicating this is no longer the case (e.g. Takakura et al., 2019). Some recent studies even suggest that climate change could have catastrophic effects on the French economy, with estimated losses as high as 47% in Kotz et al. (2024) and 95% in Neal et al. (2025). However, it is important to note that these results are based on the high-end warming scenario SSP5-8.5, which is increasingly considered unlikely (Gillett, 2024). Figure 1.2 also shows that the variation across estimates of the cost of climate change has widened over time: while the range was -2% to +2% before 2018, it has expanded to span from -10% to +95% after 2018. This result also holds when controlling for the level of warming, although the effect is less pronounced (see in Appendix B, Figure 1.6).

Figure 1.3 provides an overview of the distribution of climate change costs for France within a 1°C range around 2°C, 3°C, and 4°C of warming relative to pre-industrial levels. The 2°C range includes the Paris Agreement targets as well as projected warming under the SSP1-2.6 scenario for 2050 and 2100. The 3°C range reflects expected warming under current business-as-usual trajectories. The 4°C range corresponds to SSP5-8.5 in 2100—a high-end warming scenario that remains possible but is considered unlikely under the current global trajectory. Focusing on the median estimated cost of climate change across the literature, we find that the cost is consistently positive—even though this is not self-evident for a high-latitude country like France—and increases with the level of warming: 0.08% at 2°C, 0.77% at 3°C, and 4.35% at 4°C. However, the median cost may not capture the full picture, given the wide dispersion in the cost

estimates. As shown in Figure 1.4, even within the +2°C warming scenario, the distribution is highly skewed: while some studies predict a gain of +0.4% of GDP for France, others estimate a loss of up to 23% (see also in Appendix B, Figure 1.7a for an indication of the studies involved).

Figure 1.1: The economic consequences of climate change for France, across warming scenarios (zoom on studies with loss of GDP below 20%)



Lecture: Each point represents a specific estimate of GDP loss. A single study may contribute multiple points, corresponding to different model specifications or warming levels. Studies are classified according to their methodology, following Piontek, Kalkuhl, et al. (2019), which is indicated by the shape of the point.

3.2 National institutional literature

Qualitative results

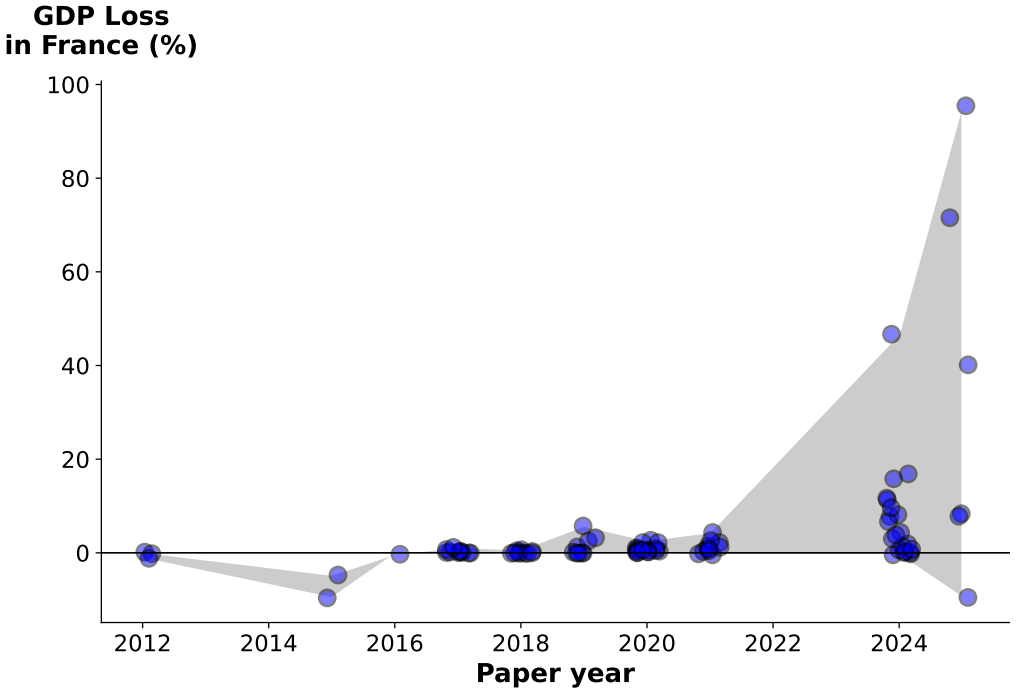
A total of 60 country-specific sectoral studies provide a quantified assessment of climate risk in the case of France. In other words, they go beyond qualitative evaluations by offering numerical estimates of potential impacts. This figure reflects the level of resources mobilized to enhance the understanding of climate-related risks. Studies are classified into ten impact categories: water resources, agriculture, forestry, coastal risks, biodiversity, energy, infrastructure and networks, buildings, tourism, and health. In each of these impact categories, there is at least one quantitative study. However, these studies may cover only a partial aspect of the category, so that only 4 out of 10 categories are comprehensively quantified. These are: water resources, coastal risks, energy and buildings (see in Appendix C, Table 1.3). For instance, regarding the 'energy' category, the electricity grid operator has published an assessment of the impacts of climate change on electricity supply and demand (RTE, 2021), and insurance companies have produced multiple evaluations of climate change effects on buildings (Covéa et al., 2022; France Assureurs, 2021). By contrast, regarding the 'infrastructure and networks' category, the effects of climate change have been assessed for some types of infrastructure (such as transport and electricity), but not for others (such as telecommunications) (Carbone4, 2021).

However, even these quantifications are fragile. First, some are subject to high uncertainties according to the studies themselves. For example, due to remaining uncertainties around hydrological impacts, current estimates of climate change consequences for nuclear and hydroelectric production are regarded by the authors as preliminary and in need of further refinement (RTE, 2021). Second, studies sometimes contradict each other on the magnitude of the impact. For instance, estimates of the number of homes at risk from sea level rise, for instance, vary widely: one projects 90 homes at risk on the Aquitaine coast by 2040 (Cerema, 2020), while another projects 1,541 homes at risk as early as 2025 (IgA et al., 2019). Finally, some results have been called into question in light of recent natural disasters. In 2022, for example, insured losses related to clay shrink-swell phenomena reached €3.3 billion (France Assureurs, 2023), compared to a mean annual cost of €1.4 billion projected for the period 2020–2050 in earlier studies (France Assureurs, 2021).

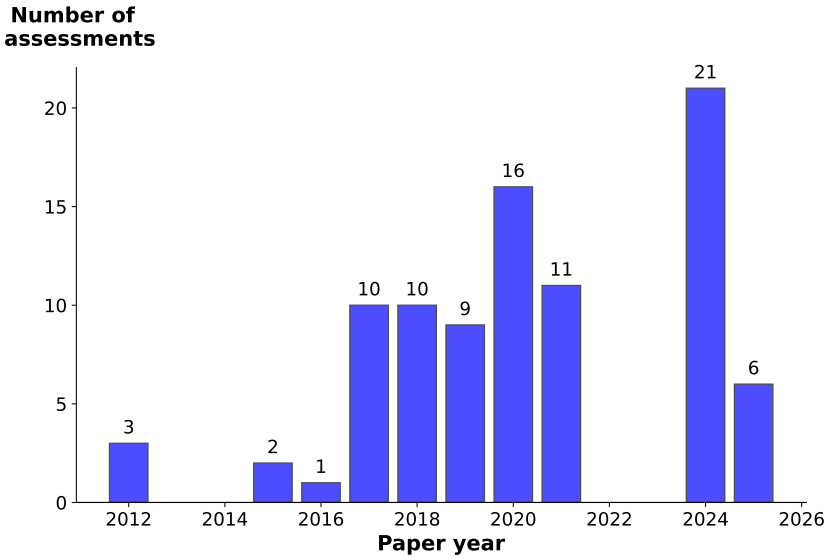
It should be noted that even when quantification is comprehensive, this does not necessarily imply that the results are monetized. Only two out of ten categories—buildings and coastal risks—are monetized in a comprehensive manner (see in Appendix C, Table 1.4). For instance, assessments of damages to buildings are available in monetary terms (euros) (France Assureurs, 2021), whereas assessments of the effects of climate change on water availability typically stop at highly geographically disaggregated hydrological evaluations without making the associated economic implications explicit (Inrae et al., 2024). This is problematic because monetization can be important to prioritize adaptation needs, to conduct cost-benefit analyses of adaptation solutions or even to convey a sense of urgency.

Figure 1.2: Estimated economic cost of climate change in France, by year of study publication.

(a) Estimated economic cost of climate change in France, by year of study publication.

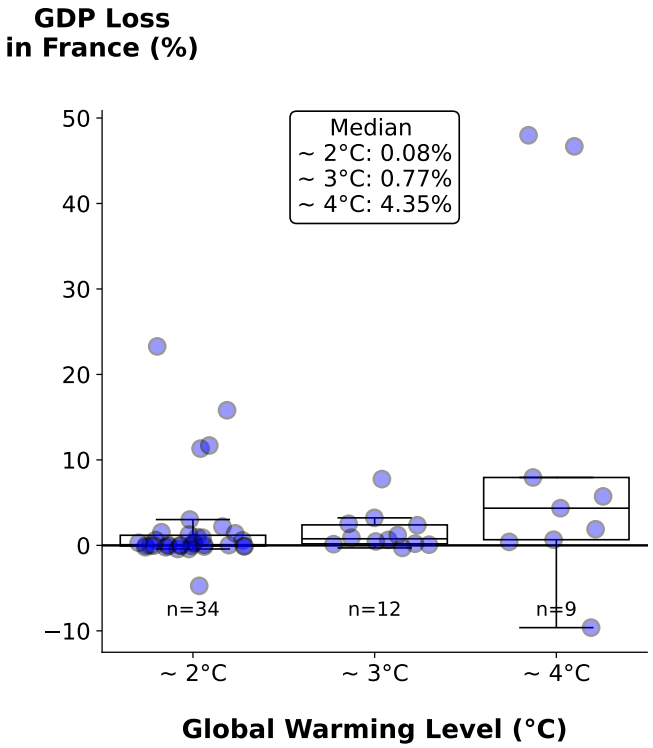


(b) Number of publications, by year of study publication.



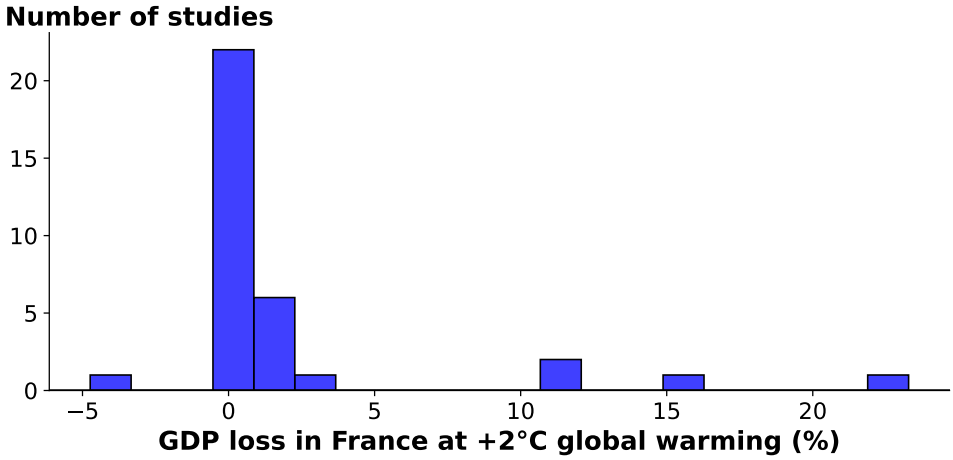
Lecture: Each point represents a specific estimate of GDP loss. A single study may contribute multiple points, corresponding to different model specifications and warming scenarios. The grey area indicates the space between the highest and lowest GDP loss reported in the literature for each year of publication. Negative values indicate a GDP gain relative to a no–climate change scenario. All warming scenarios are represented here.

Figure 1.3: Distribution of climate change costs for France at 2°C, 3°C, and 4°C.



Lecture: Each point represents the estimated GDP loss for France corresponding to a specific study and warming level. If a study provides multiple estimates for the same warming level, the point represents the arithmetic mean of those estimates. This approach prevents assigning undue weight to studies that include multiple assessments due to varying model specifications. Warming categories are defined as follows: 2°C = [1.5, 2.4], 3°C = [2.5, 3.4], and 4°C = [3.5, 4.4]. Boxplots indicate the median, the first and third quartiles; whiskers extend to the most extreme data points within 1.5 times the interquartile range.

Figure 1.4: Asymmetry in the cost distribution at 2°C.



Lecture: If a study provides multiple estimates for the same warming level, only the arithmetic mean of those estimates is counted here. This approach prevents assigning undue weight to studies that include multiple assessments due to varying model specifications. The 2°C range includes the Paris Agreement targets (+2°C) as well as projected warming under the SSP1-2.6 scenario for 2050 (1,7°C) and 2100 (1.8°C).

Finally, some important dimensions of climate change impacts remain overlooked, notably cross-border risks and inequalities in exposure and vulnerability. Cross-border risks refer to the transmission of climate impacts across national boundaries, for instance through disruptions in trade, migration, or financial systems (Carter et al., 2021). These dimensions are almost systematically overlooked in these strictly country-level risk assessments. Similarly, disparities in exposure and vulnerability—both geographical and socioeconomic—are not systematically documented across impact categories.

Quantitative results

In Table 1.2, we aggregate the costs reported in the various studies across ten categories of impacts. In some cases, only physical (non-monetary) assessments—such as hydrological variables or agricultural yields—are available, and thus no monetary valuation is provided. All these studies are based on climate projections, generally following the Representative Concentration Pathway 8.5 (RCP8.5) scenario, but focus on impacts expected by 2050, corresponding to an average warming of approximately +2.0°C (IPCC, 2021). The costs, expressed in current euros based on the economic characteristics of the 2020s, are related to the 2021 GDP—the most recent precise estimate—in order to express them in relative terms.

The impacts presented here are both economic and socio-economic, incorporating, for instance, the valuation of carbon and the statistical value of life. Taking into account all socio-economic costs, the cost of climate change for France amounts to 1.96% of GDP; when considering only strictly economic costs (i.e. excluding health and carbon sinks), it is 1.14% of GDP. It appears that risks related to health (mortality induced by heatwaves) and to labor productivity account for a major share of the estimated costs. This finding is consistent with assessments conducted at the European continental scale as well as in the United States (Ciscar et al., 2019). However, the absence of quantified costs for sectors such as tourism (3,6% of French GDP in 2022), and water scarcity—one of the main risks identified for Europe (IPCC, 2023)—already constitutes a major limitation.

So far, all the studies reviewed in this section are sectoral. However, one analysis has been conducted at the national level in France, accounting for a wide range of sectoral impacts (16 overall) and incorporating them into an economic model to assess not only direct impacts but also indirect macroeconomic effects (Ademe, 2023). The study uses a climate scenario close to SSP3-7.0, reaching a warming level of 2.1°C around 2050 and 3.5°C by the end of the century. For 2050, the estimated cost of climate change in France is 6.3% of GDP, with 4.2% resulting from impacts on international supply chains and 2.1% from domestic impacts within French territory (notably agriculture and natural disasters).

Comparing both sources

Two types of literature have been mobilized for this review: (i) global macroeconomic studies, (ii) assessments mentioned in the French national institutional literature. Since the second type of estimates primarily focus on a +2°C warming horizon around 2050, we adopt this level of warming and time frame to compare the three lines of evidence. When comparing the aggregate

cost of climate change in France, we find that global macroeconomic studies yield the lowest estimates (with a median loss of 0.08% of GDP), followed by the aggregation of the national institutional sectoral literature (1.14%), and finally the single macroeconomic national study, which estimates a cost of 6.3%, including a domestic component of 2.1%. It should be noted, however, that global macroeconomic studies display a high degree of variability, with some estimates—particularly those based on statistical methods—reaching up to a loss of 11.7% (Kotz et al., 2024), or even as high as 72% under a specific model specification of Neal et al. (2025). Besides, even when aggregate costs appear relatively similar, the sectoral composition can differ profoundly. For instance, the Ademe study reports 2.1% in domestic costs, primarily driven by natural disasters and agriculture, whereas the local sectoral studies estimating a 1.14% cost are mainly driven by impacts on labor productivity (Ademe, 2023).

Table 1.1: Aggregation of bottom-up cost estimates from country-specific sectoral studies

Sector	Cost: € billion per year in 2050 (Source)	Cost: % of 2021 GDP
Water resources	NA	NA
Agriculture	Projected crop losses: €1bn/year (CGAAER, 2022)	0.04%
Forestry	NA	NA
Coastal Risks	Coastal floods: €0.21bn/year (France Assureurs, 2021)	0.008%
Biodiversity	Social cost due to loss of carbon sinks: €0.61bn/year (CGDD, 2019)	0.02%
Energy	NA	NA
Infrastructures & networks	€1.6bn/year (Carbone4, 2021)	0.06%
Buildings	Continental floods: €0.10bn/year Shrink–Swell: €0.57bn/year (France Assureurs, 2023)	0.03%
Tourism	NA	NA
Health	Mortality due to heat waves (value of a statistical life): €20bn/year (Gasparrini et al., 2017)	0.80%
	Labor productivity: €25bn/year (Szewczyk et al., 2021)	1%
Socioeconomic cost		**1.96%**
Economic cost		**1.14%**

Lecture: NA = Not Assessed. Productivity losses have been included under the "Health" category; however, they represent an impact that affects all sectors of the economy. According to the French national statistical institute (INSEE), the most recent semi-final value of French GDP is for 2021, amounting to €2,498 billion. Regarding the biodiversity impact category, only the social costs associated with the loss of carbon sinks are available: 2.5 billion tons of CO_2, corresponding to €0.610 billion per year, assuming a 2% discount rate and a carbon price of €775 per ton in 2050 (Quinet, 2019). Economic costs correspond to all sectoral assessments, excluding mortality due to heatwaves and the social cost associated with the loss of carbon sinks.

4 Discussion and conclusion

To sum up, we have shown that the national institutional literature contains many references providing quantitative information on the impacts of climate change on the French national territory. However, these references are not exhaustive and are rarely monetized. This result highlights the difficulty of obtaining a precise bottom-up overview of the economic impacts of climate change on a country—even one that is high-income and has long engaged in adaptation planning. However, this situation is not universal, as some countries have developed more systematic assessments of climate change impacts, such as the UK Climate Change Committee reports (Climate Change Committee, 2021; Paul Watkiss Associates, 2021) or the US National Climate Assessment (USGCRP et al., 2023), aiming at a broad quantification and monetization of climate damages.

In addition, we explored the estimated costs of climate change for France as reported in the international macroeconomic literature. First, we observe here that focusing on a single country does not necessarily reduce the uncertainty on the economic cost of climate change. As we noted in the introduction, there is considerable discrepancy in the global macroeconomic literature, regarding the economic costs of climate change for the world as a whole. This literature still displays considerable divergence even when focused on France, although one might have expected that the core of this global variability could lie in the consequences of climate change on low-income countries. Second, while estimated losses for France were relatively modest—or even suggested potential gains—for studies conducted prior to 2018, more recent studies have reported losses exceeding 5% of GDP. This comes more than a decade after such magnitudes were already established at the global level in the Stern Review (Stern, 2006). Third, by comparing our two sources of information, we find that the estimated economic cost of climate change for France according to the institutional literature appears higher than that suggested by the median of the global macroeconomic literature (1.19% or 6.3% versus 0.08% of GDP at around +2°C in 2050). However, there is a substantial gap between national institutional assessments and recent macroeconomic studies, which, using econometric methods, suggest that climate change could result in significant economic losses for France.

This comparison allows us to draw two broader conclusions. First, one of the major challenges in estimating the damages caused by climate change lies in the divergence between process-based models and econometric methods. One might expect that the inclusion of national climate risk assessments —relying on more granular and context-specific data—could help bridge the gap between process-based approaches and recent econometric studies, which tend to produce the highest cost estimates. Here, we see that local policy documents do not provide a bottom-up foundation for recent top-down macroeconomic assessments. Second, if aggregated local policy assessments suggest a lower cost of climate change than the macroeconomic literature, this may indicate that certain categories of impacts are either underestimated—or entirely omitted—in local assessments, or that the highest macroeconomic estimates may be overstated.

Several hypotheses could explain this gap and would warrant further investigation. First, as highlighted above, the absence of monetization for certain impact categories in local policy

documents may partially explain the gap; incorporating monetary values could help reduce it. Second, given that bottom-up studies span a longer period (from 2012 to 2021 in our review), due to the time required to build explicit sectoral impact models, there may be a methodological lag relative to the econometric literature, particularly regarding the treatment of climate modelling. Finally, cross-border impact propagation is considered a key factor explaining the gap between recent and earlier econometric estimates of the cost of climate change (Neal et al., 2025; Zappalà, 2023). However, it is not accounted for in the bottom-up policy literature, despite being a major component of Ademe's national macroeconomic study (Ademe, 2023). Future studies aiming to develop a bottom-up foundation for cross-border impact assessment would be particularly valuable.

Ultimately, the question arises as to whether using cost estimates is an appropriate basis for making decisions about adaptation. After all, we show here that the various lines of evidence regarding these costs can still be contradictory— both regarding their aggregate level and their sectoral distribution. Several studies highlight the intrinsic difficulty of assessing the costs of climate change, due to the challenge of capturing complex, cascading, and transboundary consequences of climate impacts (Simpson et al., 2021), as well as the presence of deep uncertainty surrounding future climate risks and socio-economic trajectories (Hallegatte, 2009). In practice, different estimates of climate change costs should be mobilized according to specific policy needs. The answer depends on the intended use of these cost estimates. If the objective is to anticipate worst-case scenarios, statistical studies clearly provide the highest cost estimates. If the goal is to conduct long-term macroeconomic projections incorporating the effects of climate change, the full range of uncertainty should be encompassed. If the purpose is to prioritize between adaptation projects, local policy documents are, in principle, more appropriate, as they rely on locally grounded data. However, as we have seen, these studies still do not cover all sectors, even in high-income countries such as France. Even when sectoral studies are available, the gap between the results of statistical studies and the aggregation of sectoral studies raises concerns about whether sectoral assessments fully capture indirect and cascading effects, which are often difficult to evaluate. In such cases, relying solely on sectoral studies could lead to under-investment in climate change adaptation. In any case, the need to regularly update sectoral studies is clear in order to move swiftly and remain aligned with the evolving climate and economic state of the art, especially since cost-benefit analysis remains part of the adaptation decision-making toolkit (IMF, 2022; UNFCC, 2022)—particularly in forms adapted to uncertain and flexible settings (Haasnoot et al., 2020).

5 References

Acevedo, Sebastian, Mico Mrkaic, Natalija Novta, Evgenia Pugacheva, and Petia Topalova (2020). "The Effects of Weather Shocks on Economic Activity: What are the Channels of Impact?" *Journal of Macroeconomics* 65, p. 103207. URL: https://linkinghub.elsevier.com/retrieve/pii/S0164070420301336 (visited on 01/06/2025).

Adélaïde, Lucie, Olivier Chanel, and Mathilde Pascal (2021). *Évaluation monétaire des effets sanitaires des canicules en France métropolitaine entre 2015 et 2020*. Tech. rep. 12. Santé publique France, pp. 215–233. URL: https://www.santepubliquefrance.fr/determinants-de-sante/climat/fortes-chaleurs-canicule/documents/article/evaluation-monetaire-des-effets-sanitaires-des-canicules-en-france-metropolitaine-entre-2015-et-2020.

Ademe (2012). *Livre vert du projet CLIMATOR (2007-2010). Changement climatique, agriculture et forêt en France : simulations d'impacts sur les principales espèces*. Tech. rep., p. 334. URL: https://www.adaptation-changement-climatique.gouv.fr/agir/espace-documentaire/livre-vert-du-projet-climator.

— (2022a). *État des lieux et étude prospective sur les impacts du changement climatique pour le bâtiment aux horizons 2050 et 2100. Se préparer, s'organiser et agir collectivement*. Tech. rep. URL: https://librairie.ademe.fr/urbanisme-et-batiment/5969-etat-des-lieux-et-etude-prospective-sur-les-impacts-du-changement-climatique-pour-le-batiment-aux-horizons-2050-et-2100.html.

— (2022b). *Feuilleton Transition(s) 2050. Adaptation au changement climatique : transports, agriculture, forêts, industries, bâtiments*. Tech. rep., p. 29. URL: https://transitions2050.ademe.fr/uploads/Feuilleton_adaptation_changement_climatique_transitions2050_ADEME.pdf.

— (2023). *Les risques climatiques et leurs coûts pour la France. Une évaluation macroéconomique*. Tech. rep., p. 68. URL: https://librairie.ademe.fr/changement-climatique/6712-les-risques-climatiques-et-leurs-couts-pour-la-france.html#.

ANCT (2021). *Accompagner en ingénierie les territoires de montagne vers une stratégie de développement touristique adaptée aux enjeux des transitions écologiques et de la diversification touristique*. Tech. rep., p. 18. URL: https://agence-cohesion-territoires.gouv.fr/sites/default/files/2021-05/DP_AvenirMontagne_v5.pdf.

Anses (2018). *Évaluation des risques induits par le changement climatique sur la santé des travailleurs*. Tech. rep., p. 240. URL: https://www.anses.fr/fr/content/effets-du-changement-climatique-en-milieu-de-travail-des-risques-professionnels-augment%C3%A9s-et.

Association française de l'assurance (2015). *Risques climatiques : quel impact sur l'assurance contre les aléas naturels à l'horizon 2040 ?* Tech. rep., p. 32. URL: https://www.actu-environnement.com/media/pdf/news-25800-assureur-risque-climat-2040.pdf.

Atout France (2013). *Panorama du tourisme de la montagne (édition 2012-2013). Carnet n° 2 – L'emploi et les retombées économiques*. Tech. rep. Editions Atout France, p. 232. URL: https://www.atout-france.fr/publications/panorama-du-tourisme-de-la-montagne-edition-2012-2013-cahier-ndeg2-emploi-et-retombees.

Avdeenko, Alexandra and Markus Frölich (2025). "Cost and Benefits of Climate Change Adaptation Policies: Evidence from an RCT and Extreme Flooding in Pakistan". *Journal of the European Economic Association*, jvaf012. URL: https://academic.oup.com/jeea/advance-article/doi/10.1093/jeea/jvaf012/8090509 (visited on 06/12/2025).

Bachner, Gabriel, Birgit Bednar-Friedl, and Nina Knittel (2019). "How does climate change adaptation affect public budgets? Development of an assessment framework and a demonstration for Austria". *Mitigation and Adaptation Strategies for Global Change* 24.7, pp. 1325–1341. URL: http://link.springer.com/10.1007/s11027-019-9842-3 (visited on 08/08/2023).

Bachner, Gabriel, Daniel Lincke, and Jochen Hinkel (2022). "The macroeconomic effects of adapting to high-end sea-level rise via protection and migration". *Nature Communications* 13.1, p. 5705. URL: https://www.nature.com/articles/s41467-022-33043-z (visited on 06/12/2025).

Bilal, Adrien and Diego Känzig (2024). *The Macroeconomic Impact of Climate Change: Global vs. Local Temperature*. Tech. rep. w32450. Cambridge, MA: National Bureau of Economic Research, w32450. URL: http://www.nber.org/papers/w32450.pdf (visited on 06/16/2025).

Bosello, Francesco, Fabio Eboli, and Roberta Pierfederici (2012). "Assessing the Economic Impacts of Climate Change - An Updated CGE Point of View". *SSRN Electronic Journal*. URL: http://www.ssrn.com/abstract=2004966 (visited on 01/06/2025).

Burke, Marshall, W. Matthew Davis, and Noah S. Diffenbaugh (2018). "Large potential reduction in economic damages under UN mitigation targets". *Nature* 557.7706, pp. 549–553. URL: https://www.nature.com/articles/s41586-018-0071-9 (visited on 01/06/2025).

Burke, Marshall, Solomon M. Hsiang, and Edward Miguel (2015). "Global non-linear effect of temperature on economic production". *Nature* 527.7577, pp. 235–239. URL: http://www.nature.com/articles/nature15725 (visited on 12/21/2022).

Callendar (2022a). *Feux de forêt. Effets du changement climatique sur l'exposition des installations Seveso*. Tech. rep., p. 14. URL: http://callendar.climint.com/fr/feux-foret-climat-risques-pour-industrie/.

— (2022b). *Immobilier et climat. Le marché français face au risque de submersion*. Tech. rep., p. 15. URL: http://callendar.climint.com/wp-content/uploads/2022/02/Climat-et-immobilier-V1.0.pdf.

Carbone4 (2021). *Le rôle des infrastructures dans la transition bas-carbone et l'adaptation au changement climatique de la France*. Tech. rep.

Carter, Timothy R., Magnus Benzie, Emanuele Campiglio, Henrik Carlsen, Stefan Fronzek, Mikael Hildén, et al. (2021). "A conceptual framework for cross-border impacts of climate change". *Global Environmental Change* 69, p. 102307. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378021000868 (visited on 08/08/2023).

CCR (2015). *Modélisation de l'impact du changement climatique sur les dommages assurés dans le cadre du régime Catastrophes Naturelles*. Tech. rep., p. 32. URL: https://www.ccr.fr/documents/35794/35836/Etude+Climatique+2018+version+complete.pdf/6a7b6120-7050-ff2e-4aa9-89e80c1e30f2?t=1536662736000.

CCR and Météo-France (2018). *Conséquences du changement climatique sur le coût des catastrophes naturelles en France à horizon 2050*. Tech. rep.

Cerema (2019). *Vulnérabilités et risques : les infrastructures de transport face au climat*. Tech. rep.

— (2020). *Connaissance du trait de cpite. Évaluation prospective des enjeux affectés par le recul du trait de côte*. Tech. rep., p. 23. URL: https://www.cerema.fr/fr/actualites/evaluation-prospective-enjeux-affectes-recul-du-trait-cote.

CGAAER (2017). *Eau, agriculture et changement climatique. Statu quo ou anticipation ?* Tech. rep. 16072, p. 66. URL: https://agriculture.gouv.fr/sites/default/files/cgaaer_16072_2017_rapport.pdf.

— (2022). *Evaluation du coût du changement climatique pour les filières agricoles et alimentaires*. Tech. rep. 21044, p. 117. URL: https://agriculture.gouv.fr/evaluation-du-cout-du-changement-climatique-pour-les-filieres-agricoles-et-alimentaires-0.

CGDD (2017). *Thema - Indisponibilité d'une infrastructure de transports Mesurer et réduire les coûts*. Tech. rep.

— (2018). *EFESE - Les écosystèmes forestiers*. Tech. rep., p. 449. URL: https://www.ecologie.gouv.fr/sites/default/files/publications/efese_ecosystemes_forestiers.pdf.

— (2019). *La séquestration de carbone par les écosystèmes en France*. Tech. rep., p. 102. URL: https://observatoire.foret.gouv.fr/api-obs/upload/EFESE_2019_sequestration_ecosysteme.pdf.

CGEDD (2021). *Cartographie de l'exposition des maisons individuelles au retrait-gonflement des argiles*. Tech. rep. URL: https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2021-06/note_methode_croisement_retrait_gonflement_argiles_juin2021v3.pdf.

CGEDD and CGAAER (2020). *Changement climatique, eau, agriculture. Quelles trajectoires d'ici 2050 ?* Tech. rep., p. 333. URL: https://www.vie-publique.fr/rapport/277711-changement-climatique-eau-agriculture-quelles-trajectoires-2050.

CGEDD, CGAAER, and IgF (2010). *Rapport de la mission interministérielle Changement climatique et extension des zones sensibles aux feux de forêts*. Tech. rep., p. 190. URL: https://www.vie-publique.fr/rapport/31347-changement-climatique-et-extension-des-zones-sensibles-aux-feux-de-foret.

Ciscar, Juan-Carlos, James Rising, Robert E Kopp, and Luc Feyen (2019). "Assessing future climate change impacts in the EU and the USA: insights and lessons from two continental-scale projects*". *Environmental Research Letters* 14.8, p. 084010. URL: https://iopscience.iop.org/article/10.1088/1748-9326/ab281e (visited on 04/10/2023).

Climate Change Committee (2021). *Independent Assessment of UK Climate Risk. Advice to Government For the UK's third Climate Change Risk Assessment (CCRA3)*. Tech. rep. URL: https://www.theccc.org.uk/publication/independent-assessment-of-uk-climate-risk/.

COACCH (2021). *The Economic Cost of Climate Change in Europe: Synthesis Report on Interim Results. Policy brief by the COACCH project*. Tech. rep. URL: https://www.coacch.eu/wp-content/uploads/2018/03/COACCH-policy-brief-2-Sector-results.pdf.

Cour des comptes (2022). *L'entretien des routes nationales et départementales*. Tech. rep., p. 139. URL: https://www.ccomptes.fr/system/files/2022-03/20220310-entretien-routes-nationales-departementales.pdf.

— (2023). *L'adaptation au changement climatique du parc de réacteurs nucléaires*. Tech. rep., p. 116. URL: https://www.ccomptes.fr/system/files/2023-03/20230321-Adaptation-du-parc-de-reacteurs-nucleaires-au-changement-climatique_0.pdf.

Covéa and RiskWeatherTech (2022). *Changement climatique & Assurance : Quelles conséquences sur la sinistralité à horizon 2050 ?* Tech. rep., p. 43. URL: https://www.covea.eu/sites/default/files/2022-02/202202_Livre_Blanc_Cov%C3%A9a_Risques_Climatiques.pdf.

Delahais and Robinet (2023). *Coût de l'inaction face au changement climatique en France : que sait-on ?* Tech. rep.

Dellink, Rob, Elisa Lanzi, and Jean Chateau (2019). "The Sectoral and Regional Economic Consequences of Climate Change to 2060". *Environmental and Resource Economics* 72.2, pp. 309–363. URL: http://link.springer.com/10.1007/s10640-017-0197-5 (visited on 08/22/2023).

Deloitte (2021). *France's turning point Accelerating new growth on the path to net zero*. Tech. rep. URL: https://www.deloitte.com/fr/fr/services/risk-advisory/research/transition-climatique-tournant-decisif-pour-la-france.html?icid=learn_more_content_click.

DG Trésor (2021). *Évaluations économiques des services rendus par la biodiversité*. Tech. rep. 294, p. 12. URL: https://www.tresor.economie.gouv.fr/Articles/2021/12/09/evaluations-economiques-des-services-rendus-par-la-biodiversite.

Dottori, Francesco, Lorenzo Mentaschi, Alessandra Bianchi, Lorenzo Alfieri, and Luc Feyen (2023). "Cost-effective adaptation strategies to rising river flood risk in Europe". *Nature Climate Change* 13.2, pp. 196–202. URL: https://www.nature.com/articles/s41558-022-01540-0 (visited on 06/12/2025).

Duru, Michel, Pierre-Marie Aubert, Christian Couturier, and Sylvain Doublet (2021). *Scénarios de systèmes alimentaires à l'horizon 2050 au niveau européen et français : quels éclairages pour les politiques publiques*. Tech. rep. URL: https://agronomie.asso.fr/fileadmin/user_upload/revue_aes/aes_vol11_n1_juin_2021/pdf/aes_vol11_n1_05_duru-et-al.pdf.

European Environment Agency (2024). *European Climate Risk Assessment*. LU: Publications Office. URL: https://data.europa.eu/doi/10.2800/8671471 (visited on 06/05/2025).

Fondapol (2020). *Les assureurs face au défi climatique*. Tech. rep., p. 52. URL: https://www.fondapol.org/etude/les-assureurs-face-au-defi-climatique/.

Forster, Piers M., Chris Smith, Tristram Walsh, William F. Lamb, Robin Lamboll, Christophe Cassou, et al. (2025). "Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence". *Earth System Science Data* 17.6, pp. 2641–2680. URL: https://essd.copernicus.org/articles/17/2641/2025/ (visited on 07/03/2025).

France Assureurs (2021). *Impact du changement climatique sur l'assurance à l'horizon 2050*. Tech. rep., p. 30. URL: https://www.franceassureurs.fr/lassurance-protege-finance-et-emploie/lassurance-protege/actualites-protege/changement-climatique-quel-impact-sur-lassurance-a-lhorizon-2050/.

— (2023). *L'assurance des événements naturels en 2022*. Tech. rep.

France Stratégie (2022). *Risques climatiques, réseaux et interdépendances : le temps d'agir*. Tech. rep.

— (2023). *Le travail à l'épreuve du changement climatique*. Tech. rep. 123, p. 16. URL: https://www.strategie-plan.gouv.fr/files/files/Publications/Rapport/fs-2023-na123-adaptation_changement_climatique-juin_2.pdf.

— (2024). *Prélèvements et consommations d'eau : quels enjeux et usages ?* Tech. rep. 136, p. 16.

García-León, David, Ana Casanueva, Gabriele Standardi, Annkatrin Burgstall, Andreas D. Flouris, and Lars Nybo (2021). "Current and projected regional economic impacts of heatwaves in Europe". *Nature Communications* 12.1, p. 5807. URL: https://www.nature.com/articles/s41467-021-26050-z (visited on 11/23/2022).

Gasparrini, Antonio, Yuming Guo, Francesco Sera, Ana Maria Vicedo-Cabrera, Veronika Huber, Shilu Tong, et al. (2017). "Projections of temperature-related excess mortality under climate change scenarios". *The Lancet Planetary Health* 1.9, e360–e367. URL: https://linkinghub.elsevier.com/retrieve/pii/S2542519617301560 (visited on 01/10/2023).

Gillett, Nathan P. (2024). "Halving of the uncertainty in projected warming over the past decade". *npj Climate and Atmospheric Science* 7.1, p. 146. URL: https://www.nature.com/articles/s41612-024-00693-3 (visited on 04/25/2025).

Haasnoot, Marjolijn, Robbert Biesbroek, Judy Lawrence, Veruska Muccione, Robert Lempert, and Bruce Glavovic (2020). "Defining the solution space to accelerate climate change adaptation". *Regional Environmental Change* 20.2, p. 37. URL: http://link.springer.com/10.1007/s10113-020-01623-8 (visited on 11/13/2023).

Hallegatte, Stéphane (2009). "Strategies to adapt to an uncertain climate change". *Global Environmental Change* 19.2, pp. 240–247. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378008001192 (visited on 04/21/2023).

Haut Conseil pour le climat (2021). *Renforcer l'atténuation, engager l'adaptation*. Tech. rep., p. 183. URL: https://www.hautconseilclimat.fr/publications/rapport-annuel-2021-renforcer-lattenuation-engager-ladaptation/.

Howard, Peter H. and Thomas Sterner (2017). "Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates". *Environmental and Resource Economics* 68.1, pp. 197–225. URL: http://link.springer.com/10.1007/s10640-017-0166-z (visited on 01/06/2025).

Hsiang, Solomon M., Robert Kopp, Amir Jina, James Rising, Michael Delgado, Shashank Mohan, et al. (2017). "Estimating economic damage from climate change in the United States". *Science* 356.6345, pp. 1362–1369. URL: https://www.science.org/doi/10.1126/science.aal4369 (visited on 01/06/2025).

Hyyrynen, Matti, Markku Ollikainen, Janina Käyhkö, Juuso Suomi, Jussi Lintunen, Jukka Käyhkö, et al. (2025). "Cooling is a cost-efficient way to adapt to heatwaves even in high-latitude cities". *Climatic Change* 178.5, p. 96. URL: https://link.springer.com/10.1007/s10584-025-03913-8 (visited on 06/12/2025).

IgA, CGEDD, and IgF (2019). *Recomposition spatiale des territoires littoraux*. Tech. rep., p. 233. URL: https://www.igf.finances.gouv.fr/files/live/sites/igf/files/contributed/IGF%20internet/2.RapportsPublics/2019/2018-M-088-03-Territoires%20littoraux.pdf.

IGEDD and IgF (2022). *Le financement de la stratégie nationale pour la biodiversité (SNB) pour 2030*. Tech. rep., p. 416. URL: https://www.igf.finances.gouv.fr/files/live/sites/igf/files/contributed/IGF%20internet/2.RapportsPublics/2023/2022-M-025-03_Rapport_financement_SNB_pour_2030.pdf.

IMF (2022). *Economic Principles for Integrating Adaptation to Climate Change into Fiscal Policy*. Tech. rep. URL: https://www.imf.org/-/media/Files/Publications/Staff-Climate-Notes/2022/English/CLNEA2022001.ashx.

Inrae and Office international de l'eau (2024). *Explore2 - des futurs de l'eau*. Tech. rep. URL: https://professionnels.ofb.fr/fr/node/1244.

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Tech. rep.

— (2023). *Climate Change 2023 – Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Tech. rep. Intergovernmental Panel on Climate Change (IPCC). URL: https://www.ipcc.ch/report/ar6/syr/ (visited on 06/27/2025).

JRC (2020a). *Climate change impacts and adaptation in Europe: JRC PESETA IV final report*. LU: Publications Office. URL: https://data.europa.eu/doi/10.2760/171121 (visited on 06/17/2025).

— (2020b). *PESTEA IV Climate change impacts and adaptation in Europe*. Tech. rep.

Kahn, Matthew E., Kamiar Mohaddes, Ryan N.C. Ng, M. Hashem Pesaran, Mehdi Raissi, and Jui-Chung Yang (2021). "Long-term macroeconomic effects of climate change: A cross-country analysis". *Energy Economics* 104, p. 105624. URL: https://linkinghub.elsevier.com/retrieve/pii/S0140988321004898 (visited on 04/11/2023).

Kalkuhl, Matthias and Leonie Wenz (2020). "The impact of climate conditions on economic production. Evidence from a global panel of regions". *Journal of Environmental Economics and Management* 103, p. 102360. URL: https://linkinghub.elsevier.com/retrieve/pii/S0095069620300838 (visited on 01/10/2024).

Khan, Mizan R. and Sirazoom Munira (2021). "Climate change adaptation as a global public good: implications for financing". *Climatic Change* 167.3-4, p. 50. URL: https://link.springer.com/10.1007/s10584-021-03195-w (visited on 08/10/2023).

Kompas, Tom, Van Ha Pham, and Tuong Nhu Che (2018). "The Effects of Climate Change on GDP by Country and the Global Economic Gains From Complying With the Paris Climate Accord". *Earth's Future* 6.8, pp. 1153–1173. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2018EF000922 (visited on 01/06/2025).

Kotz, Maximilian, Anders Levermann, and Leonie Wenz (2024). "The economic commitment of climate change". *Nature* 628.8008, pp. 551–557. URL: https://www.nature.com/articles/s41586-024-07219-0 (visited on 12/12/2024).

Linsenmeier, Manuel (2023). "Temperature variability and long-run economic development". *Journal of Environmental Economics and Management* 121, p. 102840. URL: https://linkinghub.elsevier.com/retrieve/pii/S009506962300058X (visited on 01/11/2024).

Maddison, David and Katrin Rehdanz (2011). "The impact of climate on life satisfaction". *Ecological Economics* 70.12, pp. 2437–2445. URL: https://linkinghub.elsevier.com/retrieve/pii/S0921800911003028 (visited on 01/06/2025).

Météo-France (2011). *Projet ClimSec. Impact du changement climatique en France sur la sécheresse et l'eau du sol*. Tech. rep. URL: https://www.umr-cnrm.fr/IMG/pdf/2011_fmaif_rapport_final_v2.2.pdf.

Ministère de l'Ecologie, du Développement Durable, des Transports et du Logement (2011). *1er Plan national d'adaptation au changement climatique (2011-2015)*. Tech. rep. URL: https://www.ecologie.gouv.fr/sites/default/files/documents/ONERC_PNACC_1_complet.pdf.

— (2013). *Explore2070. Eau et changement climatique*. Tech. rep. URL: https://professionnels.ofb.fr/fr/node/44.

Ministère de l'Agriculture et de l'Alimentation (2020). *Feuille de route pour l'adaptation des forêts au changement climatique. Agir pour des forêts résilientes et un maintien des services qu'elles rendent*. Tech. rep., p. 26. URL: https://agriculture.gouv.fr/francerelance-adapter-les-forets-au-changement-climatique.

— (2022). *Conclusions du Varenne agricole de l'eau et de l'adaptation au changement climatique*. Tech. rep., p. 25. URL: https://agriculture.gouv.fr/conclusions-du-varenne-agricole-de-leau-et-de-ladaptation-au-changement-climatique.

Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt and Ecofor (2014). *Projet SICFOR Du Suivi aux Indicateurs de Changement climatique en FORêt*. Tech. rep., p. 102. URL: http://www.gip-ecofor.org/doc/drupal/Sicfor_rapport-VF.pdf.

Ministère de la Transition Écologique (2022). *Evaluation à mi-parcours du PNACC-2*. Tech. rep. URL: https://www.ecologie.gouv.fr/sites/default/files/documents/Evaluation%20%C3%A0%20mi-parcours%20du%20PNACC-2.pdf.

— (2025). *3e Plan national d'adaptation au changement climatique (2025-2029)*. Tech. rep. URL: https://www.ecologie.gouv.fr/sites/default/files/documents/PNACC3.pdf.

Ministère de la Transition écologique et de la Cohésion des territoires (2022). *Évolutions de la ressource en eau renouvelable en France métropolitaine de 1990 à 2018*. Tech. rep., p. 64. URL: https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2022-06/datalab_102_ressources_en_eau_juin2022.pdf.

Ministère de la Transition Écologique et Solidaire (2018). *2e Plan national d'adaptation au changement climatique (2018-2022)*. Tech. rep. URL: https://www.ecologie.gouv.fr/sites/default/files/documents/2018.12.20_PNACC2.pdf.

Mohaddes, K. and M. Raissi (2024). "Rising Temperatures, Melting Incomes: Country-Specific Macroeconomic Effects of Climate Scenarios". URL: https://www.repository.cam.ac.uk/handle/1810/369914 (visited on 06/17/2025).

Moody's Analytics (2019). *The Economic Implications of Climate Change*. Tech. rep. URL: https://www.eticanews.it/wp-content/uploads/2019/07/economic-implications-of-climate-change.pdf.

Morris, Jennifer, Steven K. Rose, John Reilly, Angelo Gurgel, Sergey Paltsev, and C. Adam Schlosser (2025). "Reconciling widely varying estimates of the global economic impacts from climate change". *Nature Climate Change* 15.2, pp. 124–127. URL: https://www.nature.com/articles/s41558-024-02232-7 (visited on 03/06/2025).

Neal, Timothy, Ben R Newell, and Andy Pitman (2025). "Reconsidering the macroeconomic damage of severe warming". *Environmental Research Letters* 20.4, p. 044029. URL: https://iopscience.iop.org/article/10.1088/1748-9326/adbd58 (visited on 04/23/2025).

Nordhaus, William and Andrew Moffat (2017). *A Survey of Global Impacts of Climate Change: Replication, Survey Methods, and a Statistical Analysis*. Tech. rep. w23646. Cambridge, MA: National Bureau of Economic Research, w23646. URL: http://www.nber.org/papers/w23646.pdf (visited on 06/17/2025).

OCDE (2006). *Changements climatiques dans les Alpes européennes. Adapter le tourisme d'hiver et la gestion des risques naturels*. Tech. rep., p. 136. URL: https://www.oecd-ilibrary.org/environment/changements-climatiques-dans-les-alpes-europeennes_9789264031715-fr.

Onerc (2006). *Stratégie nationale d'adaptation au changement climatique*. La Documentation française. URL: https://www.ecologie.gouv.fr/sites/default/files/documents/ONERC_Rapport_2006_Strategie_Nationale_WEB.pdf.

— (2009). *Changement climatique : coûts des impacts et pistes d'adaptation*. Tech. rep. La Documentation française, p. 194. URL: https://medias.vie-publique.fr/data_storage_s3/rapport/pdf/094000463.pdf.

— (2014). *L'arbre et la forêt à l'épreuve d'un climat qui change*. Tech. rep. La Documentation française, p. 182. URL: http://www.gip-ecofor.org/doc/drupal/ONERC_Rapport_2014_Arbre_Et_Foret_WEB.pdf.

— (2018). *Les événements météorologiques extrêmes dans un contexte de changement climatique*. Tech. rep. La Documentation française, p. 199. URL: https://www.ecologie.gouv.fr/sites/default/files/ONERC_Rapport_2018_Evenements_meteorologiques_extremes_et_CC_WEB.pdf.

— (2022). *La prospective au service de l'adaptation au changement climatique*. Tech. rep. La Documentation française, p. 385.

Paul Watkiss Associates (2021). *Monetary Valuation of Risks and Opportunities in CCRA3. Report to the Climate Change Committee as part of the UK Climate Change Risk Assessment 3*. Tech. rep. URL: https://www.ukclimaterisk.org/wp-content/uploads/2021/06/Monetary-Valuation-of-Risks-and-Opportunities-in-CCRA3.pdf.

Piontek, Franziska, Laurent Drouet, Johannes Emmerling, Tom Kompas, Aurélie Méjean, Christian Otto, et al. (2021). "Integrated perspective on translating biophysical to economic impacts of climate change". *Nature Climate Change* 11.7, pp. 563–572. URL: http://www.nature.com/articles/s41558-021-01065-y (visited on 04/06/2022).

Piontek, Franziska, Matthias Kalkuhl, Elmar Kriegler, Anselm Schultes, Marian Leimbach, Ottmar Edenhofer, et al. (2019). "Economic Growth Effects of Alternative Climate Change Impact Channels in Economic Modeling". *Environmental and Resource Economics* 73.4, pp. 1357–1385. URL: http://link.springer.com/10.1007/s10640-018-00306-7 (visited on 06/25/2025).

Pretis, Felix, Moritz Schwarz, Kevin Tang, Karsten Haustein, and Myles R. Allen (2018). "Uncertain impacts on economic growth when stabilizing global temperatures at 1.5°C or 2°C warming". *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376.2119, p. 20160460. URL: https://royalsocietypublishing.org/doi/10.1098/rsta.2016.0460 (visited on 01/06/2025).

Quinet (2019). *La valeur de l'action pour le climat*. Tech. rep.

Réseau Action Climat (2014). *Adaptation de l'agriculture aux changements climatiques. Recueil d'expériences territoriales*. Tech. rep., p. 58. URL: https://reseauactionclimat.org/wp-content/uploads/2017/06/Adaptation-de-l%E2%80%99agriculture-aux-changements-climatiques-%E2%80%93-Recueil-d%E2%80%99expe%C2%B4riences-territoriales.pdf.

Rose, Steven K., Delavane B. Diaz, and Geoffrey J. Blanford (2017). "UNDERSTANDING THE SOCIAL COST OF CARBON: A MODEL DIAGNOSTIC AND INTER-COMPARISON STUDY". *Climate Change Economics* 08.02, p. 1750009. URL: https://www.worldscientific.com/doi/abs/10.1142/S2010007817500099 (visited on 01/06/2025).

Roson, Roberto and Dominique van der Mensbrugghe (2012). "Climate change and economic growth: impacts and interactions". *International Journal of Sustainable Economy* 4.3, pp. 270–285.

Roson, Roberto and Martina Sartori (2016). "Estimation of Climate Change Damage Functions for 140 Regions in the GTAP 9 Database". *Journal of Global Economic Analysis* 1.2.

Roux, Alice, Antoine Colin, Dhôte Jean-François, and Bertrand Schmitt (2020). *Filière forêt-bois et atténuation du changement climatique. Entre séquestration du carbone en forêt et développement de la bioéconomie*. Quae.

RTE (2021). *Futurs énergétiques*. Tech. rep., p. 988. URL: https://www.rte-france.com/analyses-tendances-et-prospectives/bilan-previsionnel-2050-futurs-energetiques.

Sénat (2019). *Adapter la France aux dérèglements climatiques à l'horizon 2050*. Tech. rep.

— (2022). *Feux de forêt et de végétation. Prévenir l'embrasement*. Tech. rep. URL: https://www.senat.fr/notice-rapport/2021/r21-856-notice.html.

Simpson, Nicholas P., Katharine J. Mach, Andrew Constable, Jeremy Hess, Ryan Hogarth, Mark Howden, et al. (2021). "A framework for complex climate change risk assessment". *One Earth* 4.4, pp. 489–501. URL: https://linkinghub.elsevier.com/retrieve/pii/S2590332221001792 (visited on 08/08/2023).

Spandre, Pierre, Hugues François, Deborah Verfaillie, Marc Pons, Matthieu Vernay, Matthieu Lafaysse, et al. (2019). "Winter tourism under climate change in the Pyrenees and the French Alps: relevance of snowmaking as a technical adaptation". *The Cryosphere* 13.4, pp. 1325–1347. URL: https://tc.copernicus.org/articles/13/1325/2019/ (visited on 06/18/2025).

Stern, Nicholas (2006). "Stern Review: The economics of climate change".

Swiss-Re (2021). *The economics of climate change: no action not an option*. Tech. rep. URL: https://www.swissre.com/dam/jcr:e73ee7c3-7f83-4c17-a2b8-8ef23a8d3312/swiss-re-institute-expertise-publication-economics-of-climate-change.pdf.

Szewczyk, Wojciech, Ignazio Mongelli, and Juan-Carlos Ciscar (2021). "Heat stress, labour productivity and adaptation in Europe—a regional and occupational analysis". *Environmental Research Letters* 16.10, p. 105002. URL: https://iopscience.iop.org/article/10.1088/1748-9326/ac24cf (visited on 11/23/2022).

Takakura, Jun'ya, Shinichiro Fujimori, Naota Hanasaki, Tomoko Hasegawa, Yukiko Hirabayashi, Yasushi Honda, et al. (2019). "Dependence of economic impacts of climate changeon anthropogenically directed pathways". *Nature Climate Change* 9.10, pp. 737–741. URL: https://www.nature.com/articles/s41558-019-0578-6 (visited on 01/06/2025).

Tol, Richard S. J. (2018). "The Economic Impacts of Climate Change". *Review of Environmental Economics and Policy* 12.1, pp. 4–25. URL: https://www.journals.uchicago.edu/doi/10.1093/reep/rex027 (visited on 06/17/2025).

UNFCC (2022). *Methodologies for assessing adaptation needs and their application - Technical paper*. Tech. rep. URL: https://unfccc.int/sites/default/files/resource/J0160_Adaptation%20Needs%20Technical%20Report%20final.pdf.

United Nations Environment Programme, Maria Del Pilar Bueno Rubial, Alexandre Magnan, Lars Christiansen, Henry Neufeldt, Anne Hammill, et al. (2024). *Adaptation Gap Report 2024: Come hell and high water - As fires and floods hit the poor hardest, it is time for the world to step up adaptation actions*. United Nations Environment Programme. URL: https://wedocs.unep.org/20.500.11822/46497 (visited on 06/05/2025).

USGCRP, Allison R. Crimmins, Christopher W. Avery, David R. Easterling, Kenneth E. Kunkel, Brooke C. Stewart, et al. (2023). *Fifth National Climate Assessment*. Tech. rep. U.S. Global Change Research Program. URL: https://nca2023.globalchange.gov/ (visited on 06/20/2025).

Van Der Wijst, Kaj-Ivar, Francesco Bosello, Shouro Dasgupta, Laurent Drouet, Johannes Emmerling, Andries Hof, et al. (2023). "New damage curves and multimodel analysis suggest lower optimal temperature". *Nature Climate Change* 13.5, pp. 434–441. URL: https://www.nature.com/articles/s41558-023-01636-1 (visited on 12/12/2024).

Waidelich, Paul, Fulden Batibeniz, James Rising, Jarmo S. Kikstra, and Sonia I. Seneviratne (2024). "Climate damage projections beyond annual temperature". *Nature Climate Change* 14.6, pp. 592–599. URL: https://www.nature.com/articles/s41558-024-01990-8 (visited on 02/11/2025).

WWF (2018). *La nature face au choc climatique: L'impact du changement climatique sur la biodiversité au coeur des Ecorégions Prioritaires du WWF*. Tech. rep., p. 44. URL: https://www.wwf.fr/sites/default/files/doc-2018-03/180314_Rapport_Especes_Climat.pdf.

— (2021). *Dérèglement climatique : le monde du sport à +2°C et +4°C*. Tech. rep., p. 63. URL: https://www.wwf.fr/sites/default/files/doc-2021-07/02072021_Rapport_Dereglement-climatique_le_monde_du_sport_a_plus_2_et_4_degres_WWF%20France_4.pdf.

Zappalà, Guglielmo (2023). "Sectoral Impact and Propagation of Weather Shocks". *IMF Working Papers* 2023.053, p. 1. URL: https://elibrary.imf.org/openurl?genre=journal&issn=1018-5941&volume=2023&issue=053 (visited on 06/16/2025).

Appendices

A Studies reviewed

A.1 Global macroeconomic studies

Table 1.2 lists the global macroeconomic studies used in this paper and classifies them based on the methodological approach adopted in each study, following the typology of Piontek, Drouet, et al. (2021), which distinguishes between "Direct impacts", "Final impacts (bottom-up with sector interactions)", "Final impacts (econometric)", and "Damage functions".

Each of these studies provides an assessment of the economic costs of climate change at the global level and includes specific estimates for France, or at least for Europe. In total, 21 studies were identified: 15 provide results specific to France (Acevedo et al., 2020; Burke, Hsiang, et al., 2015; COACCH, 2021; Deloitte, 2021; Kahn et al., 2021; Kalkuhl et al., 2020; Kompas et al., 2018; Kotz et al., 2024; Mohaddes et al., 2024; Moody's Analytics, 2019; Neal et al., 2025; Pretis et al., 2018; Roson and Sartori, 2016; Swiss-Re, 2021; Waidelich et al., 2024), and 6 provide results at the European level (Bosello et al., 2012; Dellink et al., 2019; JRC, 2020a; Rose et al., 2017; Roson and Mensbrugghe, 2012; Takakura et al., 2019). Some studies were published in peer-reviewed journals (Acevedo et al., 2020; Burke, Hsiang, et al., 2015; Dellink et al., 2019; Khan et al., 2021; Kalkuhl et al., 2020; Kompas et al., 2018; Kotz et al., 2024; Neal et al., 2025; Pretis et al., 2018; Rose et al., 2017; Roson and Sartori, 2016; Takakura et al., 2019; Waidelich et al., 2024), others were published by academics as working papers (Bosello et al., 2012; Mohaddes et al., 2024), others were produced by public institutions (COACCH, 2021; JRC, 2020a), and still others by private actors (Deloitte, 2021; Moody's Analytics, 2019; Swiss-Re, 2021). What these studies have in common is that they are global—covering various countries or world regions—and macroeconomic in scope, as they provide an assessment of the costs of climate change across multiple sectors.

For each study, data were obtained either directly from a database provided in the article or in its supplementary material, or extracted from figures by measuring axis lengths using the ImageJ software[1]. Regarding the study by Kalkuhl et al. (2020), results were obtained through the NGFS Phase IV implementation of the econometric panel of Kalkuhl et al. (2020)[2]. Full references for all papers are provided in the References section at the end of the supplementary material. A database including the estimated costs for France reported in each study is available in the GitHub repository associated with this paper: https://github.com/ADelahais/Climate_change_cost_France.

Some papers produced assessements of the cost of climate change for the whole world, but could not be included in our review. For some studies, only global estimates were available, with no specific values reported for France or Europe (Howard et al., 2017; Hsiang et al., 2017;

[1] See: https://imagej.net/ij/.
[2] See: https://data.ece.iiasa.ac.at/ngfs-phase-4/#/downloads.

Linsenmeier, 2023; Maddison et al., 2011; Nordhaus et al., 2017; Tol, 2018). For one study, the underlying data were not available (Burke, Davis, et al., 2018). The study by Bilal et al. (2024) has not been included, as the cost of climate change assessed in their paper does not correspond to a long-term GDP loss in response to permanent global warming, but rather to the transitory response to a +1°C temperature shock, followed by a return to the pre-shock equilibrium. However, their main methodological innovation—using global temperature change instead of local temperature change as the independent variable—is incorporated in the study by Neal et al. (2025), and is therefore taken into account in our review. Finally, the study by van der Van Der Wijst et al. (2023) was not included, as it reproduces the estimates from the COACCH programme, which is already covered in the review (COACCH, 2021).

Table 1.2: Global macroeconomic studies where an assessment of the cost of climate change for France (or at least Europe) is available

Method	Papers
Direct impacts	(Roson and Sartori, 2016) (Takakura et al., 2019)
Final impacts (bottom-up with sector interactions)	(Bosello et al., 2012) (Kompas et al., 2018) (Dellink et al., 2019) (Roson and Mensbrugghe, 2012) (Deloitte, 2021) (JRC, 2020b) (COACCH, 2021) (Swiss-Re, 2021) (Moody's Analytics, 2019)
Final impacts (econometric)	(Burke, Hsiang, et al., 2015) (Pretis et al., 2018) (Acevedo et al., 2020) (Kalkuhl et al., 2020) (Kahn et al., 2021) (Kotz et al., 2024) (Waidelich et al., 2024) (Mohaddes et al., 2024) (Neal et al., 2025)
Damage functions	(Rose et al., 2017)

A.2 National institutionnal literature

Table 1.3 lists the adaptation planning and eveluation documents providing quantitative (monetized or not) assessments of climate risks available at the national level in France, and classifies them based on ten categories of climate change impacts. It primarily draws on the "grey literature" produced by French public and private institutions. However, adaptation documents sometimes also refer to academic studies with a global scope but that provide specific estimates for France—such as Gasparrini et al. (2017) or Szewczyk et al. (2021). They have been included in the review as well. A total of 60 references were reviewed.

Beyond these sectoral assessments, we identified one study that evaluates the multi-sectoral costs of climate change in France using a CGE model (Ademe, 2023).

Table 1.3: National institutional documents used in this review, by category of impact

Category of impacts	Documents
Water resources	(Sénat, 2019) (Météo-France, 2011) (Ministère de la Transition écologique et de la Cohésion des territoires, 2022) (Ministère de l'Agriculture et de l'Alimentation, 2022) (Inrae et al., 2024) (France Stratégie, 2024)
Agriculture	(Sénat, 2019) (Ademe, 2012) (CGAAER, 2022) (CGAAER, 2017) (CGEDD and CGAAER, 2020) (Haut Conseil pour le climat, 2021) (Ministère de l'Agriculture et de l'Alimentation, 2022) (Onerc, 2022) (Réseau Action Climat, 2014) (Duru et al., 2021)
Forestry	(Ademe, 2012) (Callendar, 2022a) (CGEDD, CGAAER, and IgF, 2010) (CGDD, 2018) (Haut Conseil pour le climat, 2021) (Ministère de l'Agriculture et de l'Alimentation, 2020)

(continued on next page)

	(Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt et al., 2014)
	(Onerc, 2018)
	(Onerc, 2014)
	(Onerc, 2009)
	(Roux et al., 2020)
	(Sénat, 2019)
	(Sénat, 2022)
Coastal risks	(Ademe, 2022a)
	(Callendar, 2022b)
	(Cerema, 2020)
	(France Assureurs, 2021)
	(IgA et al., 2019)
	(Onerc, 2009)
Biodiversity	(DG Trésor, 2021)
	(IGEDD et al., 2022)
	(WWF, 2018)
	(CGDD, 2019)
Energy	(Cour des comptes, 2023)
	(Onerc, 2009)
	(RTE, 2021)
Infrastructure & networks	(Carbone4, 2021)
	(Cerema, 2019)
	(CGDD, 2017)
	(Cour des comptes, 2022)
	(France Stratégie, 2022)
	(RTE, 2021)
Buildings	(Ademe, 2022a)
	(Association française de l'assurance, 2015)
	(CCR, 2015)
	(CCR and Météo-France, 2018)
	(CGEDD, 2021)
	(Fondapol, 2020)
	(Covéa et al., 2022)
	(France Assureurs, 2021)
	(Haut Conseil pour le climat, 2021)

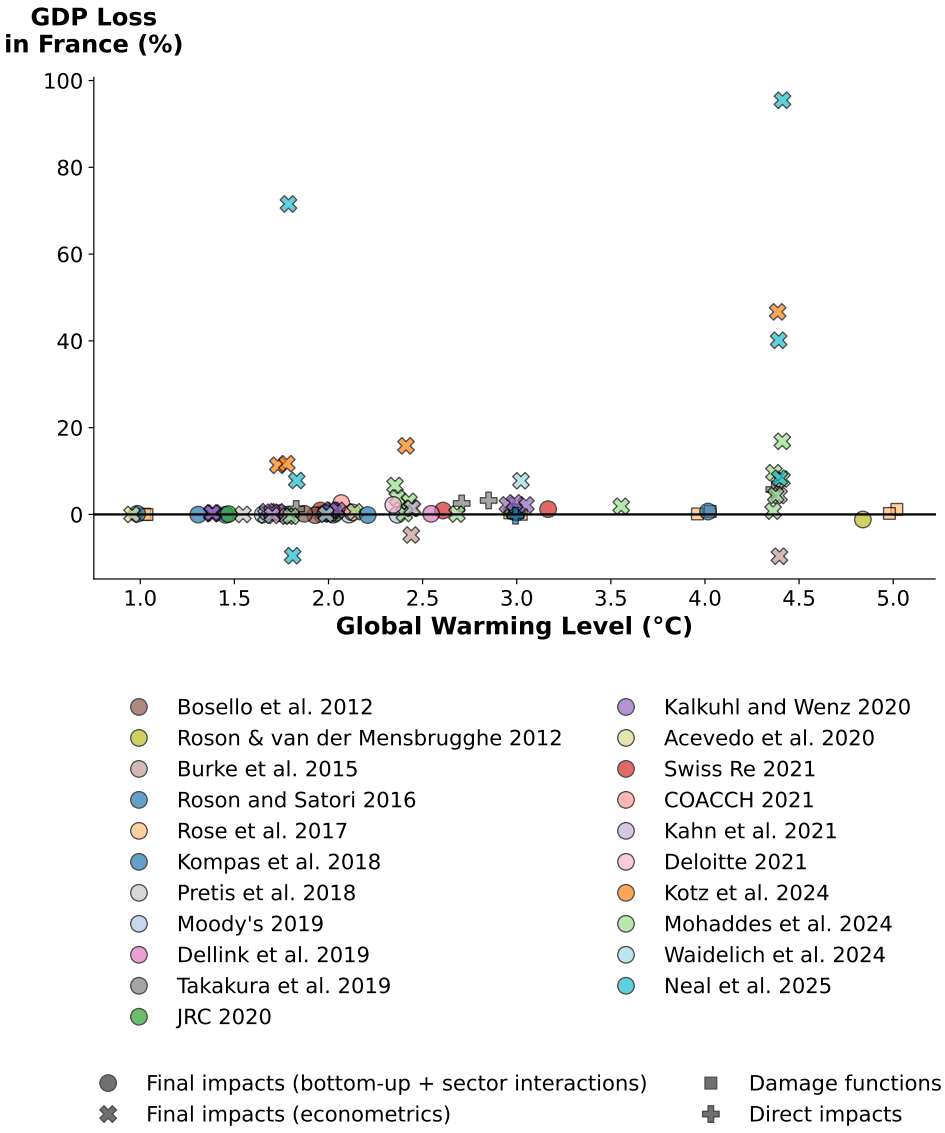
(continued on next page)

	(Onerc, 2009)
Tourism	(Atout France, 2013) (ANCT, 2021) (OCDE, 2006) (Onerc, 2009) (Sénat, 2019) (Spandre et al., 2019) (WWF, 2021)
Health	(Adélaïde et al., 2021) (Ademe, 2022b) (Anses, 2018) (France Stratégie, 2023) (García-León et al., 2021) (Gasparrini et al., 2017) (Onerc, 2022) (Sénat, 2019) (Szewczyk et al., 2021) (WWF, 2021)

B Additional figures

Figure 1.5 reproduces Figure 1.1 from the main text, but distinguishes the individual estimates according to the study from which they originate. Figure 1.6 reproduces Figure 1.2 from the main text, but distinguishes the individual estimates according to the global warming level range they correspond to. As can be seen, for each warming range, estimates of the cost of climate change for France are modest prior to 2018 and increase significantly thereafter. Figure 1.7 reproduces Figure 1.4 from the main text, attributing each estimate either to its source study [Panel (a)] or to the methodological approach it uses [Panel (b)].

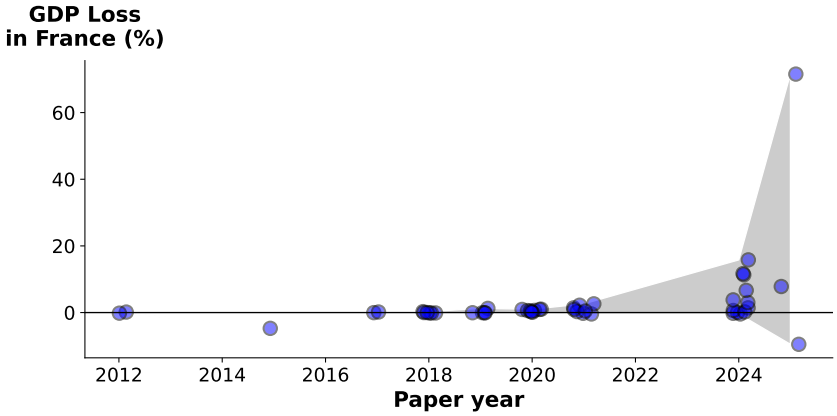
Figure 1.5: The economic consequences of climate change for France, across warming scenarios.



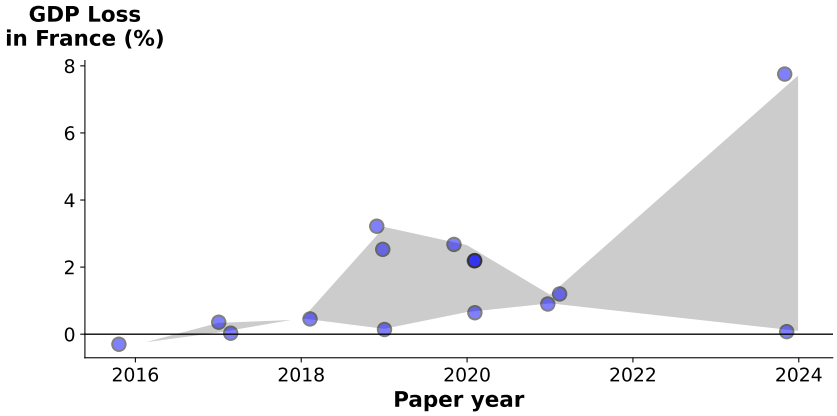
Lecture: Each point represents a specific estimate of GDP loss. A single study may contribute multiple points, corresponding to different model specifications or warming levels. Studies are classified according to their methodology, following (Piontek et al., 2021), which is indicated by the shape of the point.

Figure 1.6: Estimated economic cost of climate change in France, by year of study publication, in each specific warming range (2°C, 3°C and 4°C)

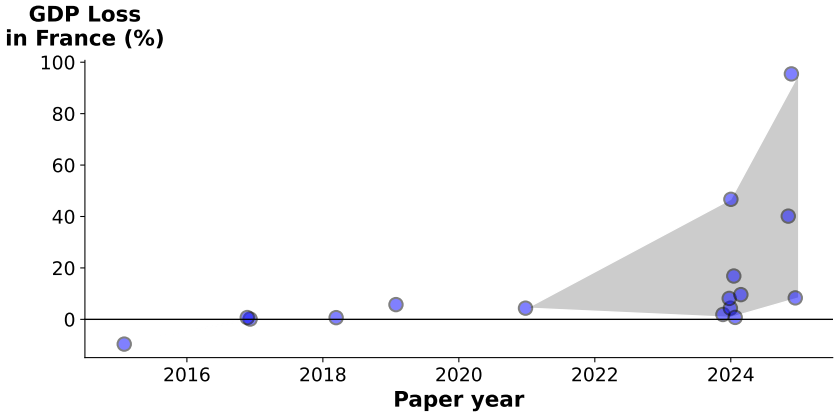
(a) Global warming level around +2°C.



(b) Global warming level around +3°C.



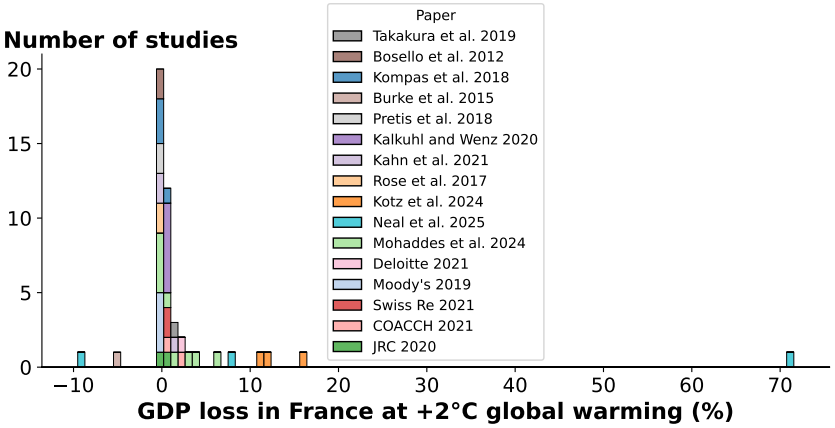
(c) Global warming level around +4°C.



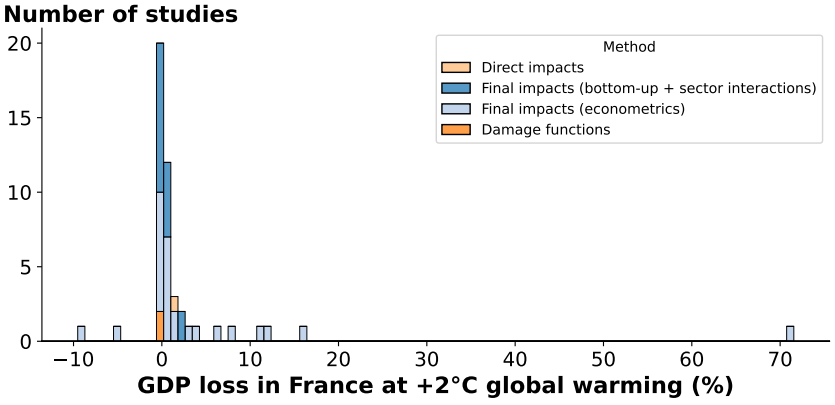
Lecture: Each point represents a specific estimate of GDP loss. A single study may contribute multiple points, corresponding to different model specifications and warming scenarios. The grey area indicates the space between the highest and lowest GDP loss reported in the literature for each year of publication. Negative values indicate a GDP gain relative to a no–climate change scenario. All warming scenarios are represented here.

Figure 1.7: Distribution of climate change costs for France at a +2°C global warming level

(a) Disaggregation by study.



(b) Disaggregation by method.



C Quantification and monetization

Table 1.4: Are the main impact categories comprehensively quantified and monetized in local risk assessments?

Impact Category	Comprehensive quantification?	Justification	Comprehensive monetization?	Justification	Main sources
Water resources	Yes	Hydrological projections are available across the entire French territory.	No	Only hydrological projections are available; the associated economic consequences are not assessed.	(Inrae et al., 2024; Ministère de l'Ecologie, du Développement Durable, des Transports et du Logement, 2013)
Agriculture	No	Only a limited number of crops were included in the nationwide CLIMATOR assessment.	No	CLIMATOR only assesses agricultural productivity and results are not monetized. Another study projects current damages.	(Ademe, 2012; CGAAER, 2022)
Forestry	No	Same as Agriculture.	No	No comprehensive quantification to begin with.	–
Coastal risks	Yes	The evolution of insurance risk for coastal floods under future climate change is assessed. The number of houses at risk of sea level rise is also assessed.	Yes	Projections are available in €.	(France Assureurs, 2021)
Biodiversity	No	Apart from carbon sink estimates, no quantitative assessment has been conducted.	No	No comprehensive quantification to begin with.	(CGDD, 2019)
Energy	Yes	Assessments of the effects of climate change on supply and demand have been conducted by the national transmission system operator (RTE).	No	Projections are expressed in MWh, with no corresponding monetary estimates.	(RTE, 2021)
Infrastructure and networks	No	Certain types of infrastructure (e.g. transport, electricity) have been assessed, while others (e.g. telecoms) have not.	No	No comprehensive quantification to begin with.	(Carbone4, 2021)
Buildings	Yes	Insurance risk projections for shrink-swell and continental floods under future climate change are available.	Yes	Projections are available in €.	(France Assureurs, 2021)
Tourism	No	Only ski resort viability has been assessed, not other forms of tourism.	No	No comprehensive quantification to begin with.	–
Health	No	Only heatwave-related mortality/productivity are assessed. Other health effects are not considered.	No	No comprehensive quantification to begin with.	–

Chapter 2

Countries' unequal exposure to climate change impacts through international trade

Revise & Resubmit at One Earth.
Joint work with Vincent Viguié (CIRED).

Abstract

Countries can suffer supply chain disruptions and important economic losses when their trade partners are hit by extreme events. As climate risks are expected to increase in the future, climate-related disruptions to supply chains are also likely to become more frequent and severe. However, the magnitude of this risk, and the relative exposure of different countries and different sectors is not clear. Here, we combine international trade data with climate risk indices to measure the exposure of countries' economies to foreign climate risks. We find that this indirect exposure is highly heterogeneous between countries. While its geographical pattern generally differs from those of direct climate change impacts, several countries suffer a double exposure and are exposed to both risks, as a result of regional trade integration and geographic concentration of climate risks. Moreover, almost every country faces high exposure for at least one broad category of products.

Keywords: Trade, Supply chains, Extreme events, Cross-border climate impacts, Climate change adaptation.

Contents

1 Introduction **55**
2 Methods **57**
2.1 Trade networks 57
2.2 Climate risk indices 57
2.3 Measuring cross-border climate exposure 58
2.4 Robustness analysis 58
3 Results **59**
3.1 Cross-border exposure is heterogeneous across countries 59
3.2 Developed countries are among the least exposed for imports 60
3.3 Countries with high cross-border risks also tend to experience significant domestic climate risks 61
3.4 Exposure through exports differs from exposure through imports 61
3.5 Even when aggregate exposure is low, substantial risks may persist for specific products 65
4 Discussion and conclusion **67**
5 References **68**
A Measuring cross-border climate exposure **73**
A.1 Climate risk indices 73
A.2 Measuring cross-border climate exposure with input-output data 74
B Distribution of exposure and its decomposition **80**
C Descriptive results for all four exposure measures **86**
C.1 Descriptive results for all countries 87
C.2 Discussion of a few specific country cases 89
D Exposure by product among developed countries **106**
E Sensitivity analysis on risk classification **117**
E.1 Sensitivity analysis on risk threshold 117
E.2 Do the results depend on only one country? 120
F Robustness of the spatial distribution of local climate risk **127**
F.1 Aggregating biophysical and vulnerability indicators 127
F.2 Climate change impact on GDP 129

1 Introduction

Over the past few years, disruptions in global supply chains have emerged as a prominent policy concern. Even though not the only factor, extreme events have contributed to this recent surge. For instance, the 2020-2023 global chip shortage has been partly attributed to the 2021 drought in Taiwan (Barbiroglio, 2021). Similarly, the significant rise in global food prices since 2022 has been linked to the fact that the last few years ranked, globally, among the driest in the recent past (Ryan, 2023). As climate risks—whether through extreme events or long-term trends—are expected to increase in the future, climate-related disruptions to supply chains are also likely to become more frequent and severe (IPCC, 2021). This is why, alongside other channels such as finance networks, human migration, and geopolitics (Carter et al., 2021), trade has been recognized as a specific pathway for cross-border impacts of climate change: countries

can suffer economic losses when their trade partners are hit by climate impacts. The risk has sometimes been estimated to possibly exceed the risk of local climate impacts in some countries (PwC, 2013; Schenker, 2013), but its quantitative assessments remain scarce, and it is generally not integrated into countries' climate change vulnerability assessments (IPCC, 2023). A better view of this risk could aid its integration into adaptation strategies, and facilitate cooperation between countries, which is essential for adapting to cross-border risks (Benzie et al., 2019; Adaptation Without Borders, 2023).

An emerging literature tries to measure and compare the exposure of countries to supply chain risks, through input-output (Baldwin et al., 2023a; OECD, 2023a) or customs data (UE Commission, 2021; Jaravel et al., 2021). However, these studies, often conducted in the context of geopolitical trade competition or in the aftermath of the COVID-19 pandemic, define risk as 'being dependent on foreign countries' or 'importing products from a limited number of countries', with no consideration of climate change. Yet, as climate risk is heterogeneously distributed across the globe, depending on climate-riskier countries might be more of a concern than depending on unspecified foreign countries, since they would be more frequently or severely affected by climate impacts, which constitute the concrete manifestations of climate risks.

Another body of literature explores the effect of climate change on supply chains but focuses on a limited number of economic sectors or climate change-related hazards, such as floods, droughts, etc. Some studies analyse how climate change might affect international trade in a definite industry (Fleming et al., 2014; Langholtz et al., 2014; Parajuli et al., 2019; Nakano, 2021; Hedlund, Carlsen, et al., 2022). Other estimate the supply chain consequences of climate risks across all industries–using economic models based on Multi-Regional Input-Output Tables (MRIOT)– but focus on a limited number of hazards (Schenker, 2013; Wenz et al., 2016; Willner et al., 2018; Kuhla et al., 2021; Sun et al., 2024). Hedlund, Fick, et al. (2018) propose indicators to assess cross-border climate risks across multiple dimensions (e.g., transboundary water dependency, remittance flows, openness to asylum), with trade being one channel. However, they measure exposure through trade solely by a country's openness to commerce, without distinguishing between trade partners of different risk levels.

Here, we aim at providing a first global view on countries' exposure to climate risks through international trade, considering all economic sectors and a wide range of climate risks. To do so, we combine the main publicly-available databases on global trade networks and country-level climate risks to systematically quantify national economies' exposure to potential supply-chain disruptions from climate risks. We find a strong heterogeneity in cross-border climate risk. Notably, countries facing greater threats to their upstream supply chains tend to be countries also exposed to high climate risks on their own territory, as a result of both regional trade integration and geographic concentration of climate risks. However, all countries face significant exposure for at least one type of product. These conclusions appear robust across the diverse databases publicly available on climate risk and on trade.

2 Methods

We use a framework originally proposed by Nakano to study the exposure of four countries' motor industry to foreign climate risk (Nakano, 2017; Nakano, 2021), and we extend it to global, multi-sector and multi-hazard databases: we integrate MRIOT data with country-specific climate risk indices, to evaluate countries exposure to foreign climate risk through trade.

2.1 Trade networks

Trade networks are described through OECD Inter-Country Input-Output (ICIO) (2018 version) (OECD, 2023b) and EORA26 (2016 version) (Lenzen et al., 2012), two sets of MRIOT data. Designed to study international trade, ICIO has a detailed description of economic sectors (45) and is centred around 66 countries that account for more than 90% of annual trade. It has been used in projects which aim at assessing and comparing countries' dependence on foreign clients and suppliers (Baldwin et al., 2023a; OECD, 2023a). EORA26 on the other side is coarser in terms of sector disaggregation (26 sectors) but takes into account more than 180 countries, which allows to describe trade among high climate risk countries in Africa or Asia. Other often used MRIOTs, such as WIOD42 or EXIOBASE43, do not cover as many countries (respectively 43 and 44 countries).

2.2 Climate risk indices

Even though all countries are concerned with climate change, the degree of climate risk, as measured by hazards, exposure and vulnerability is spatially heterogeneous. Several climate risk indices have been developed by public institutions to help decision makers pinpoint countries most at risk from actual and future climate change (Feldmeyer et al., 2021; Birkmann et al., 2021; Garschagen et al., 2021). Here, we use ND-GAIN and INFORM Climate Change, the only publicly available indices that are built explicitly on future climate change projections (University of Notre Dame Adaptation Initiative, 2023; European Commission. Joint Research Centre., 2022). Each country is given a climate risk score that accounts for hazard, exposure and vulnerability. While ND-GAIN represents a wide range of climate impacts, both slow and fast-onset (e.g. food production, water availability, health, infrastructure), INFORM Climate Change focuses on future population exposure to fast-onset climate impacts (flood, drought, epidemics) (Appendix A for a detailed presentation of climate risk indices). These indices are country-specific and not country-sector-specific.

We use the climate risk indices to classify countries into two levels of local climate risk: low and high, through a threshold score. INFORM Climate Change already distinguishes five risk categories (very low, low, medium, high, and very high), based on a clustering method. We set the threshold at 3.5/10, that is between original low and medium risk categories. No risk classification is already available for ND-GAIN: 50/100 is chosen so that the list of high risk countries is generally consistent between both indices. These lists align well with both multidimensional risk analysis (Warren et al., 2022; Byers et al., 2018) and the literature on climate change impact on GDP (Burke et al., 2015; Kalkuhl et al., 2020) (Appendix F). Based

on these thresholds, the two indices largely agree on which countries are considered risky, but they diverge in specific cases: for instance, China is classified as risky by the INFORM Climate Change index but not by ND-GAIN, whereas Argentina is considered risky by ND-GAIN but not by INFORM Climate Change (for a visual representation of the division between countries with low and high local climate risk, see Figure 2.1 for INFORM Climate Change and Figure 2.5 in Appendix A for both indices). The categorization of countries into "developed", "developing" and "least developed" is sourced from the statistical portal of the United Nations Conference on Trade and Development (UNCTAD, 2024).

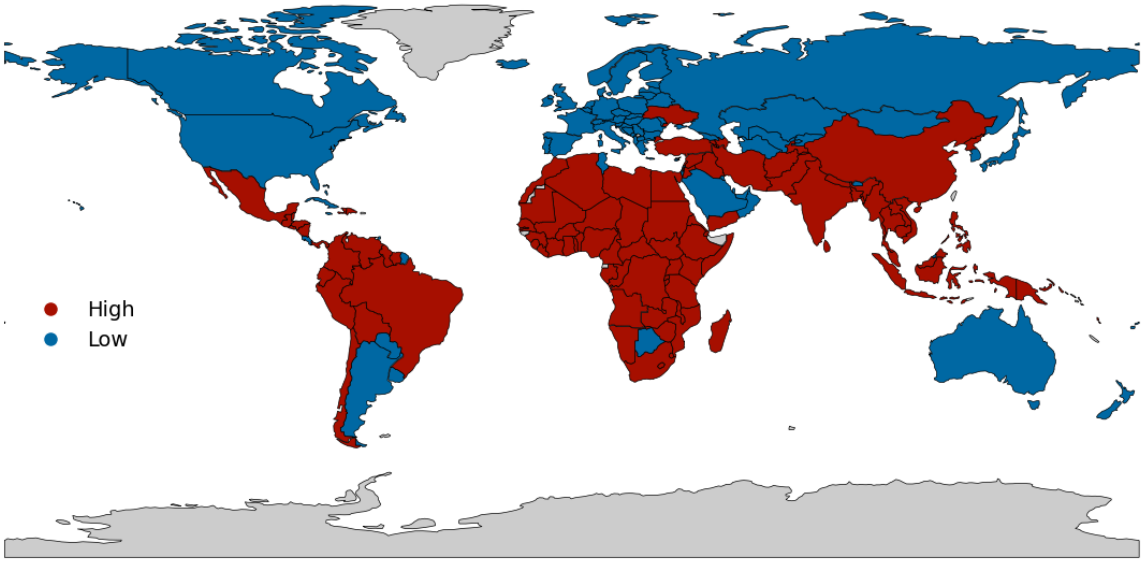
2.3 Measuring cross-border climate exposure

Global trade networks data are combined with country indices characterizing future climate risk. For a given country, both firms and consumers are exposed to climate impacts through international trade. Companies are linked to high climate risk countries through import of intermediate consumption and export of their own production. Households face risks on imported final consumption. We define four measures of exposure: cross-border climate exposure on imports of intermediate or final consumption, on exports to foreign consumers or foreign companies. They are defined as trade dependence on the climate-riskiest countries, i.e. the share of imported (resp. exported) intermediate consumption (resp. final consumption) coming from (resp. going to) high climate risk countries. This can be determined using the Leontief matrix, which accounts for both direct imports (resp. exports) from (resp. to) high risk countries and indirect exposure, as high risk countries are present upward along the supply chain (Baldwin et al., 2023b) (see Appendix A for explicit formulas and discussion). Exposure, as defined here, is distinct from the share of trade with high climate risk countries. By construction, exposure is a product of dependence on foreign countries (i.e. how reliant a country's economy is on imports or exports) and share of trade with high climate risk countries (i.e. the percentage of imports or exports from or to countries with a high climate risk).

2.4 Robustness analysis

The indicators were separately computed 4 times with each database choice (ND-GAIN/ICIO, ND-GAIN/EORA26, INFORM/ICIO, INFORM/EORA26), and for each of the 4 types of exposure (imports of intermediate and final consumption and exports for intermediate and final exposure, see Appendix C). Robustness checks have also been done on risk thresholds (Appendix E). In the main text, when presenting indicators on country aggregate exposure, we mostly refer to results obtained with EORA26 to cover as many countries as possible. We mostly refer to results obtained with ICIO to quantify exposure by product, since its higher number of sectors offers a finer description of international trade.

Figure 2.1: Climate Risk by Country according to INFORM Climate Change



Lecture: INFORM Climate Change risk index is available for several warming scenarios and reference year. The pessimistic scenario (RCP8.5) in the year 2050 has been chosen here. The corresponding map for ND-GAIN is available in Appendix A, see Figure 2.5.

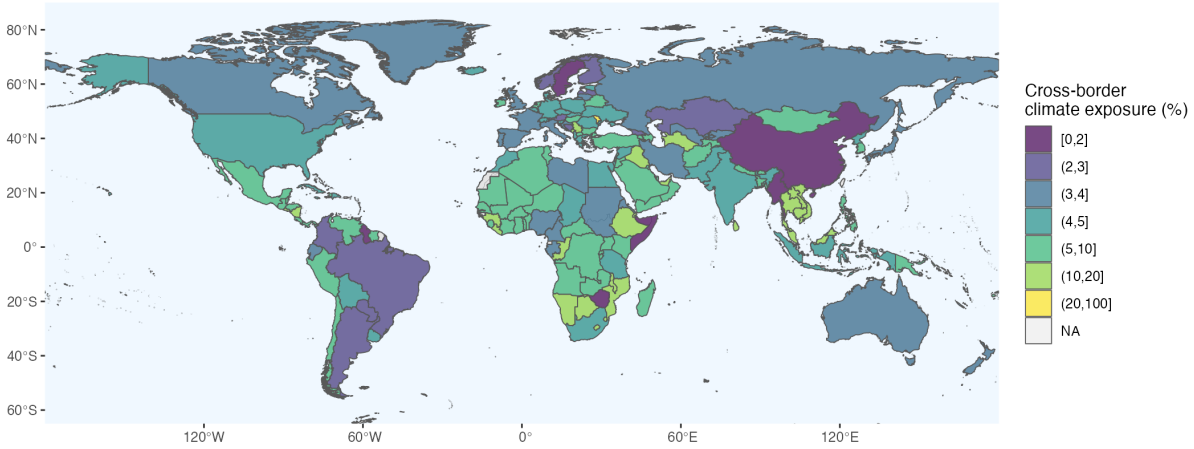
3 Results

3.1 Cross-border exposure is heterogeneous across countries

The value of cross-border exposure indicators relies on the choice of a specific risk index and input-output table. For instance, the level of exposure hinges on whether China is deemed a high climate risk country or not. Detailed descriptive results for all four exposure measures, across all combinations of climate risk indices and input-output tables, are available in Appendix C. Nevertheless, several qualitative messages remain valid across all configurations of climate risk index and input-output tables. Below, numerical results are reported using INFORM Climate Change as the climate risk index, since qualitative outcomes are consistent whether INFORM Climate Change or ND-GAIN is used. For trade data, EORA26 is used in the aggregate analysis due to its broader country coverage. First, cross-border climate exposure varies significantly between countries. We find that the median exposure for intermediate consumption is 5.4%, while it is more than twice higher (13.1%) for the top 10% of countries (Figure 2.2 for exposure by country, see also Figure 2.6 in Appendix B, for distributions for all datasets). This discrepancy is due to both large variations in the dependence on foreign countries (while median is 22%, 90th percentile is 34%) and in the share of high risk suppliers (median 32% and 90th percentile 48%) (see Figure 2.7 and Figure 2.8 in Appendix B for all results). Dependence on foreign countries and share of high risk suppliers are generally both lower than 40%, because national production is predominantly meant for national consumption, and low risk countries account for a high share of global trade (53% of trade in intermediate products occurs between low risk countries and 41% between a low and high risk country).

Figure 2.3a categorizes countries based on these two criteria: whether their dependence on foreign countries exceeds the global median and whether their suppliers present higher risks than the global median. For instance, France has both a low dependence on imports (17.3%) and a low share of risky trade partners (21%), resulting in a low total exposure (3.6%). At the other end of the spectrum, Vietnam shows both high import dependence (45.5%) and a high share of risky trade partners (39.7%), leading to a high total exposure (16.9%). However, for some countries, one dimension can offset the other. In Tunisia's case, the share of risky trade partners is relatively low (20.6%), but dependence on foreign countries is above the median (25.9%), resulting in an exposure of 5.3%. Conversely, the United States has low dependence on foreign countries (9.4%), but a share of risky trade partners above the median (42.9%). These results are due to the size of the country, as larger economies are more likely to be self-sufficient, and to the choice of trade partners.

Figure 2.2: Distribution of cross-border climate exposure for imports of intermediate consumption across countries (data used: INFORM Climate Change for climate risk, EORA26 for global trade data)



See Appendix C for robustness tests with other datasets and other exposure measures.

3.2 Developed countries are among the least exposed for imports

Identification of countries least and most exposed differ when considering exposure on imports or exports. For imports of intermediates, developed countries are among the least exposed to climate cross-border risk: with a median exposure of 4.2%, 75% of developed countries exhibit lower exposure than the global median, and 88% show lower exposure than the median for non-developed countries (Figure 2.9a in Appendix B). Among developed countries, all in North America and 93% in Western Europe fall below the global median. However, the underlying reasons vary among countries. As can be seen on Figure 2.3a, some developed nations exhibit low cross-border exposure due to their low dependence on foreign countries, despite having a high proportion of high-risk suppliers (e.g., the US). In contrast, others have a high dependence

on foreign countries but a low proportion of high-risk suppliers (e.g., most European countries).

The disparity in exposure on imports between developed and other countries can be explained by the fact that, in general, a large fraction of a country's trade is with its immediate neighbours (Disdier et al., 2008), and that climate risks are geographically concentrated (Warren et al., 2022). In fact, the relationship is significant: the riskier a country is, the higher the proportion of its suppliers is exposed to climate risk (Figure 2.3c). While the extent of foreign dependence for a country depends on factors such as the size of an economy or its position in the international division of labor (OECD, 2023a), the share of high climate risk trade partners is correlated to whether or not a country is itself at high climate risk. Developed countries, which are among the least climate-risky according to risk indices (see Appendix F), also have a lower share of high climate risk suppliers (20%), compared with developing/least developed countries (35%) (Figure 2.9c in Appendix B). This does not mean that developing countries cannot have low exposure. For example, China has an exposure of 1.8%, which can be explained by its low dependence on imports (11%)—as expected given its size as a large economy—and a share of risky trade partners below the median (17%). This reflects China's diverse trade integration with the rest of the world, including low-risk countries.

3.3 Countries with high cross-border risks also tend to experience significant domestic climate risks

The countries most exposed to cross-border risk are situated in the upper-right corner of Figure 2.3a and tend to be among developing and least developed nations. Furthermore, consistent with the observation that the riskier a country is, the higher the proportion of its suppliers exposed to climate risk, the majority (68%) of countries in this quadrant are also among those most directly affected by climate change impacts. This figure is even higher if we take into account countries population size (Figure 2.3b): 94.2% of people living in high cross border risk countries live in high direct risk countries (see Figure 2.12 in Appendix C for more results). Conversely, populations at low risk are predominantly situated in areas of low to moderate exposure.

Previous results were given for exposure on imports of intermediate consumption. The classification of countries with low and high cross-border exposure appears similar for imports of final consumption as well (see Appendix C for a discussion of all exposure measures, as well as an analysis of specific country cases).

3.4 Exposure through exports differs from exposure through imports

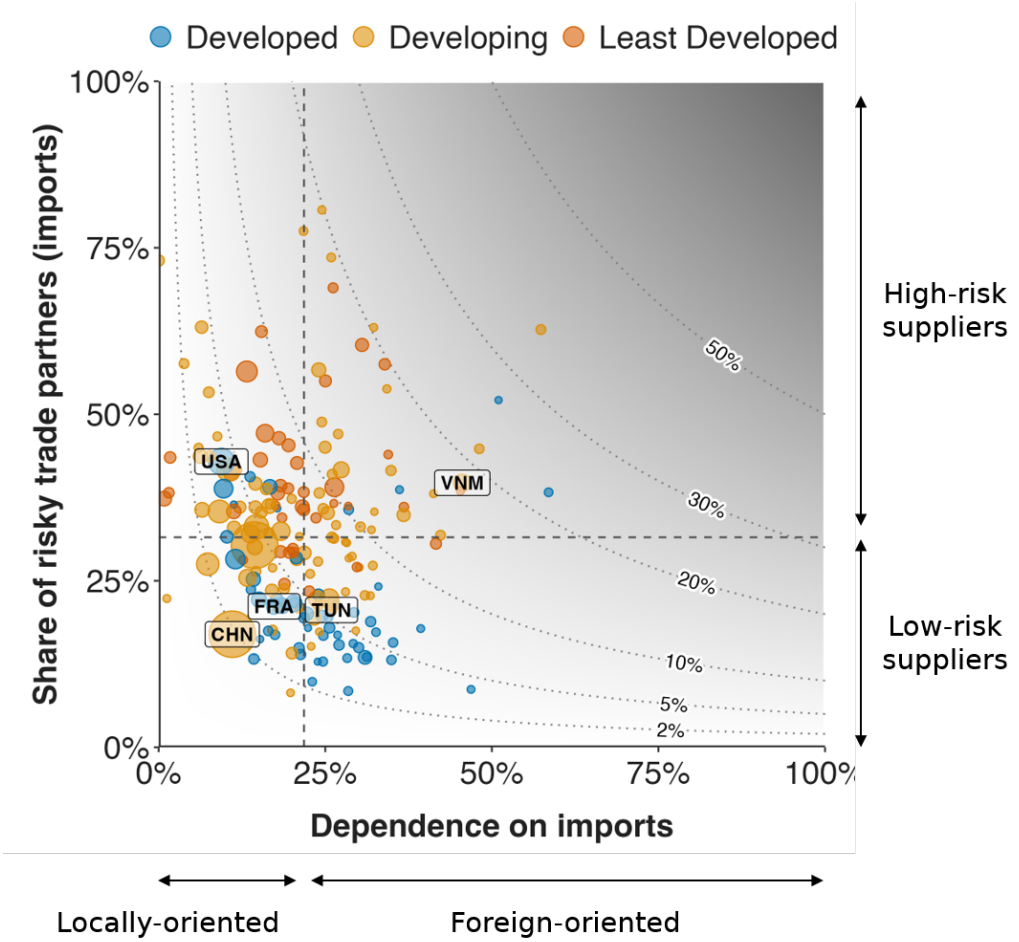
On the contrary, assessing cross-border climate exposure for exports rather than imports yields different results. While the order of magnitude of the exposure is similar to that observed for imports, the ranking of countries changes: developed nations are no longer positioned at the lower end of the exposure distribution (Figure 2.11 and Figure 2.15 in Appendix C) and high-cross border risk countries are not mainly high risk countries. This occurs mostly because

production in developed countries is typically more export-oriented than in developing/least-developed countries: although the proportion of imported intermediate consumption is comparable between these two groups (23.9% and 21.4%), developed countries have a higher share of exported gross output, at 26.4% compared to 16.6% for developing/least developed. Also, while developed countries consistently both import from and export to fewer high risk partners than their developing and least-developed counterparts (19.5% vs 35.4% for imports and 25.5% vs 31.8% for exports), the difference is smaller for exports. Overall, the higher degree of economic openness offsets the lower proportion of trade with risky partners (for all results, see Figure 2.1 in Appendix C).

However, despite this asymmetry between imports and exports, since countries with high cross-border risk for imports are mainly those with high local risk, countries that accumulate high cross-border risk for both imports and exports are predominantly high local risk countries. It should be highlighted that, from a policy perspective, exposure via exports differs from exposure via imports in several key aspects. First, it primarily impacts companies: consumers may indirectly experience income losses but this effect is out of our framework. Second, when an extreme event strikes a location, it disrupts local production and poses a clear risk for countries that import from that area. However, the impact on firms exporting to the affected area is ambiguous: exports may decrease due to a reduction in economic activity, but they could also increase to compensate for the loss in local production, potentially benefiting trading partners.

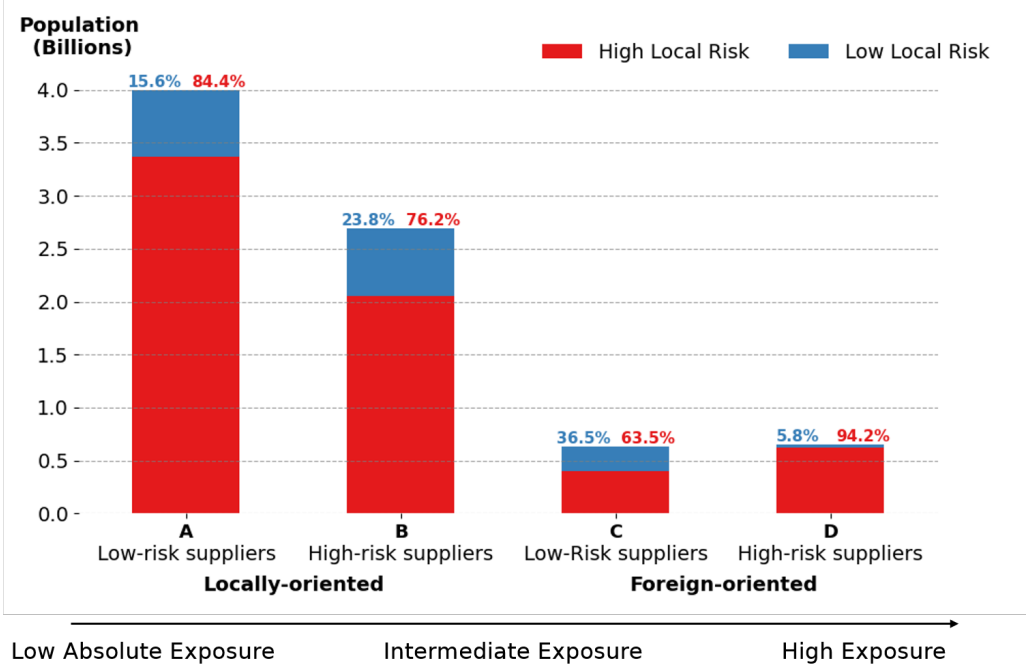
Figure 2.3: Countries most and least exposed to cross-border trade impacts (data used: INFORM Climate Change for climate risk, EORA26 for global trade data)

(a) Distribution of cross-border climate exposure for intermediate consumption across countries. Cross-border climate exposure (greyscale background color) can be due to more economic dependence on import from foreign countries (x-axis) or higher share of high risk suppliers (y-axis).



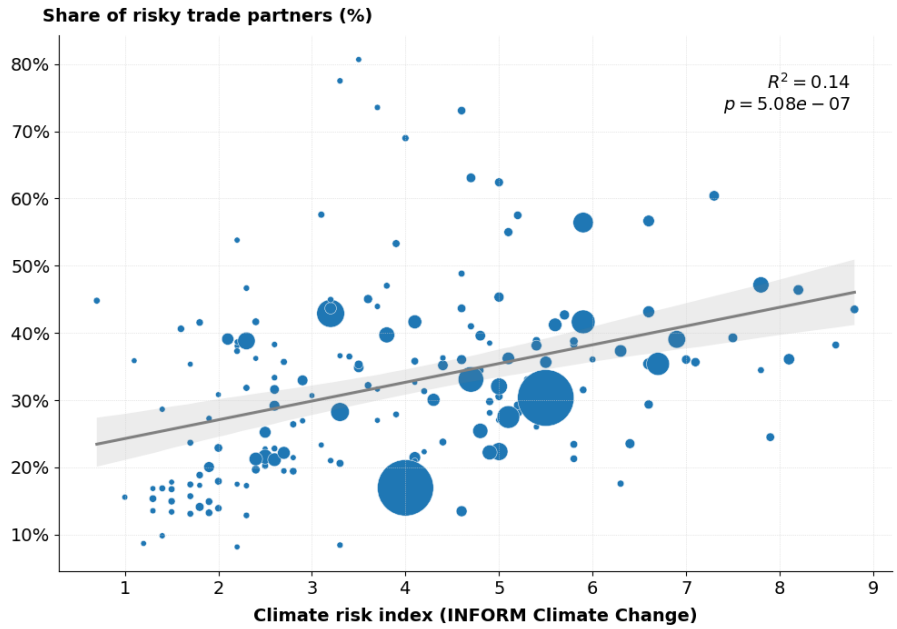
Lecture: Each country is represented by a dot, whose magnitude is proportional to the country's population, and colour indicates its development level. Dotted horizontal and vertical lines indicate median dependence on foreign countries (imports) across countries and median share of high risk suppliers. Dotted hyperbolas indicate constant cross-border climate exposure. Each quarter of the figure corresponds to a column of Panel (b). Countries discussed in the text are indicated: USA = United States of America, VNM = Vietnam, FRA = France, TUN = Tunisia, CHN = China.

(b) Share of Population Living in High or Low Local Risk Country in Each Quadrant of Panel (a).



Lecture: Each column shows how much of the population of a quarter (A, B, C and D) of Panel (a) lives in a high or low climate risk country. Population is shown instead of the number of countries pertaining to each category to avoid bias induced by low-risk small countries.

(c) Relationship between Local Climate Risk and Share of High Risk Trade Partners.



Lecture: Each point represents a country, and a point size is proportional to the country's population. A regression line is plotted along with R^2 and p-value indicating that local climate risk is significantly related to the share of high risk suppliers.

3.5 Even when aggregate exposure is low, substantial risks may persist for specific products

The low level of aggregate exposure can nonetheless conceal high exposure for certain categories of goods. The median exposure to imports for intermediate consumption is 5.4% at the country level across all nations, while the exposure for certain products is significantly higher. 185 out of 187 countries have an exposure above 10% for at least one imported product, and the median exposure across countries for the most exposed product in each country is 32%. The same applies to exports of intermediate consumption: 186 out of 187 countries have an exposure above 10% for at least one exported product, and the median exposure across countries for the most exposed product in each country is 27%.

More specifically, even developed countries, which are among the least exposed through upstream supply chains, are highly exposed through the import of several items. Below, ICIO is used as the trade data source, as it offers a finer sectoral resolution—45 sectors compared to 26 in EORA26—allowing for more precise results. We find that the most exposed categories of goods are mostly manufacturing products or raw materials, such as textiles (24%), mining and quarrying (20%) or electronics (19%), to be compared with an aggregate exposure of 3.1% with ICIO (Figure 2.4a). On the exports side, products such as basic metals (11%), chemical products (7.5%) or rubber and plastics products (6.9%) have an exposure level higher than aggregate level (3.3%) (Figure 2.4b). Products with high exposure differ between imports and exports (see Appendix D for results with all databases).

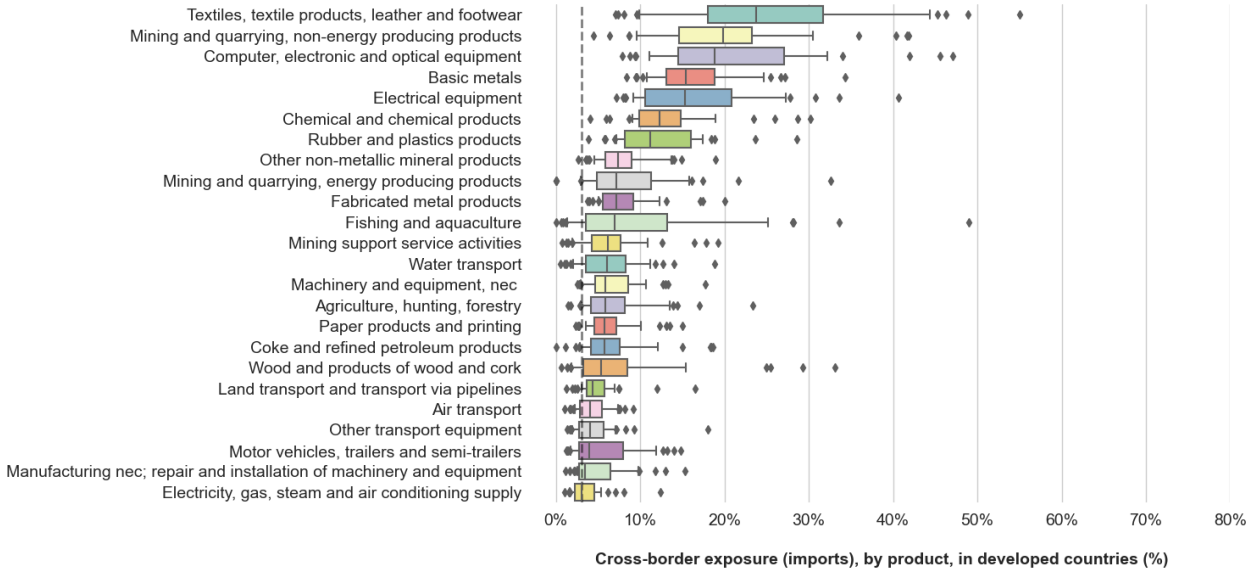
Exposure to imported products can be particularly problematic if it involves items with concentrated sources: when the majority of these goods come from a limited number of countries, it becomes more difficult for firms to find alternative suppliers in case of climate impacts in one of those regions. It appears that, in developed countries, the most exposed imported products tend to be those with a particularly concentrated supply, when compared to all available products (Figure 2.18 in Appendix D).

Finally, heterogeneity in exposure by product leads to a situation where economic sectors are not all affected the same way, as each sector tend to use imported inputs of different types. In developed countries, the impact on economic sectors is uneven: The production of textiles (9.4%) and electronic and electrical equipment (8% and 7.9%, respectively) face an exposure that is double that of the entire economy, as they rely, more than other economic sectors, on imports from countries with high climate risks. However, the difference between aggregate exposure and the highest sector exposure is smaller than the difference between aggregate exposure and the highest exposure by product (Figure 2.19 in Appendix D).

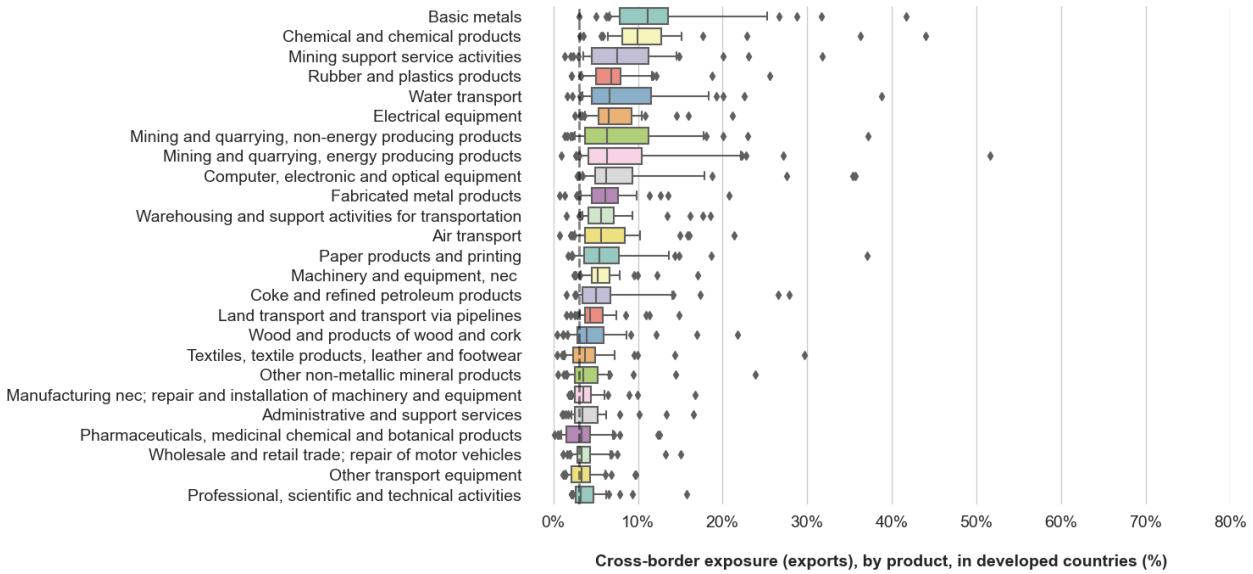
It should be noted that all results presented here depend on the quantitative threshold that distinguishes between low and high climate risk. However, our qualitative conclusions remain robust when performing a sensitivity analysis on this parameter (see Appendix E).

Figure 2.4: Exposure by product, among developed countries, for the most exposed sectors (26 sectors out of 45) (INFORM Climate Change, ICIO)

(a) Imports of intermediate production.



(b) Exports of intermediate production.



Lecture: For each selected product of the ICIO tables, a box plot represents the distribution of cross-border climate exposure on imports (Panel a) and exports (Panel b) of intermediate consumption among developed countries. The vertical dotted line represents sector-aggregated median exposure for developed countries (3.1% for imports and 3.3% for exports). Boxplots indicate median, lower and upper quartiles while whiskers extend 1st and 9th deciles. Only sectors where median exposure is above aggregate exposure are selected: 26 (imports) and 24 (exports) out of 45 (see Figure 2.17a in Appendix D, for all sectors).

4 Discussion and conclusion

An important limit of our approach is the fact that it compares current trade networks to future climate risks. Trade patterns are expected to evolve in the future due to socioeconomic factors. For instance, a large share of future economic growth is expected in Africa and Asia, regions that are currently considered to be at high climate risk (Leimbach et al., 2017). However, the effect on cross-border climate exposure is uncertain. While economic growth may increase trade with these areas, it could also reduce their vulnerability, and lower their climate risk index. Beyond socio-economic factors, climate impacts themselves may discourage trade with certain countries. This can be explored, for instance, using long-term computable general equilibrium (CGE) or quantitative trade models (Schenker, 2013; Dellink et al., 2019; Gouel et al., 2021; Cruz et al., 2024). Such a mechanism would mechanically reduce countries' exposure, assuming that economic agents respond optimally to climate risks. However, the magnitude of these potential reallocations and the identification of barriers to adjustment remain complex research questions. In particular, if the most climate-vulnerable countries end up trading more intensively among themselves due to the withdrawal of less exposed partners, accounting for endogenous responses to climate shocks could actually reinforce our findings. Such an exploration would require a clear distinction between different types of climate risks—whether stemming from extreme events or long-term trends—as the practical implications for trading partners vary accordingly. While extreme events tend to cause abrupt supply disruptions, slow-onset processes gradually affect production capacities, potentially leading to long-term trade reallocation if the affected country fails to adapt.

Available climate risk indices and trade data also limit our investigation. First, as climate risk is given by a country index, sub-national risk heterogeneity is not represented (i.e. risk in one part of a country vs. in another). However, as climate risk is often homogeneous across world regions, spanning on multiple countries (Byers et al., 2018), and as human activity is often located in the more vulnerable areas at the subnational level (Rentschler et al., 2023), the impact on our result may either be moderate or lead to an underestimation. Second, the same risk level is given for all types of economic activities, while some industries are more vulnerable than others to climatic conditions (for instance, agriculture vs. manufacturing). Nevertheless, even though sectors are not equally vulnerable to climate change, climate risks have the potential to disrupt any economic sector (e.g. manufacturing or services might be impacted by heatwaves, droughts impact tourism, energy production and not only agriculture) (Desmet et al., 2015). In the future, development of climate risk indices by sector could help refine our assessment.

A thorough evaluation of the economic costs associated with the cross-border risk should take into account market mechanisms (e.g. substitution between suppliers or buyers) or network effects (e.g. amplify direct costs because of low substitution or low product homogeneity, see Henriet et al., 2012; Elliott et al., 2022). Such features cannot be assessed with the data used here, but models of economic cost propagation through trade networks, a field in rapid development, could be employed to this end, by progressively incorporating a broader range of direct impacts (Kuhla et al., 2021; Sun et al., 2024). Acknowledging these limitations, we

do not claim to assess future climate risks on supply chains, but rather to document several robust stylized facts under the assumption that climate change unfolds within the existing trade structure. This information provides a useful benchmark to help determine whether trade networks should be reshaped through policy intervention (e.g., incentives or tariffs, even though these measures are not without controversy, given their tendency to displace risks geographically or sectorally instead of addressing them directly, see Bednar-Friedl et al., 2022). It also offers quantitative insights to inform national adaptation strategies regarding cross-border climate risks. Policies designed to foster resilience to cross-border trade climate impacts could also be informed by integrating customs data and climate risk indices, for finer targeting at product level, and therefore better consideration of non-substitutability between suppliers (UE Commission, 2021).

To sum up, exposure to climate change through global supply chains varies greatly between countries. The countries most exposed through upstream supply chains are already at high direct risk, as a result of both regional trade integration and geographic concentration of climate risks. Conversely, developed countries, which are relatively less at risk from climate change, exhibit lower exposure to cross-boundary risks on their imports. However, disaggregating by economic sectors shows that even these lower exposed countries face strong sector exposure on a wide range of manufacturing goods. Moreover, this relatively lower exposure disappears when focusing on exports: exposure results from the interaction between dependence on foreign countries and the share of risky trade, and it appears that the former offsets the latter in the case of exports.

This shows that, from a developed countries perspective, financing climate adaptation in the Global South could be justified from a national resilience perspective. Besides, several developing or least developed countries appear to be doubly disadvantaged: both by direct climate impacts and trade cross-boundary risks. These results both confirm and refine the concerns of "double exposure" of the poorest countries, already highlighted by Hedlund, Fick, et al. (2018). Diversifying future trade could be a solution for them, even though trading with more distant partners might be costlier. There is an academic debate about whether international trade could enhance resilience or lead to higher exposure to climate change impacts (Wenz et al., 2016; Janssens et al., 2021). Whether trade openness is beneficial or detrimental in the context of increasing cross-border risk is a non-trivial question, and should be studied through a complex cost-benefit analysis. In the short term, the benefits stem from the smoothing of local shocks through imports, while the costs relate to the propagation of foreign shocks. In the long term, outcomes would also depend on the reconfiguration of trade networks and its implications for gains from trade. Our results highlight that the choice of trade partners plays a key role in this issue, because in current trade networks direct and trade-related climate risks can be correlated.

5 References

Adaptation Without Borders (2023). *The Global Transboundary Climate Risk Report*. Tech. rep. URL: https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Rapport/the_global_transboundary_climate_risk_report.pdf.

Baldwin, Richard, Rebecca Freeman, and Angelos Theodorakopoulos (2023a). *Hidden Exposure : Measuring US Supply Chain Reliance*. Tech. rep. URL: http://www.nber.org/papers/w31820.pdf.

— (2023b). "Horses for Courses: Measuring Foreign Supply Chain Exposure". *SSRN Electronic Journal*. URL: https://www.ssrn.com/abstract=4335496 (visited on 05/20/2025).

Barbiroglio, Emanuela (2021). "No Water No Microchips: What Is Happening In Taiwan?" *Forbes*.

Bednar-Friedl, Birgit, Nina Knittel, Joachim Raich, and Kevin M. Adams (2022). "Adaptation to transboundary climate risks in trade: Investigating actors and strategies for an emerging challenge". *WIREs Climate Change* 13.2. URL: https://onlinelibrary.wiley.com/doi/10.1002/wcc.758 (visited on 08/08/2023).

Benzie, Magnus and Åsa Persson (2019). "Governing borderless climate risks: moving beyond the territorial framing of adaptation". *International Environmental Agreements: Politics, Law and Economics* 19.4-5, pp. 369–393. URL: http://link.springer.com/10.1007/s10784-019-09441-y (visited on 07/02/2024).

Birkmann, Joern, Daniel Feldmeyer, Joanna M McMillan, William Solecki, Edmond Totin, Debra Roberts, et al. (2021). "Regional clusters of vulnerability show the need for transboundary cooperation". *Environmental Research Letters* 16.9, p. 094052. URL: https://iopscience.iop.org/article/10.1088/1748-9326/ac1f43 (visited on 09/20/2023).

Burke, Marshall, Solomon M. Hsiang, and Edward Miguel (2015). "Global non-linear effect of temperature on economic production". *Nature* 527.7577, pp. 235–239. URL: http://www.nature.com/articles/nature15725 (visited on 12/21/2022).

Byers, Edward, Matthew Gidden, David Leclère, Juraj Balkovic, Peter Burek, Kristie Ebi, et al. (2018). "Global exposure and vulnerability to multi-sector development and climate change hotspots". *Environmental Research Letters* 13.5, p. 055012. URL: https://iopscience.iop.org/article/10.1088/1748-9326/aabf45 (visited on 08/22/2023).

Carter, Timothy R., Magnus Benzie, Emanuele Campiglio, Henrik Carlsen, Stefan Fronzek, Mikael Hildén, et al. (2021). "A conceptual framework for cross-border impacts of climate change". *Global Environmental Change* 69, p. 102307. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378021000868 (visited on 08/08/2023).

Cruz, José-Luis and Esteban Rossi-Hansberg (2024). "The Economic Geography of Global Warming". *Review of Economic Studies* 91.2, pp. 899–939. URL: https://academic.oup.com/restud/article/91/2/899/7107009 (visited on 05/06/2025).

Dellink, Rob, Elisa Lanzi, and Jean Chateau (2019). "The Sectoral and Regional Economic Consequences of Climate Change to 2060". *Environmental and Resource Economics* 72.2, pp. 309–363. URL: http://link.springer.com/10.1007/s10640-017-0197-5 (visited on 08/22/2023).

Desmet, Klaus and Esteban Rossi-Hansberg (2015). "On the spatial economic impact of global warming". *Journal of Urban Economics* 88, pp. 16–37. URL: https://linkinghub.elsevier.com/retrieve/pii/S0094119015000339 (visited on 12/14/2022).

Disdier, Anne-Célia and Keith Head (2008). "The Puzzling Persistence of the Distance Effect on Bilateral Trade". *Review of Economics and Statistics* 90.1, pp. 37–48. URL: https://direct.mit.edu/rest/article/90/1/37-48/58643 (visited on 01/31/2024).

Eckstein, David, Maik Winges, Vera Künzel, and Laura Schäfer (2019). *Global Climate Risk Index 2020 Who Suffers Most from Extreme Weather Events? Wether-Related Loss Events in 2018 and 1999 to 2018*. Bonn: Germanwatch Nord-Süd Initiative e.V.

Elliott, Matthew and Benjamin Golub (2022). "Networks and Economic Fragility". *Annual Review of Economics* 14.1, pp. 665–696. URL: https://www.annualreviews.org/doi/10.1146/annurev-economics-051520-021647 (visited on 07/12/2023).

European Commission. Joint Research Centre. (2022). *INFORM Climate Change: quantifying the impacts of climate and socio economic trends on the risk of future humanitarian crises and disasters*. LU: Publications Office. URL: https://data.europa.eu/doi/10.2760/383939 (visited on 10/10/2023).

Feldmeyer, Daniel, Joern Birkmann, Joanna M. McMillan, Lindsay Stringer, Walter Leal Filho, Riyanti Djalante, et al. (2021). "Global vulnerability hotspots: differences and agreement between international indicator-based assessments". *Climatic Change* 169.1-2, p. 12. URL: https://link.springer.com/10.1007/s10584-021-03203-z (visited on 09/20/2023).

Fleming, A., A.J. Hobday, A. Farmery, E.I. Van Putten, G.T. Pecl, B.S. Green, et al. (2014). "Climate change risks and adaptation options across Australian seafood supply chains – A preliminary assessment". *Climate Risk Management* 1, pp. 39–50. URL: https://linkinghub.elsevier.com/retrieve/pii/S2212096313000065 (visited on 01/28/2024).

Garschagen, Matthias, Deepal Doshi, Jonathan Reith, and Michael Hagenlocher (2021). "Global patterns of disaster and climate risk—an analysis of the consistency of leading index-based assessments and their results". *Climatic Change* 169.1-2, p. 11. URL: https://link.springer.com/10.1007/s10584-021-03209-7 (visited on 09/20/2023).

Gouel, Christophe and David Laborde (2021). "The crucial role of domestic and international market-mediated adaptation to climate change". *Journal of Environmental Economics and Management* 106, p. 102408. URL: https://linkinghub.elsevier.com/retrieve/pii/S0095069620301315 (visited on 09/01/2022).

Hedlund, Johanna, Henrik Carlsen, Simon Croft, Chris West, Örjan Bodin, Emilie Stokeld, et al. (2022). "Impacts of climate change on global food trade networks". *Environmental Research Letters* 17.12, p. 124040. URL: https://iopscience.iop.org/article/10.1088/1748-9326/aca68b (visited on 08/09/2023).

Hedlund, Johanna, Stephen Fick, Henrik Carlsen, and Magnus Benzie (2018). "Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk". *Global Environmental Change* 52, pp. 75–85. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378017312505 (visited on 02/29/2024).

Henriet, Fanny, Stéphane Hallegatte, and Lionel Tabourier (2012). "Firm-network characteristics and economic robustness to natural disasters". *Journal of Economic Dynamics and Control* 36.1, pp. 150–167. URL: https://linkinghub.elsevier.com/retrieve/pii/S0165188911001825 (visited on 08/13/2023).

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Tech. rep.

— (2023). *Climate Change 2023 – Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Tech. rep. Intergovernmental Panel on Climate Change (IPCC). URL: https://www.ipcc.ch/report/ar6/syr/ (visited on 06/27/2025).

Janssens, Charlotte, Petr Havlík, Tamás Krisztin, Justin Baker, Stefan Frank, Tomoko Hasegawa, et al. (2021). "International trade is a key component of climate change adaptation". *Nature Climate Change* 11.11, pp. 915–916. URL: https://www.nature.com/articles/s41558-021-01201-8 (visited on 11/09/2022).

Jaravel, Xavier and Isabelle Méjean (2021). "Quelle stratégie de résilience dans la mondialisation ?:" *Notes du conseil d'analyse économique* n° 64.10, pp. 1–12. URL: https://www.cairn.info/revue-notes-du-conseil-d-analyse-economique-2020-10-page-1.htm?ref=doi (visited on 08/11/2023).

Kalkuhl, Matthias and Leonie Wenz (2020). "The impact of climate conditions on economic production. Evidence from a global panel of regions". *Journal of Environmental Economics and Management* 103, p. 102360. URL: https://linkinghub.elsevier.com/retrieve/pii/S0095069620300838 (visited on 01/10/2024).

Kuhla, Kilian, Sven Norman Willner, Christian Otto, Tobias Geiger, and Anders Levermann (2021). "Ripple resonance amplifies economic welfare loss from weather extremes". *Environmental Research Letters* 16.11, p. 114010. URL: https://iopscience.iop.org/article/10.1088/1748-9326/ac2932 (visited on 11/07/2023).

Langholtz, Matthew, Erin Webb, Benjamin L. Preston, Anthony Turhollow, Norman Breuer, Laurence Eaton, et al. (2014). "Climate risk management for the U.S. cellulosic biofuels supply chain". *Climate Risk Management* 3, pp. 96–115. URL: https://linkinghub.elsevier.com/retrieve/pii/S2212096314000199 (visited on 01/28/2024).

Leimbach, Marian, Elmar Kriegler, Niklas Roming, and Jana Schwanitz (2017). "Future growth patterns of world regions – A GDP scenario approach". *Global Environmental Change* 42, pp. 215–225. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378015000242 (visited on 01/30/2024).

Lenzen, Manfred, Keiichiro Kanemoto, Daniel Moran, and Arne Geschke (2012). "Mapping the Structure of the World Economy". *Environmental Science & Technology* 46.15, pp. 8374–8381. URL: https://pubs.acs.org/doi/10.1021/es300171x (visited on 03/27/2024).

Nakano, Katsuyuki (2017). "Screening of climatic impacts on a country's international supply chains: Japan as a case study". *Mitigation and Adaptation Strategies for Global Change* 22.4, pp. 651–667. URL: http://link.springer.com/10.1007/s11027-015-9692-6 (visited on 10/31/2023).

— (2021). "Risk assessment for adaptation to climate change in the international supply chain". *Journal of Cleaner Production* 319, p. 128785. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959652621029838 (visited on 09/28/2023).

OECD (2023a). *Global value chain dependencies under the magnifying glass*. OECD Science, Technology and Industry Policy Papers 142. URL: https://www.oecd-ilibrary.org/science-and-technology/global-value-chain-dependencies-under-the-magnifying-glass_b2489065-en (visited on 11/01/2023).

— (2023b). "OECD Inter-Country Input-Output Database". URL: http://oe.cd/icio.

— (2024). "Towards Demystifying Trade Dependencies: At What Point Do Trade Linkages Become a Concern ?" URL: https://www.oecd-ilibrary.org/trade/towards-demystifying-trade-dependencies_2a1a2bb9-en.

Parajuli, Ranjan, Greg Thoma, and Marty D. Matlock (2019). "Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: A review". *Science of The Total Environment* 650, pp. 2863–2879. URL: https://linkinghub.elsevier.com/retrieve/pii/S0048969718338920 (visited on 01/28/2024).

Piontek, Franziska, Laurent Drouet, Johannes Emmerling, Tom Kompas, Aurélie Méjean, Christian Otto, et al. (2021). "Integrated perspective on translating biophysical to economic impacts of climate change". *Nature Climate Change* 11.7, pp. 563–572. URL: http://www.nature.com/articles/s41558-021-01065-y (visited on 04/06/2022).

PwC (2013). "International Threats and Opportunities of Climate Change to the UK". *Final report*.

Rentschler, Jun, Paolo Avner, Mattia Marconcini, Rui Su, Emanuele Strano, Michalis Vousdoukas, et al. (2023). "Global evidence of rapid urban growth in flood zones since 1985". *Nature* 622.7981, pp. 87–92. URL: https://www.nature.com/articles/s41586-023-06468-9 (visited on 01/31/2024).

Ryan, Carol (2023). "Where Heat Waves Lead, Food Inflation Will Follow". *The Wall Street Journal*.

Schenker, Oliver (2013). "Exchanging Goods and Damages: The Role of Trade on the Distribution of Climate Change Costs". *Environmental and Resource Economics* 54.2, pp. 261–282. URL: http://link.springer.com/10.1007/s10640-012-9593-z (visited on 08/22/2023).

Sun, Yida, Shupeng Zhu, Daoping Wang, Jianping Duan, Hui Lu, Hao Yin, et al. (2024). "Global supply chains amplify economic costs of future extreme heat risk". *Nature*. URL: https://www.nature.com/articles/s41586-024-07147-z (visited on 03/21/2024).

UE Commission (2021). *Strategic dependencies and capacities*. Tech. rep. URL: https://commission.europa.eu/system/files/2021-05/swd-strategic-dependencies-capacities_en.pdf.

UNCTAD (2024). *Country classification*. Tech. rep. URL: https://unctadstat.unctad.org/EN/Classifications.html. (visited on 05/10/2024).

University of Notre Dame Adaptation Initiative (2023). *Country Index Technical Report*. Tech. rep. URL: https://gain.nd.edu/assets/522870/nd_gain_countryindextechreport_2023_01.pdf.

Warren, Rachel, Oliver Andrews, Sally Brown, Felipe J. Colón-González, Nicole Forstenhäusler, David E. H. J. Gernaat, et al. (2022). "Quantifying risks avoided by limiting global warming to 1.5 or 2 °C above pre-industrial levels". *Climatic Change* 172.3-4, p. 39. URL: https://link.springer.com/10.1007/s10584-021-03277-9 (visited on 11/08/2023).

Welle, Torsten and Joern Birkmann (2015). "The World Risk Index – An Approach to Assess Risk and Vulnerability on a Global Scale". *Journal of Extreme Events* 02.01, p. 1550003. URL: https://www.worldscientific.com/doi/abs/10.1142/S2345737615500037 (visited on 10/10/2023).

Wenz, Leonie and Anders Levermann (2016). "Enhanced economic connectivity to foster heat stress–related losses". *Science Advances* 2.6, e1501026. URL: https://www.science.org/doi/10.1126/sciadv.1501026 (visited on 09/29/2023).

Willner, Sven Norman, Christian Otto, and Anders Levermann (2018). "Global economic response to river floods". *Nature Climate Change* 8.7, pp. 594–598. URL: https://www.nature.com/articles/s41558-018-0173-2 (visited on 08/09/2023).

Appendices

A Measuring cross-border climate exposure

Appendix A is divided in two parts. Part 1. gives more details on climate risk indices and Part 2. explains how to measure cross-border climate exposure with input-output data.

A.1 Climate risk indices

ND-GAIN and INFORM Climate Change are used here as climate risk indices (University of Notre Dame Adaptation Initiative, 2023; European Commission. Joint Research Centre., 2022). Each index assigns a climate risk score to countries—185 for ND-GAIN and 191 for INFORM Climate Change. Scores account for hazard, exposure and vulnerability, in the IPCC terminology (IPCC, 2023).

ND-GAIN is measured, for each country, as:

$$\text{Risk} = (\text{Readiness-Vulnerability}+1) \text{ x } 50$$

'Readiness' measures capacity of the country to adapt in the future and has economic (World Bank 'Doing Business' Index), governance (e.g. corruption, rule of law) and social components (e.g. inequality, infrastructure, education). 'Vulnerability' is assessed for 6 broad 'sectors': food, water, health, ecosystem services, human habitat, infrastructure. For each sector, a score is given based on 'exposure', 'sensitivity' and 'adaptive capacity' components. Hazard projections under future climate change are included in the 'exposure' component, based on a 2050 RCP4.5 scenario. For example, in the water sector, two hazard projections are included (projected changes in annual runoff and projected changes in annual groundwater recharge). In the IPCC terminology, 'readiness' measures vulnerability, while 'vulnerability' is mix of hazard ('exposure' component), exposure and vulnerability ('sensitivity' and 'adaptive capacity' components).

INFORM Climate Change is measured, for each country, as:

$$\text{Risk} = (\text{Hazard \& Exposure})^{1/3} \times \text{Vulnerability}^{1/3} \times (\text{Lack of coping capacity})^{1/3}$$

While 'Hazard & Exposure' align with the IPCC definitions, 'Vulnerability' and 'Lack of Coping Capacity' correspond to the notion of vulnerability. The 'Hazard & Exposure' category includes the following hazards: river floods, coastal floods, droughts, epidemics, earthquakes, tsunamis, cyclones, and conflict. Climate change projections are available only for river floods, coastal floods, droughts, and epidemics and are assessed for the year 2050 under the RCP8.5 scenario. Projected demographic changes under 2050 SSP3 influence exposure levels across all hazard categories. 'Vulnerability' accounts for socio-economic variables (e.g. HDI, GINI, child mortality or food security). 'Lack of coping capacity' considers institutional factors and infrastructure capacity that drive resilience (e.g. access to electricity, literacy rates, mobile cellular subscriptions, road density, healthcare access).

Vulnerability is a fundamental component of climate risk scores in both cases, making up 2/3 of the indices used to determine the final score. Currently, these indices measure vulnerability based on existing conditions, even though it is expected that vulnerability will evolve over time.

Other risk indices, such as the World Risk Index (Welle et al., 2015) and the Climate Risk Index (Eckstein et al., 2019), also exist. However, these indices primarily assess hazard and exposure based on historical extreme events, rather than future projections of climate change. For example, the World Risk Index calculates hazard and exposure for events like earthquakes, storms, droughts, and floods using current risk levels from the PREVIEW: Global Risk Data Platform. The World Risk Index accounts for climate change exclusively by assessing exposure to a 1m sea level rise. Meanwhile, the Climate Risk Index is based on past fatalities and economic losses from extreme weather events, as recorded in the Munich Re NatCatSERVICE database. In contrast, the ND-GAIN and INFORM Climate Change are the only publicly available indices that are explicitly constructed based on projections of future climate change. It should be noted that the two indices are based on different RCP scenarios—RCP 4.5 for ND-Gain and RCP 8.5 for INFORM. Nevertheless, by 2050, temperature trajectories are projected to be largely similar under both scenarios (IPCC, 2021).

Using these two risk indices, we categorize countries into two groups: low and high future local climate risk, through a threshold score. INFORM Climate Change already distinguishes five risk categories (very low, low, medium, high, and very high), based on a clustering method. We set the threshold at 3.5/10, that is between original low and medium risk categories. No risk classification is already available for ND-GAIN: 50/100 is chosen so that the list of high risk countries is generally consistent between both indices. These lists align well with both multidimensional risk analysis and the literature on climate change impact on GDP (Appendix F). Based on these thresholds, the two indices largely agree on which countries are considered risky, but they diverge in specific cases: for instance, China is classified as risky by the INFORM Climate Change index but not by ND-GAIN, whereas Argentina is considered risky by ND-GAIN but not by INFORM Climate Change (for a visual representation of the division between countries with low and high local climate risk, see Figure 2.5).

A.2 Measuring cross-border climate exposure with input-output data

For a given country, dependence on foreign countries consists of:

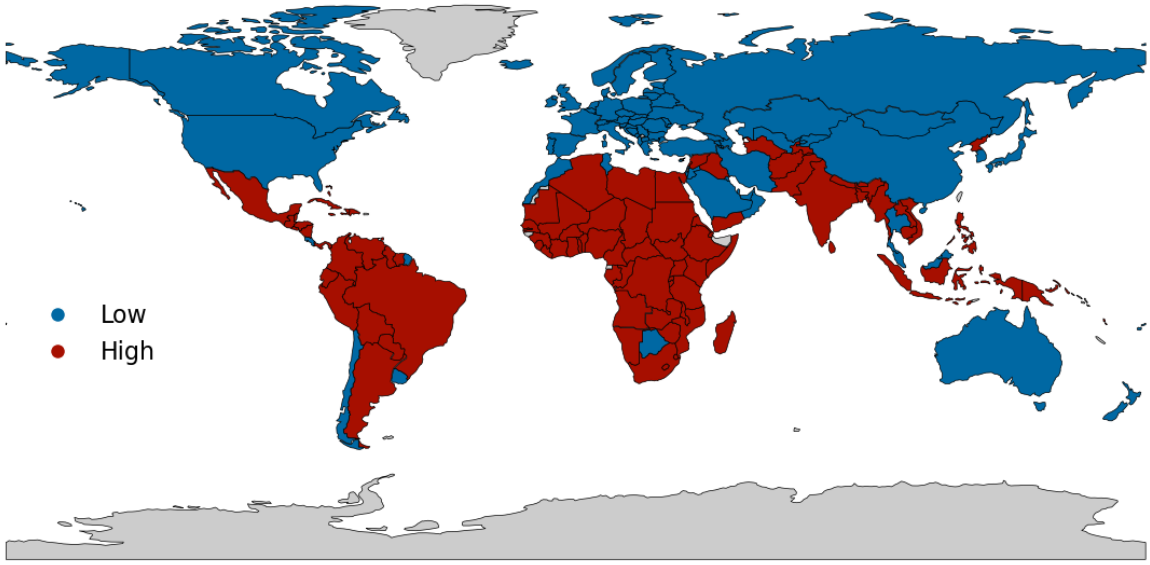
- imports of (i) intermediate consumption and (ii) final consumption,
- and exports directed to (iii) foreign companies and (iv) foreign consumers.

Four indicators are defined to assess each of these four exposures: cross-border exposure (i) on imports of intermediate goods; (ii) on imports of final consumption; (iii) on exports to foreign business interruption; (iv) on exports to foreign final consumption interruption.

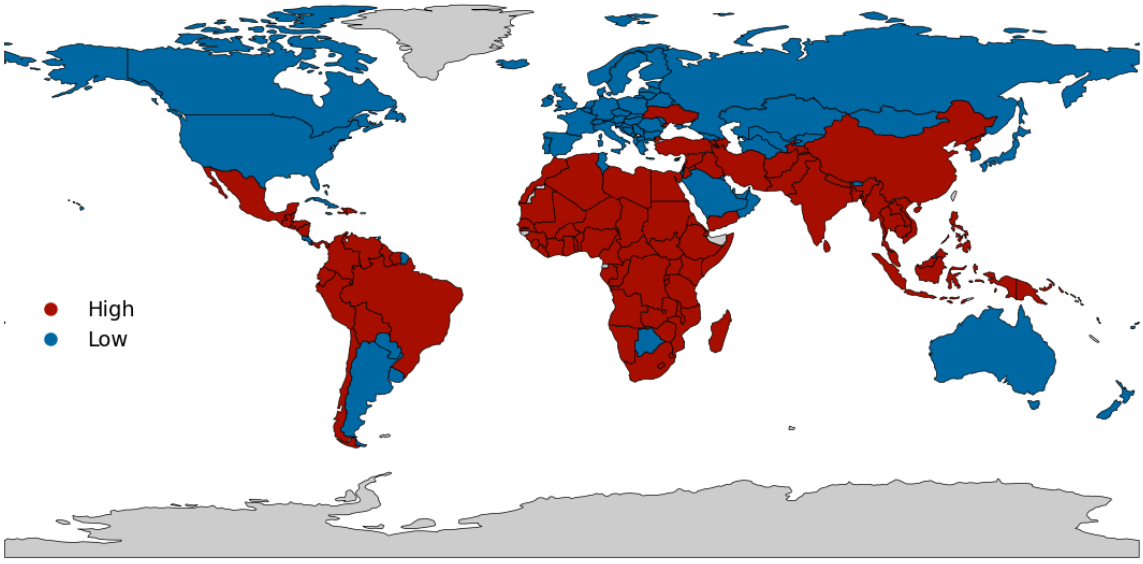
As proposed by Baldwin et al. (2023b), (i) and (iii) are measured respectively by (i) the share of intermediate consumption imported from high climate risk countries and (iii) the share of total gross production exported to high climate risk countries to be used there as intermediate consumption.

Figure 2.5: Climate risk by country according to ND-GAIN and INFORM Climate Change

(a) ND-GAIN Index.



(b) INFORM Climate Change Index.



In the spirit of Baldwin et al. (2023b), we also propose to measure (ii) as the share of final consumption imported from high climate risk countries. Furthermore, we define (iv) as the share of total gross production that would not be exported if consumers in high climate risk countries ceased their consumption.

However, two methodological points need to be considered.

Direct vs Total Exposure

On the one hand, when calculating the exposure of country A to a foreign country B, direct exposure can be assessed by comparing the inputs coming directly from country B with the total intermediate consumption used by country A. Imported intermediate consumption are directly available in the input-output table. Doing so may, however, lead to an underestimation of the exposure of country A to country B, as it does not take into account indirect dependencies via other countries: for example, the dependency of the US manufacturing sector on Chinese intermediate production is largely underestimated if indirect dependency is not taken into account (Baldwin et al., 2023a). Total dependence on a foreign country, also known as look-through exposure, can be measured with IO data, through the Leontief matrix. As we aim to capture total exposure to climate-riskier countries, a look-through perspective is used in the following.

Added-Value vs Gross-Output Measurement

On the other hand, when indirect dependence is considered, the contribution of each country along the supply chain can be valued according to their share of local added-value or local gross output. In the following, exposure is measured in terms of gross output, in order to account for the fact that climate impacts not only stop local production but also disrupt the rest of the value chain, as proposed by Baldwin et al. (2023b).

Explicit formulas

We aim to differentiate countries' foreign dependencies by categorizing them into dependencies on high climate risk countries and low climate risk countries. High climate risk countries are gathered in set R. Formulas are given for cross-border exposure at country-level and sector-level.

MRIOT Notations

- (c, s) indicates the sector s of country c.
- Production: $x = [x_{(c,s)}]$.
- Final demand matrix: $Y = [Y_{(c,s),c'}]$.
- Production for final use: $y = [y_{(c,s)}] = \left[\sum_{c'} Y_{(c,s),c'}\right]$.
- Leontief matrix: $L = [L_{(c,s),(c',s')}]$.
- Intermediate consumption matrix: $Z = [Z_{(c,s),(c',s')}]$.
- Leontief relation: $x = Ly$.
- Set of high climate risk countries (depends on both the climate risk index used and the choice of risk threshold): R.

Explicit country-level formulas

(i) Cross-border exposure on intermediate imports

Based on Baldwin et al. (2023b), it is defined, for a country c, as intermediate consumption imported from high risk countries divided by total intermediate consumption:

$$\frac{\sum_{(c',s',s),\, c' \in R,\, c' \neq c} L_{(c',s'),(c,s)}\, Y_{(c,s)}}{\sum_{(c,s)} L_{(c,s),(c,s)}\, Y_{(c,s)}}$$

(ii) Cross-border exposure on final consumption imports

Share of final consumption coming from a high climate risk country cannot be assessed, in a look-through approach, directly out of the Leontief matrix.

Here we propose to assess risk on final consumption, for a given country c, by weighting the final consumption of c coming from each trade partner by a coefficient r reflecting both the risk of this trade partner and of the intermediate consumption it used. As we want to measure cross-border risk, country c is not considered risky in its own cross-border risk analysis (even if country c is itself at high climate risk). That is why c is taken out of R when assessing share of inputs coming from high risk countries in r.

Cross-border climate exposure on imported final consumption is defined as:

$$\frac{\sum_{(c',s')} Y_{(c',s'),c} \cdot r_{(c,c',s')}}{\sum_{(c',s')} Y_{(c',s'),c}}$$

where:

$$r_{(c,c',s')} = \frac{\text{final production of } (c',s') \text{ if } c' \in R \setminus \{c\} + \text{ share of inputs of } (c',s') \text{ from countries in } R \setminus \{c\}}{\text{final production of } (c',s') + \text{ total inputs of } (c',s')}$$

$$= \frac{y_{(c',s')} \cdot \mathbb{1}_{c' \in R \setminus \{c\}} + \sum_{(c_1,s_1),\, c_1 \in R,\, c_1 \neq c} L_{(c_1,s_1),(c',s')} \cdot y_{(c',s')}}{y_{(c',s')} + \sum_{(c_1,s_1)} L_{(c_1,s_1),(c',s')} \cdot y_{(c',s')}}$$

(iii) Cross-border exposure on exports due to business interruption

Based on Baldwin et al. (2023b), it is defined, for a country c, as exports used by high risk countries as intermediate consumption, divided by total production:

$$\frac{\sum_{(s,c',s'),\, c' \in R} L_{(c,s),(c',s')}\, Y_{(c',s')}}{\sum_{s} x_{(c,s)}}$$

(iv) Cross-border exposure on exports due to final consumption interruption

The share of gross output that would not be produced if final consumers in foreign high risk countries were unable to consume cannot be directly assessed, in a look-through approach, from the Leontief matrix. Here we propose to assess this risk, for a country c, by weighting the exports going to each trade partner by a coefficient indicating how much of final production is destined to consumers in high risk countries. As we want to measure cross-border risk, country c is not considered risky in its own cross-border risk analysis (even if country c is itself at high

climate risk). That is why c is taken out of R when assessing share of inputs coming from high risk countries in r. Cross-border climate exposure on exports due to final consumption interruption is defined, for country c, as:

$$\frac{\sum_{(s,c',s')} L_{(c,s),(c',s')}\, Y_{(c',s')}\, r_{c,c',s'}}{\sum_s x_{(c,s)}}$$

where:

$$r_{c,c',s'} = \frac{\text{final production of } (c',s') \text{ destined to countries in } R \setminus \{c\}}{\text{final production of } (c',s')} = \frac{\sum_{c_1 \in R,\, c_1 \neq c} Y_{(c',s'),c_1}}{\sum_{c_1} Y_{(c',s'),c_1}}$$

To conclude, by definition, cross-border climate exposure is a product of dependence on foreign countries and the share of high climate risk trade partners.

Explicit sector-level formulas

For country c and product of type s.

(i) Cross-border exposure on imports of intermediate consumption

Dependency on product of type s for firms of country c is measured by :

$$\frac{\sum_{(c',s'),\, c' \in R,\, c' \neq c} L_{(c,s),(c',s')}\, y_{(c,s)}}{\sum_{(c',s')} L_{(c',s'),(c,s)}\, y_{(c,s)}}$$

(ii) Cross-border exposure on imports of final consumption

Dependency on product of type s for final consumers of country c is measured by :

$$\frac{\sum_{c'} Y_{(c',s),c} \cdot r_{(c,c',s)}}{\sum_{c'} Y_{(c',s),c}}$$

(iii) Cross-border exposure on exports of intermediate consumption

Dependency on product of type s for firms of country c is measured by:

$$\frac{\sum_{(c',s'),\, c' \in R,\, c' \neq c} L_{(c,s),(c',s')}\, y_{(c',s')}}{x_{(c,s)}}$$

Hirschman-Herfindahl Index

In Appendix D, analysis of exposure by product is complemented by a measure of concentration of suppliers, as a proxy for easiness of substitution. Concentration of suppliers is measured usually by Hirschman-Herfindahl Index (HHI) (OECD, 2024). In our MRIOT framework, HHI can be defined with the following formulas.

For imports of intermediate consumption of product s by country c, HHI is computed as a sum of shares of imports coming from each foreign country:

$$HHI = \sum_{c_1 \neq c} \left[\frac{\sum_{s'} L_{(c_1,s'),(c',s')}\, y_{(c',s')}}{\sum_{(c_2,s_2),\, c_2 \neq c} L_{(c_2,s_2),(c',s')}\, y_{(c',s')}} \right]^2$$

In the same way, for imports of final consumption, HHI is computed as:

$$HHI = \sum_{c_1 \neq c} \left[\frac{Y_{(c_1,s),c}}{\sum_{(c_2,s_2),\, c_2 \neq c} Y_{(c_2,s_2),c}} \right]^2$$

B Distribution of cross-border climate exposure, dependence on foreign countries and share of high risk partners

Cross-border climate exposure varies widely across countries, as shown for all combinations of climate risk index (INFORM Climate Change and ND-GAIN) and MRIOT (EORA26 and ICIO), in the case of imports of intermediate consumption, in Figure 2.6, by comparing Q2 and D9:

- EORA26/INFORM: Q2= 5.4% and D9 = 13.1%
- ICIO/INFORM: Q2= 3.8% and D9 = 10%
- EOR26/ND-GAIN: Q2= 2.4% and D9 = 7.1%
- ICIO/ND-GAIN: Q2=1.1% and D9 = 2.5%.

Two effects explain the differences across the datasets.

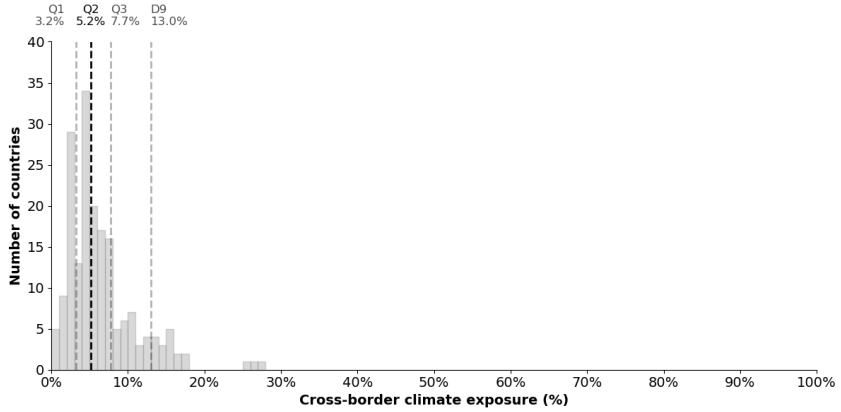
1) ICIO represents fewer countries than EORA26 (66 vs 180) and is more centred around low risk countries. As a consequence, a lot of high risk countries are aggregated into a "Rest of the world" country, which has no climate risk index. Thus, results obtained with ICIO tend to underestimate cross-border climate exposure compared to those obtained with EORA26.
2) Given our choice of risk thresholds, China is considered a high risk country with INFORM Climate Change and not with ND-GAIN. Since this country is quantitatively important in international trade, this explains why climate cross-border exposure is lower when measured with ND-GAIN.

In each case, variation in cross-border climate exposure is due to the fact that there is variation across countries in both dependence to foreign countries (see Figure 2.7, where there are not much quantitative differences between EORA26 and ICIO) and share of high risk suppliers (see Figure 2.8). As shown in Figure 2.8, using ICIO selects developed countries, which tend to have a low share of high risk trade partners, and using ND-GAIN lowers share of high risk trade partners because China is deemed low risk.

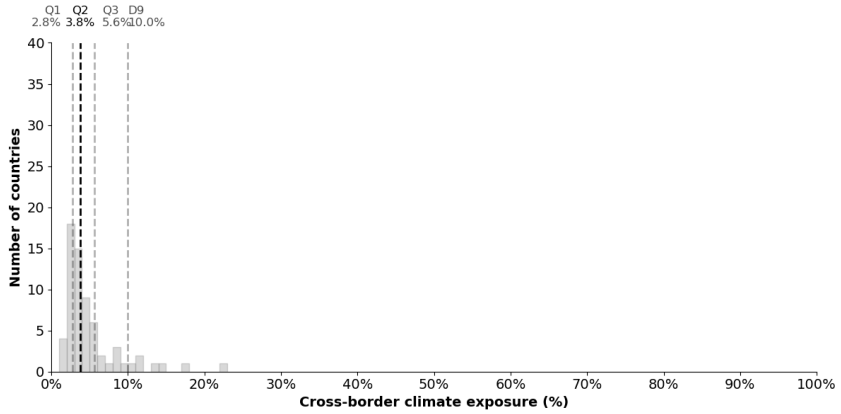
Using INFORM Climate Change with EORA26 and ICIO, Figure 2.9 shows how cross-border climate exposure and share of high risk trade partners differs between developed and developing/least developed countries. It appears that in each configuration, median exposure and share of high risk trade partners is systematically lower for developed compared to developing/least developed, even though ICIO accounts only for a partial subset of developing/least developed countries. By contrast, as can be seen in Figure 2.9 Panels (e) and (f), the distribution of dependence on foreign countries reveals no significant differences between developed and developing/least developed nations: in the case of ICIO, developed countries have slightly higher dependence on foreign countries than developing/least developed countries.

Figure 2.6: Distribution of cross-border climate exposure, across countries

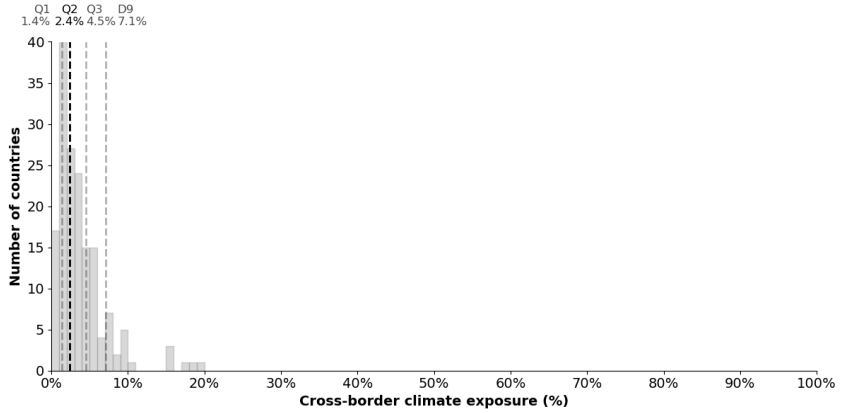
(a) Cross-border climate exposure for imports of intermediate consumption (EORA26, INFORM Climate Change) [Fig. 2b in the main text].



(b) Cross-border climate exposure for imports of intermediate consumption (ICIO, INFORM Climate Change)



(c) Cross-border climate exposure for imports of intermediate consumption (EORA26, ND-GAIN).



(d) Cross-border climate exposure for imports of intermediate consumption (ICIO, ND-GAIN).

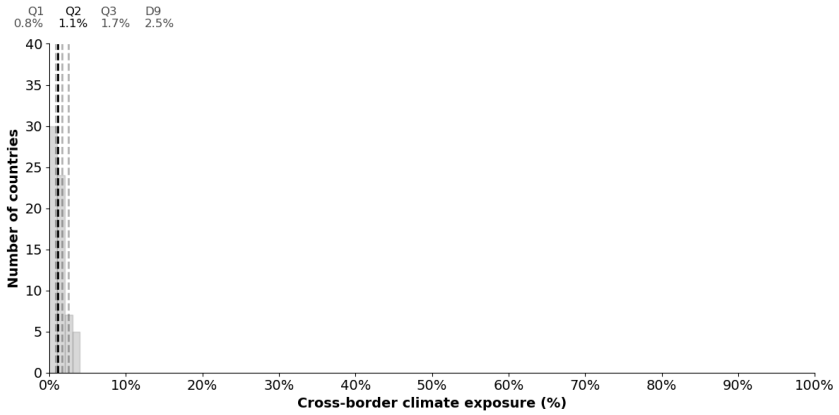
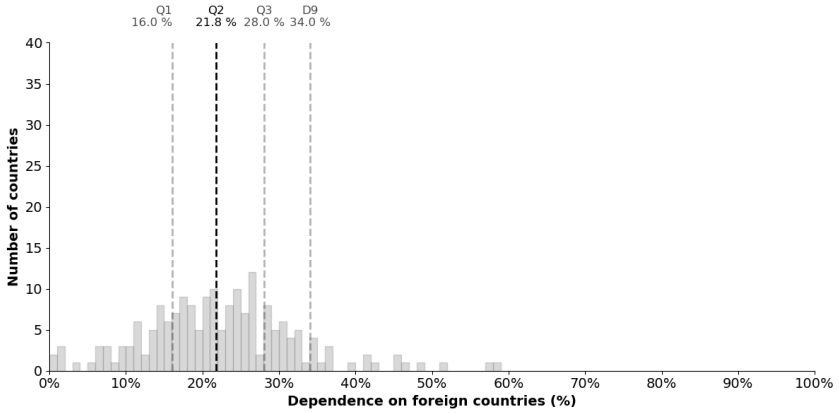


Figure 2.7: Distribution of dependence on foreign countries, across countries

(a) Dependence on foreign countries for imports of intermediate consumption (EORA26).



(b) Dependence on foreign countries for imports of intermediate consumption (ICIO).

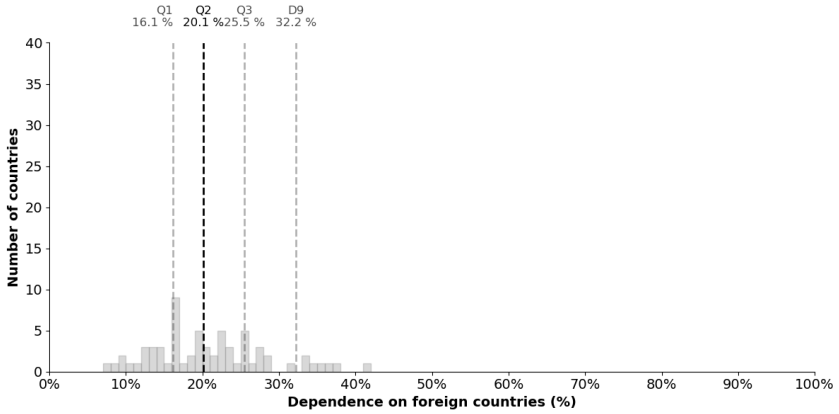
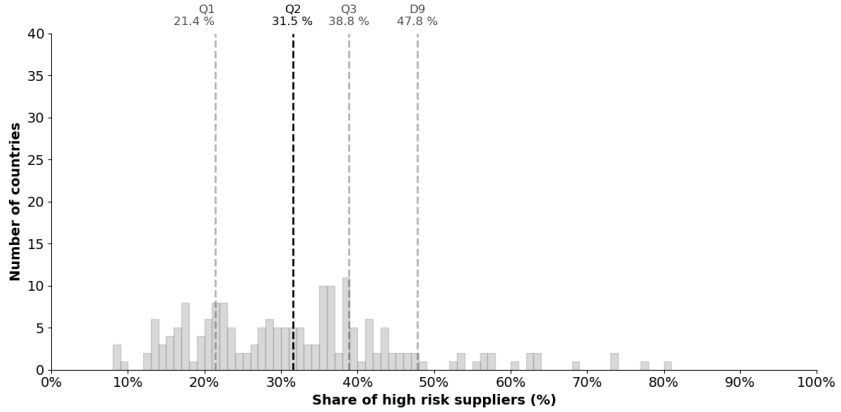
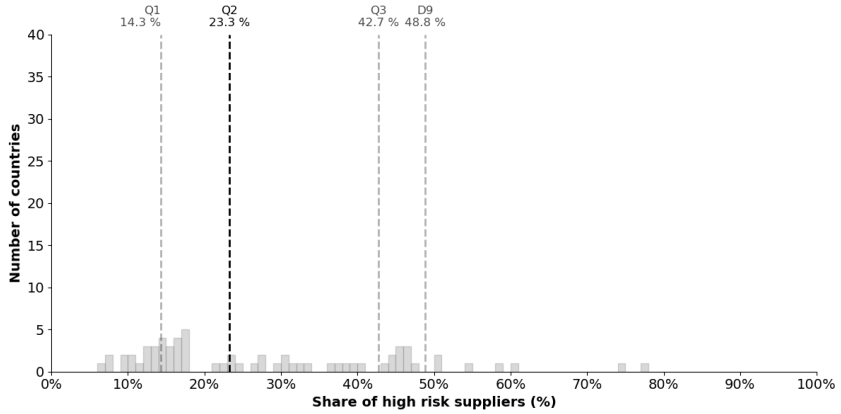


Figure 2.8: Distribution of share of high risk trade partners, across countries

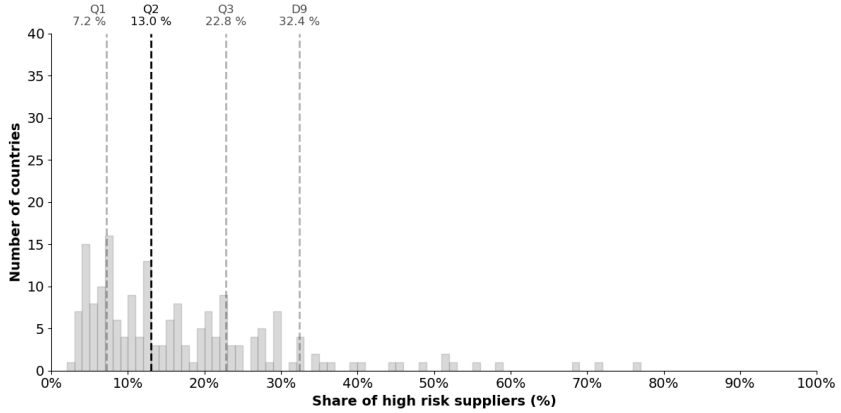
(a) Share of high risk trade partners for imports of intermediate consumption (EORA26, INFORM Climate Change).



(b) Share of high risk trade partners for imports of intermediate consumption (ICIO, INFORM Climate Change).



(c) Share of high risk trade partners for imports of intermediate consumption (EORA26, ND-GAIN).



(d) Share of high risk trade partners for imports of intermediate consumption (ICIO, ND-GAIN).

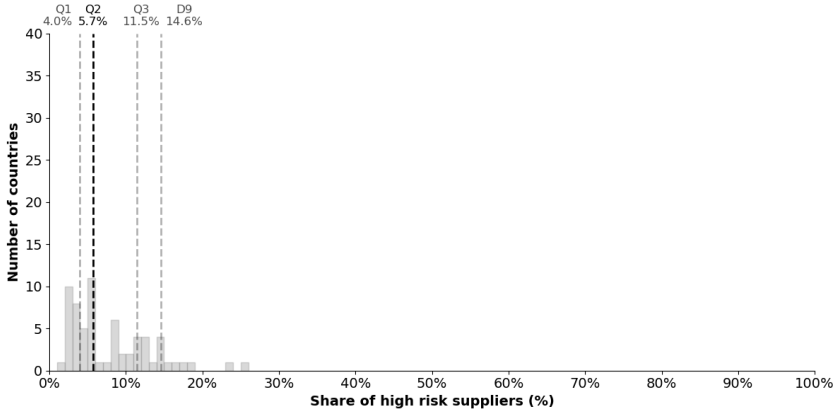
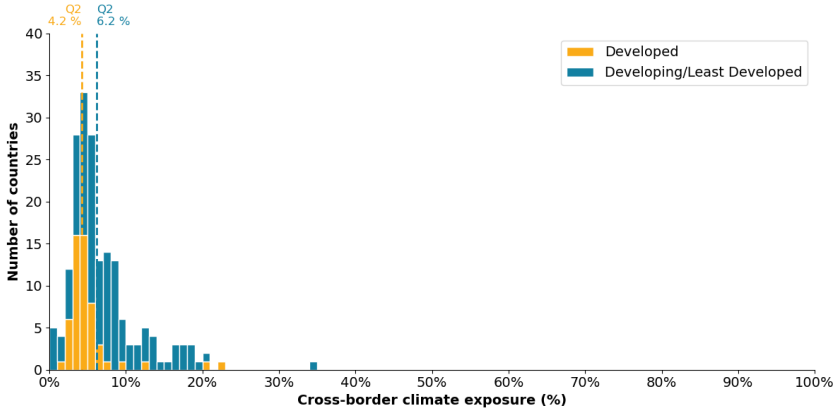
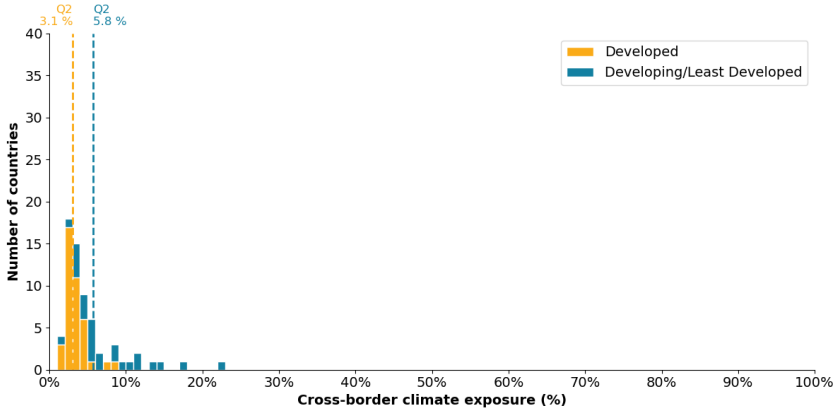


Figure 2.9: Cross-border climate exposure for imports of intermediate consumption, share of high risk suppliers and dependence on foreign countries, distinguishing between developed and developing/least developed

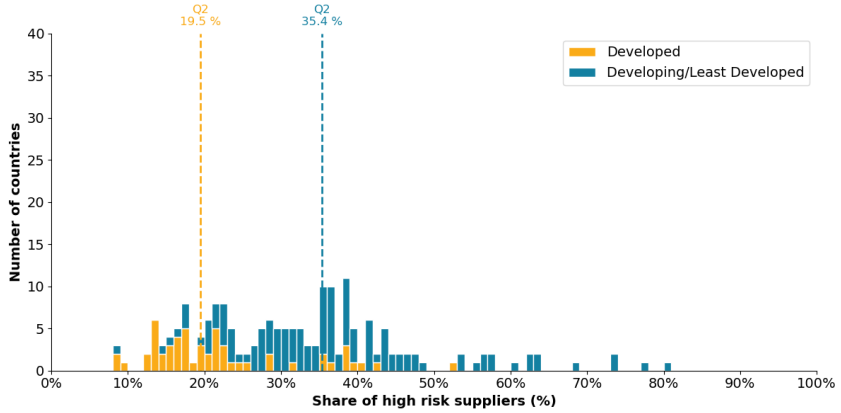
(a) Cross-border climate exposure for imports of intermediate consumption (EORA26, INFORM Climate Change).



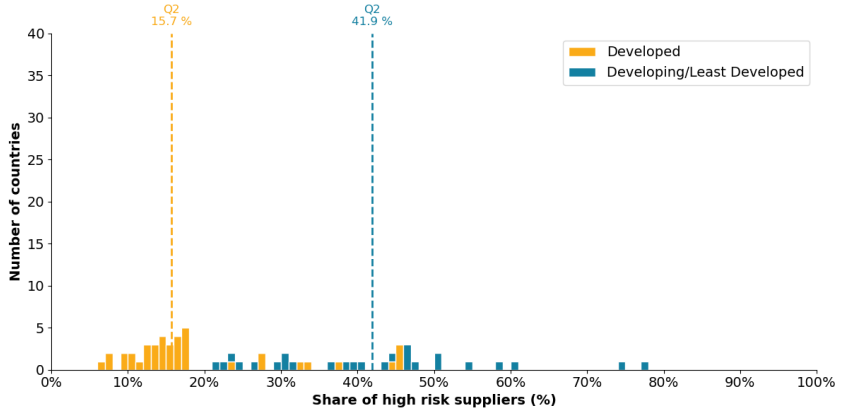
(b) Cross-border climate exposure for imports of intermediate consumption (ICIO, INFORM Climate Change).



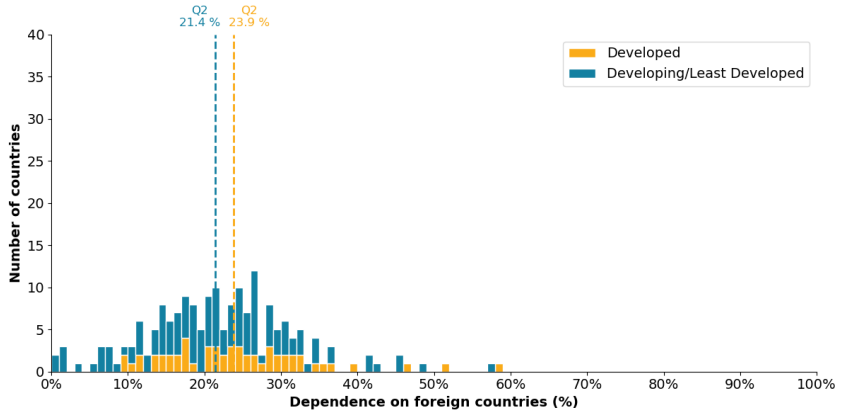
(c) Share of high risk suppliers for imports of intermediate consumption (EORA26, INFORM Climate Change).



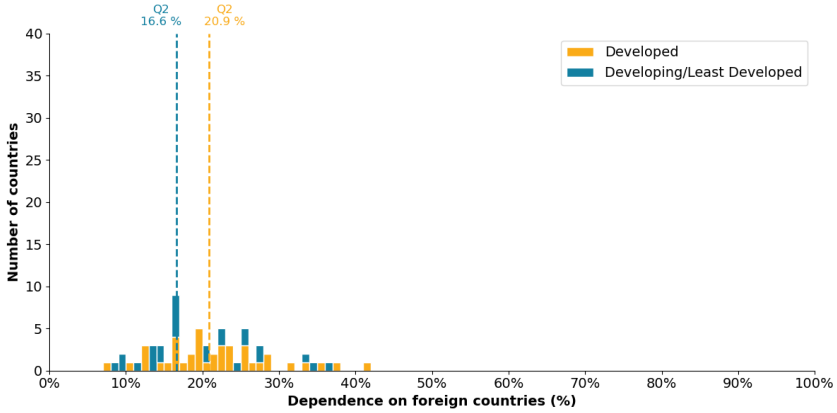
(d) Share of high risk suppliers for imports of intermediate consumption (ICIO, INFORM Climate Change).



(e) Dependence on foreign countries for imports of intermediate consumption (EORA26, INFORM Climate Change).



(f) Dependence on foreign countries for imports of intermediate consumption (ICIO, INFORM Climate Change).



C Descriptive results for all four exposure measures, across all combinations of climate risk indices and input-output tables

The "Results" section of the main text is organized to present the key findings of our analysis. Here, we comprehensively present all the results, structured according to the type of exposure measure: cross-border exposure via...

a) imports of intermediate consumption,
b) imports of final consumption,
c) exports for intermediate consumption,
d) exports for final consumption.

Each of these measures is examined across four database combinations:

(i) EORA26 with INFORM Climate Change,
(ii) ICIO with INFORM Climate Change,
(iii) EORA26 with ND-GAIN,
(iv) ICIO with ND-GAIN.

In the following, all figures are structured with one panel for each combination of measure type and database. For example, Figure 2.10 illustrates heterogeneity of exposure, where Panel (b-ii) corresponds to heterogeneity of exposure for imports of final consumption, using the EORA26 and ICIO databases along with the INFORM Climate Change index. Figures that are alike are presented one next to the other, to facilitate visual comparison.

The first part presents descriptive results for all countries, while the second part focuses on a discussion of selected country cases.

C.1 Descriptive results for all countries

Imports of intermediate consumption

This is the primary measure of exposure used in the main text.

Distribution of exposure across the world: Exposure is heterogeneous across countries. There is consistently a twofold difference between the median and the 9th decile. For EORA26/INFORM, the values are: Q2 = 5.4% and D9 = 13.1%, while for ICIO/ND-GAIN: Q2 = 1.1% and D9 = 2.5%. As explained in Supp. Mat. B, this gap is due to (i) ICIO covering fewer countries than EORA26 (66 vs. 180), with a stronger focus on low-risk countries, and (ii) under our risk threshold choices, China is classified as high-risk in INFORM Climate Change but not in ND-GAIN.

Are developed countries comparatively less exposed? As explained in the main text and as shown in Figure 2.11, Panels (a), this holds for imports of intermediate consumption across all databases, including ICIO, despite its more limited coverage of developing and least developed countries.

Are people living in high cross-border risk countries also exposed to high levels of direct risk? As shown in Figure 2.12, Panels (a), people exposed to high cross-border risk countries (rightmost bar) tend to live in countries with high direct risk. This pattern holds strongly across all databases except ICIO/ND-GAIN (Panel iv); even in this case, people in high cross-border risk countries are still disproportionately located in high direct risk countries.

Is there a positive relationship between local climate risk and the share of high-risk trade partners? As shown in Figure 2.13, Panels (a), the share of high risk trade partners increases with local risk, and this result is significant for each database (p-value $< 10^{-3}$). It also appears that the share of high-risk trade partners varies a lot with local risk: across all databases, a country facing the highest level of direct climate risk has a share of high-risk trade partners at least 20 percentage points higher than a country facing the lowest direct climate risk (except for ICIO/ND-GAIN, where it is 10 percentage points).

Imports of final consumption

Considering imports of final consumption yields qualitatively similar results to those obtained using imports of intermediate consumption.

Distribution of exposure across the world: Exposure is still heterogeneous across countries and the gap between median and D9 is still twofold. As shown in Figure 2.10 Panel (b-i), EORA26/INFORM, the values are: Q2 = 3.8% and D9 = 10.8%, while for ICIO/ND-GAIN [Panel (b-iv)]: Q2 = 0.9% and D9 = 2.2%.

Are developed countries comparatively less exposed? As shown in Figure 2.11, Panels (b), this also holds for imports of final consumption across all databases.

Are people living in high cross-border risk countries also exposed to high levels

of direct risk? As shown in Figure 2.12, Panels (b), this also holds for imports of final consumption across all databases.

Is there a positive relationship between local climate risk and the share of high-risk trade partners? As shown in Figure 2.13, Panels (b), this also holds for imports of final consumption across all databases (p-value $< 10^{-3}$). The mean gap between share of trade risk for a low and a high climate risk country is of the same magnitude as for imports of intermediate consumption.

Exports of intermediate consumption

As stated in the main text, results for exports exhibit qualitative differences compared to those for imports, whether of intermediate or final consumption.

Distribution of exposure across the world: Even with exports, exposure is still heterogeneous across the world. As shown in Figure 2.10 Panels (c), the gap between median and D9 is at least twofold. For EORA26/INFORM, the values are: Q2 = 5.2% and D9 = 13%, while for ICIO/ND-GAIN: Q2 = 1.3% and D9 = 3.4%.

Are developed countries comparatively less exposed? As shown in Figure 2.11, Panels (c), developed countries are not distinctly positioned at the lower end of the cross-border exposure distribution for exports of intermediate consumption. See also Figure 2.15 for numerical results. As shown inFigure 2.1, with the numerical values of EORA26/INFORM, this is mainly due to developed countries being generally more export-oriented than developing/least-developed ones. Although the proportions of imported final and intermediate consumption are comparable between these groups (23.9% and 21.4% for intermediates, and 14.2% and 12.8% for final goods), developed countries have a higher share of exported gross output at 26.4% compared to 16.6% for developing/least developed. While developed countries consistently trade with fewer high risk partners than their developing and least-developed counterparts, their greater economic openness for exports compensates for the lower percentage of trade with risky partners.

Are people living in high cross-border risk countries also exposed to high levels of direct risk? As shown in Figure 2.12 Panels (c), a smaller proportion of people in countries highly exposed through exports experience high direct climate impacts (59.6% for exports vs 94.2% for imports of intermediate consumption, in the case of Panel c-i). This is coherent with both low risk countries having riskier clients than suppliers and being more export-oriented.

Is there a positive relationship between local climate risk and the share of high-risk trade partners? As indicated by Figure 2.13 Panels (c), correlation between local risk and share of high trade partners is weaker in the case of exports of intermediate consumption (worst-case is R-squared = 0.04 in Panel c-i), but the relationship is still significant (p-value $< 1.9410^{-2}$). This is due to the fact that developing/least developed countries, where many of the high risk countries are, have less risky clients than suppliers.

Exports of final consumption

Results for exports of final consumption are qualitatively similar to those of exports of intermediate consumption.

Distribution of exposure across the world: As shown in Figure 2.10 Panels (d), the gap between median and D9 is at least twofold. For EORA26/INFORM, the values are: Q2 = 5.6% and D9 = 12,7%, while for ICIO/ND-GAIN: Q2 = 1.4% and D9 = 3.3%.

Are developed countries comparatively less exposed? As shown in Figure 2.11, Panels (c), developed countries are not distinctly positioned at the lower end of the cross-border exposure distribution for exports of intermediate consumption. See also Figure 2.15 for numerical results. The same explanation as for final consumption applies here: while developed countries consistently trade with fewer high risk partners than their developing and least-developed counterparts, their greater economic openness for exports compensates for the lower percentage of trade with risky partners.

Are people living in high cross-border risk countries also exposed to high levels of direct risk? As shown in Figure 2.12 Panels (d), a smaller proportion of people in countries highly exposed through exports experience high direct climate impacts (59.7% for exports vs 94.2% for imports of intermediate consumption, in the case of Panel d-i). This is coherent with both low risk countries having riskier clients than suppliers and being more export-oriented.

Is there a positive relationship between local climate risk and the share of high-risk trade partners As indicated by Figure 2.13 Panels (d), correlation between local risk and share of high trade partners is weaker in the case of exports of intermediate consumption (worst-case is R-squared = 0.04 in Panel c-i), but the relationship is still significant (p-value < 3.87 10-2). This is due to the fact that developing/least developed countries, where many of the high risk countries are, have less risky clients than suppliers.

C.2 Discussion of a few specific country cases

In the main text, we discuss four countries, each representing a different combination of two dimensions, regarding exposure on imports of intermediate consumption: (i) low or high dependence on imports or exports, and (ii) low or high share of risky trade partners. In this section, we provide a detailed account of how these countries compare across alternative measures of exposure. Figure 2.11 and Figure 2.14 provide quantitative information on these countries for each measure and each database. We report below the quantitative results for INFORM Climate Change and EORA26, mentioning the cases where the results differ across other databases (32 assessments = 4 measures x 4 databases x 2 dimensions). We also discuss the case of China, which is mentioned in the main text.

France

France exhibits low (relative to world median) dependence on both imports and exports of intermediate goods (17.3% and 16.5%, respectively) and final consumption goods (9.0% and 16.2%, respectively). It also has a low share of risky trade partners for both imports and exports of intermediate (21.2% and 28.8%) and imports of final consumption (21.9%). However, its share of risky trade partners for exports of final consumption (31.3%) is slightly higher than world median (30.7%). As a result, its exposure is relatively low across all measures (3.6% and 4.7%

for imports and exports of intermediate goods; 2.0% and 5.0% for imports and exports of final goods). These findings are consistent with France's trade integration with low-risk EU countries and its status as a large economy. However, we note that exports are significantly more exposed to risk than imports, as export partners are generally riskier than import partners. This result holds consistently across nearly all databases, except in the case of final exports, where France exhibits a lower share of risky trade partners than the median, for all databases but (EORA26, INFORM) (1 difference over 24 assessments).

Tunisia

Tunisia exhibits high dependence on both imports and exports of intermediate goods (25.9% and 21.3%, respectively) and final consumption goods (19.1% and 21.3%, respectively). It also has a low share of risky trade partners for both imports and exports of intermediate (20.6% and 21.8%) and final consumption (20.9% and 25.3%). As a result, its exposure is moderate across all measures (5.3% and 4.6% for imports and exports of intermediate goods; 3.9% and 5.4% for imports and exports of final goods). These findings are consistent with Tunisia's trade integration with low-risk European countries and its status as a small economy. This result is robust across all databases. However, this result is mainly consistent across all databases and exposure measures (8 differences over 24 assessments), but with no specific pattern in the differences.

The United States

The United States exhibits low dependence on both imports and exports of intermediate goods (9.4% and 6.9%, respectively) and final consumption goods (5.9% and 6.3%, respectively). It also has a high share of risky trade partners for both imports and exports of intermediate (42.9% and 43.2%) and final consumption (47.6% and 44.7%). As a result, its exposure is moderate across all measures (3.9% and 2.9% for imports and exports of intermediate goods; 2.7% and 2.8% for imports and exports of final goods). These findings are consistent with the US trade integration with high climate risk countries in Asia and its status as a large economy. This result is robust across all databases (0 difference over 24 assessments).

Viet Nam

Viet Nam exhibits high dependence on both imports and exports of intermediate goods (45.6% and 30.4%, respectively) and final consumption goods (32.7% and 30.4%, respectively). The Vietnamese economy is highly oriented toward international trade. It also has a high share of risky trade partners for both imports and exports of intermediate (39.7% and 42.9%) and exports of final consumption (42.0%). However, its share of risky trade partners for exports of intermediates (31%) is almost equal to the world median (31%). As a result, its exposure is high across all measures (16.9% and 12.4% for imports and exports of intermediate goods; 9.4% and 12.3% for imports and exports of final goods). These findings are consistent with the fact that Vietnam is a small, foreign oriented economy; and that its main trade partners are in Asia. This result is robust across a lot of databases (7 out of 24 assessments), but with no specific pattern in the differences: a majority of databases agree for each exposure measure, except for imports of final goods.

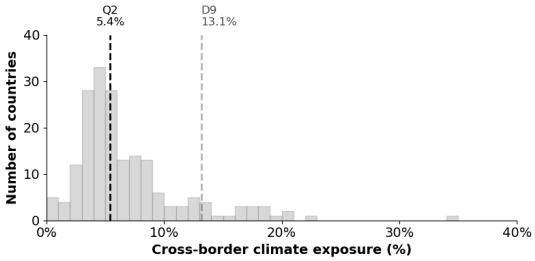
China

China exhibits low dependence on both imports and exports of intermediate goods (11.0% and 10.9%, respectively) and final consumption goods (4.5% and 10.6%, respectively). It also has a low share of risky trade partners for both imports and exports of intermediate (17.0% and 24.7%) and final consumption (13.0% and 24.2%). As a result, its exposure is relatively low across all measures (1.8% and 2.4% for imports and exports of intermediate goods; 0.5% and 2.4% for imports and exports of final goods). These findings are consistent with the fact that China is a large economy; and that its main trade partners are not only in Asia, but all over the world. However, this result is not robust across databases: the results coincides perfectly for dependence on foreign countries across all measure and databases (0 difference out of 12 assessments), but share of risky trade partner tend to give qualitative statement opposite to those of (EORA26, INFORM) in 8 out of 12 assessments.

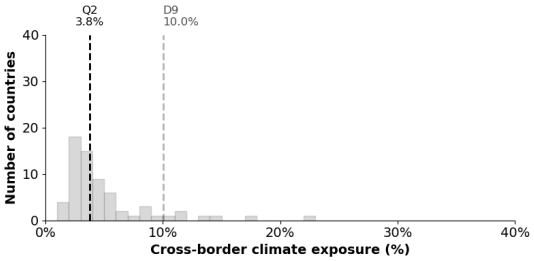
In conclusion, even country-specific results can exhibit robustness across all databases; however, discrepancies may arise for certain countries, particularly when their classification as locally risky varies between databases.

Figure 2.10: Cross-border climate exposure across consumption categories and database combinations

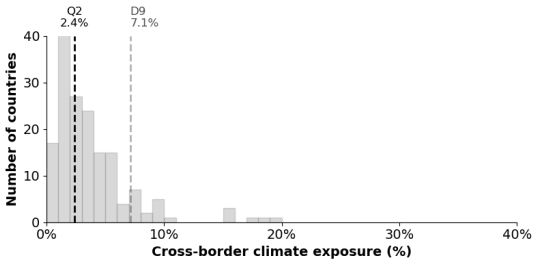
Panel (a-i) Imports of intermediate consumption (EORA26, INFORM Climate Change).



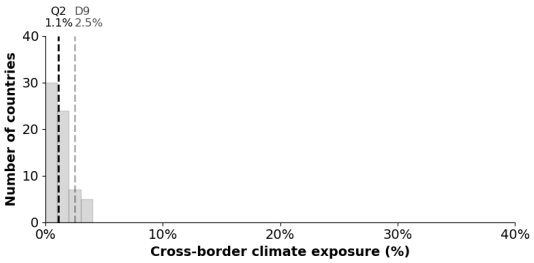
Panel (a-ii) Imports of intermediate consumption (ICIO, INFORM Climate Change).



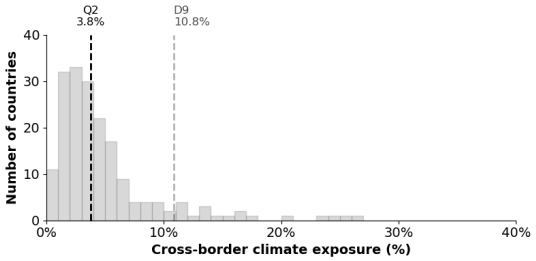
Panel (a-iii) Imports of intermediate consumption (EORA26, ND-GAIN).



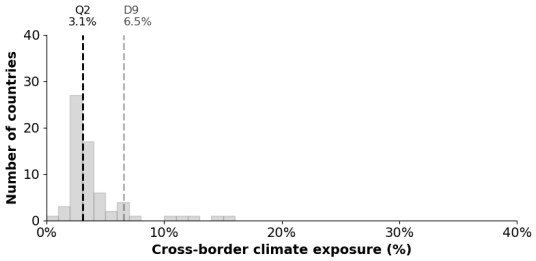
Panel (a-iv) Imports of intermediate consumption (ICIO, ND-GAIN).



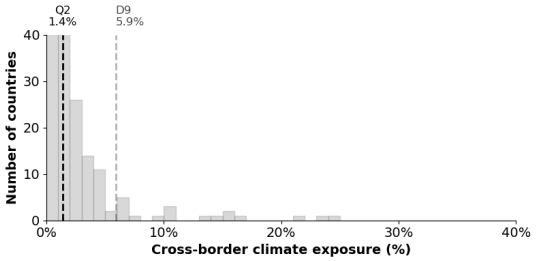
Panel (b-i) Imports of final consumption (EORA26, INFORM Climate Change).



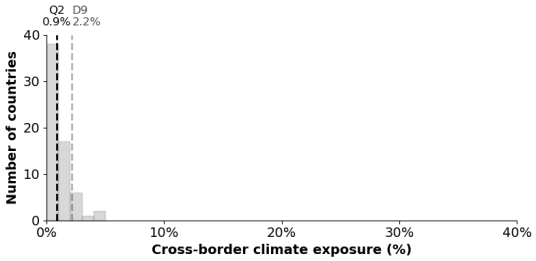
Panel (b-ii) Imports of final consumption (ICIO, INFORM Climate Change).



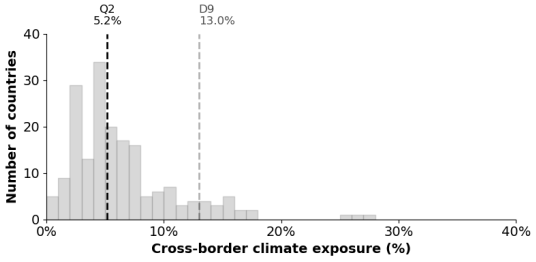
Panel (b-iii) Imports of final consumption (EORA26, ND-GAIN).



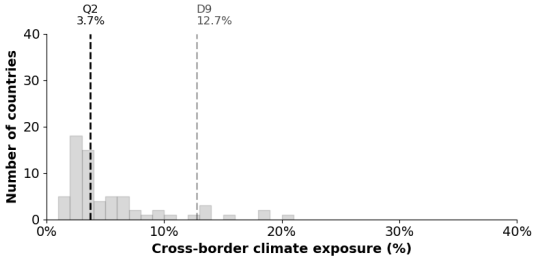
Panel (b-iv) Imports of final consumption (ICIO, ND-GAIN).



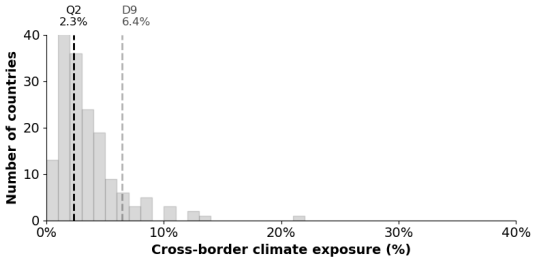
Panel (c-i) Exports of intermediate consumption (EORA26, INFORM Climate Change).



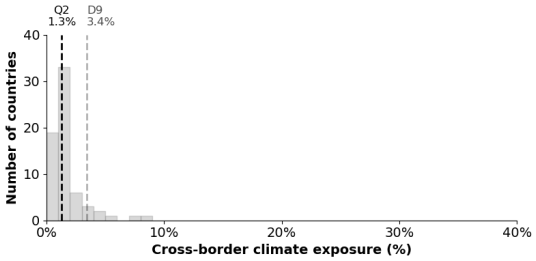
Panel (c-ii) Exports of intermediate consumption (ICIO, INFORM Climate Change).



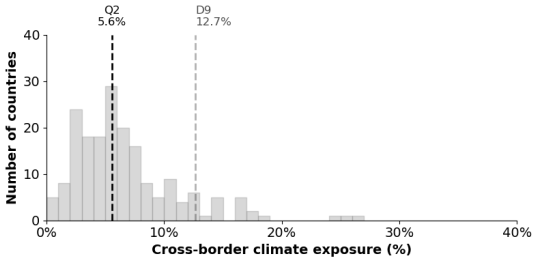
Panel (c-iii) Exports of intermediate consumption (EORA26, ND-GAIN).



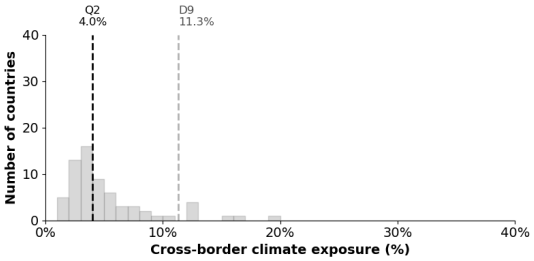
Panel (c-iv) Exports of intermediate consumption (ICIO, ND-GAIN).



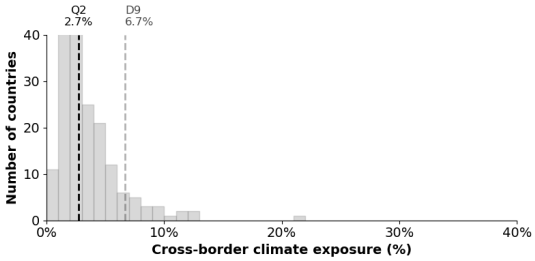
Panel (d-i) Exports of final consumption (EORA26, INFORM Climate Change).



Panel (d-ii) Exports of final consumption (ICIO, INFORM Climate Change).



Panel (d-iii) Exports of final consumption (EORA26, ND-GAIN).



Panel (d-iv) Exports of final consumption (ICIO, ND-GAIN).

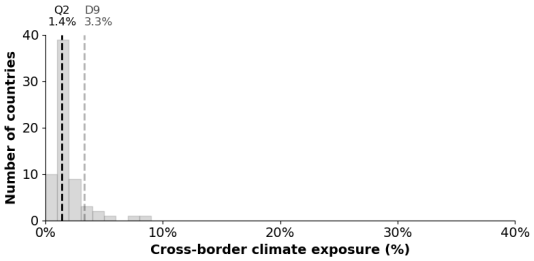
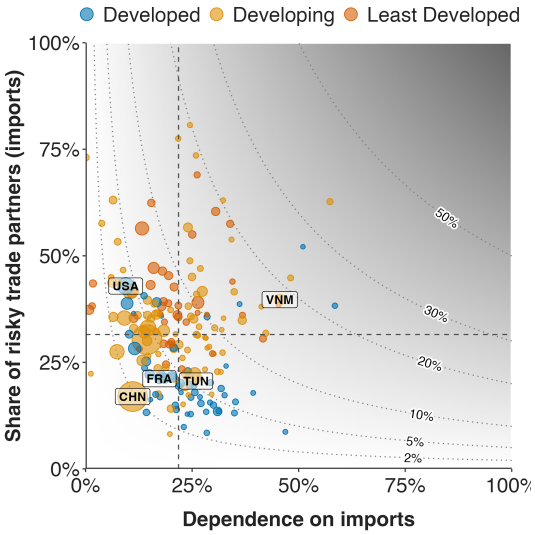
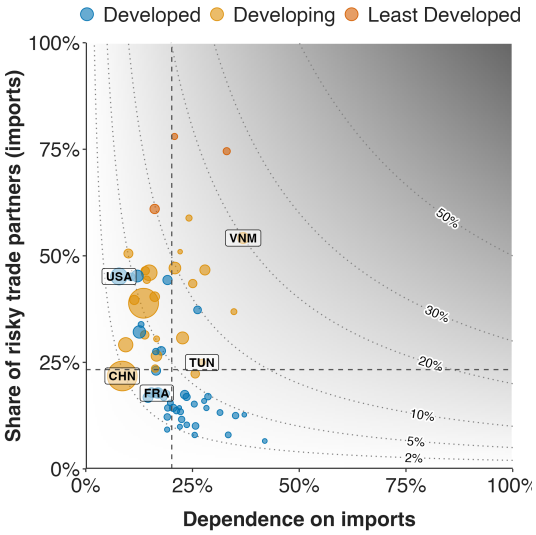


Figure 2.11: Countries most and least exposed to cross-border trade impacts

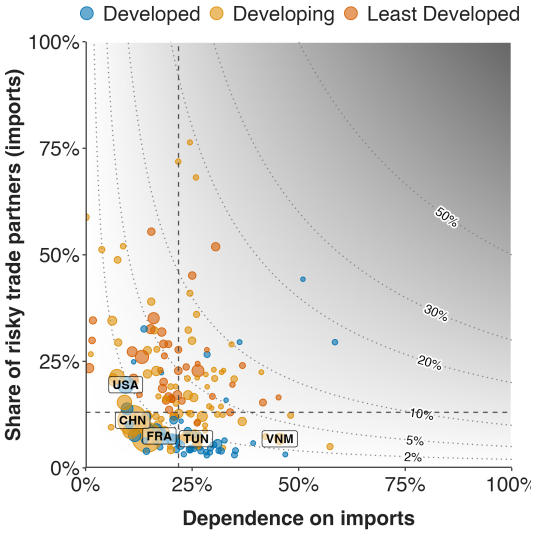
Panel (a-i)



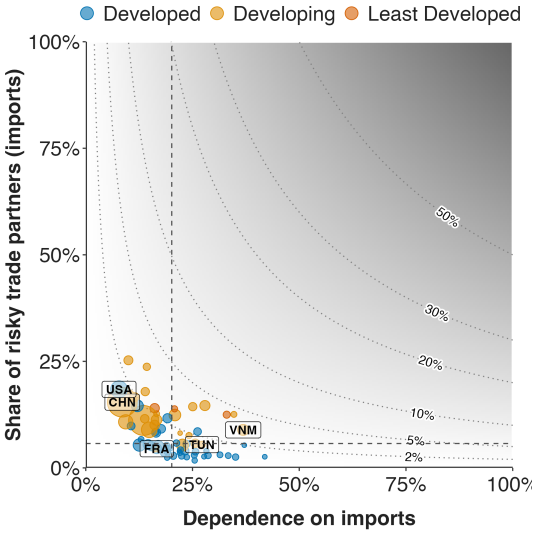
Panel (a-ii)



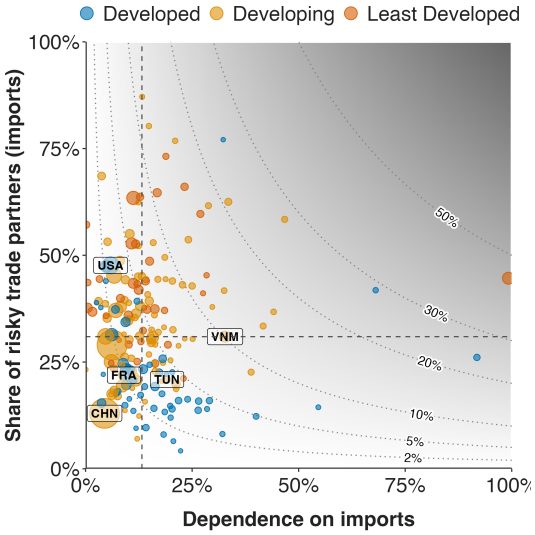
Panel (a-iii)



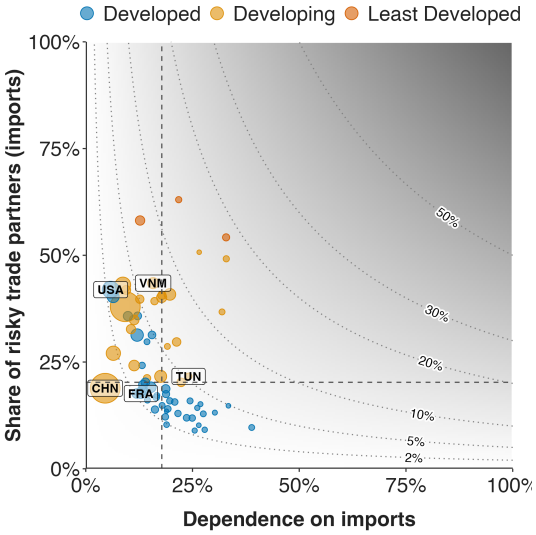
Panel (a-iv)



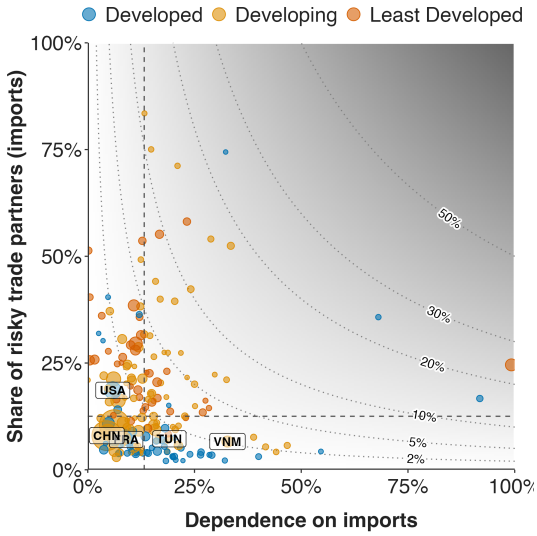
Panel (b-i)



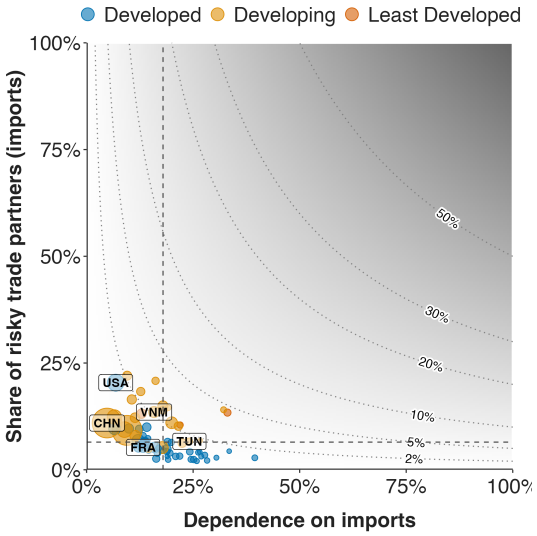
Panel (b-ii)



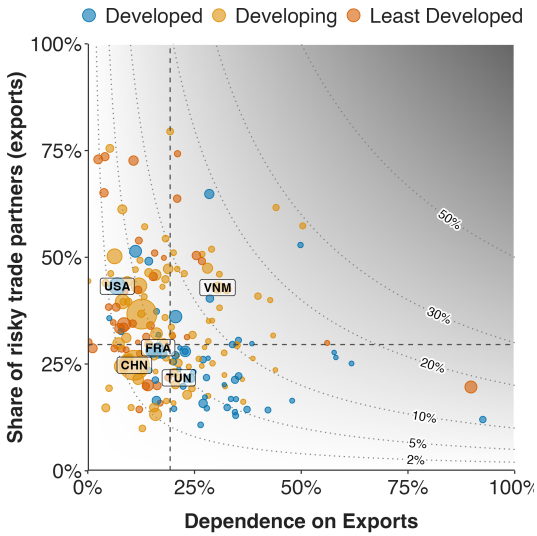
Panel (b-iii)



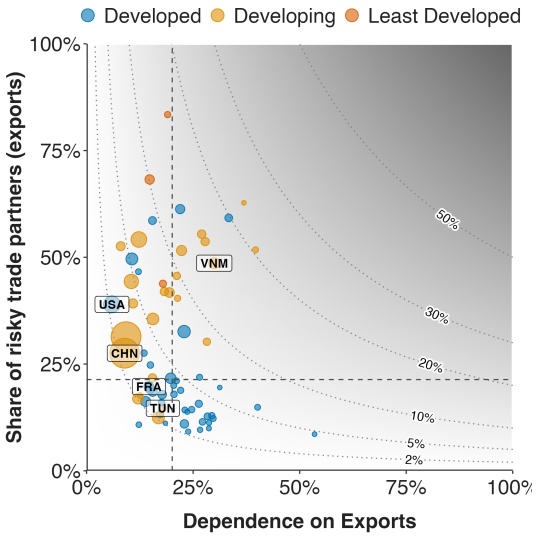
Panel (b-iv)



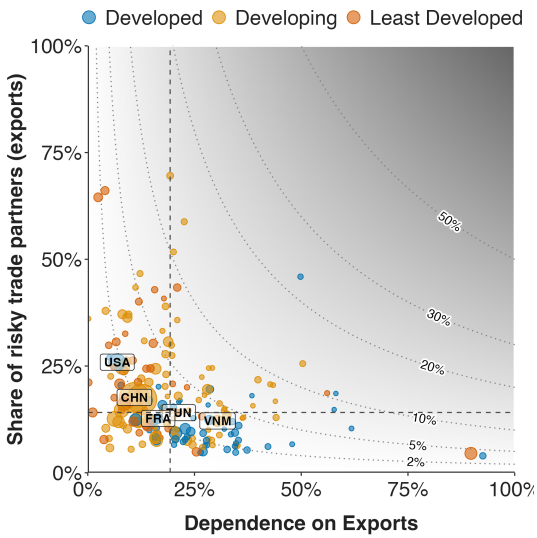
Panel (c-i)



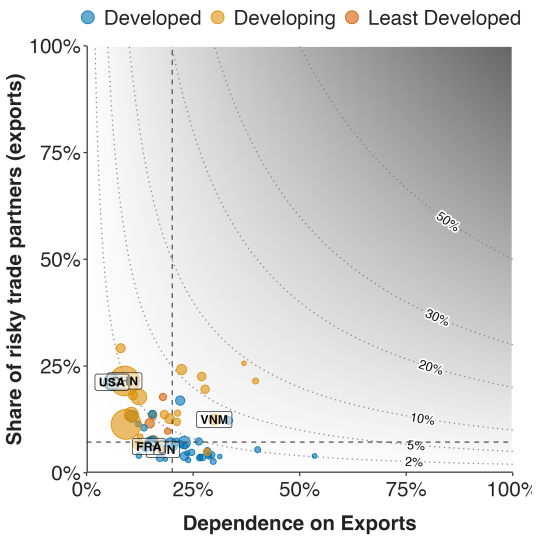
Panel (c-ii)



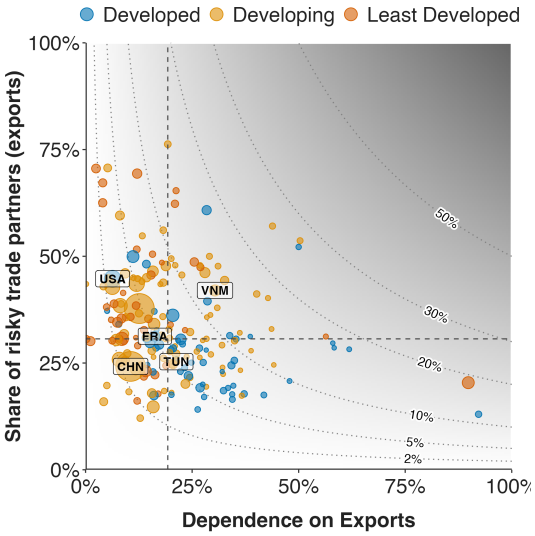
Panel (c-iii)



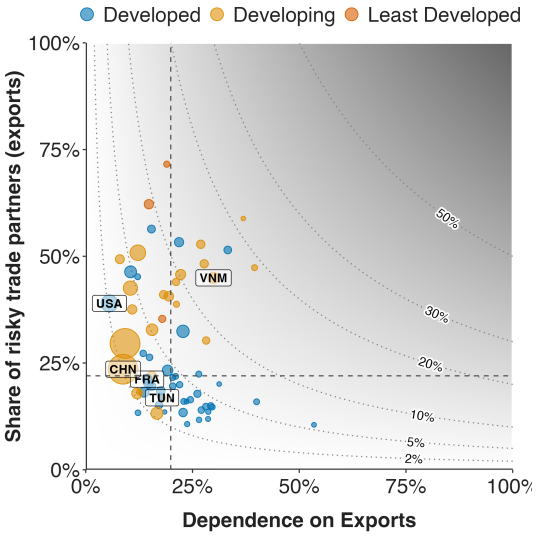
Panel (c-iv)



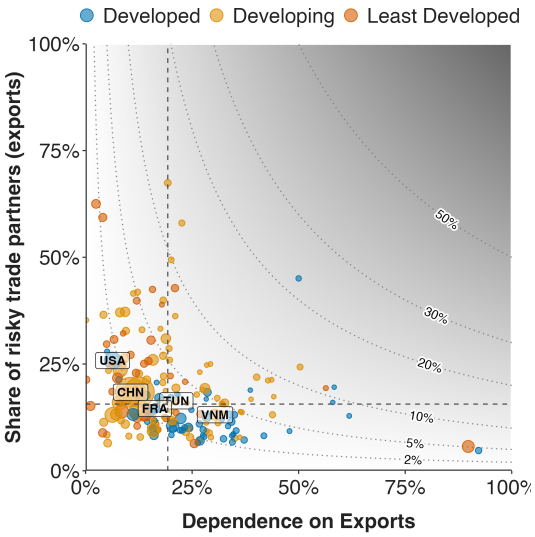
Panel (d-i)



Panel (d-ii)



Panel (d-iii)



Panel (d-iv)

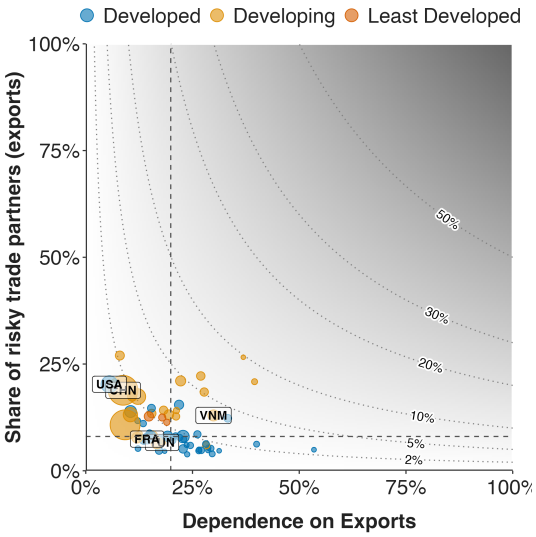
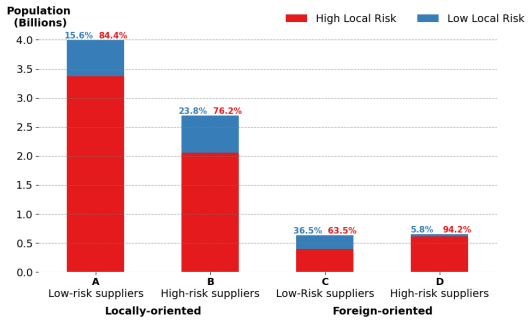
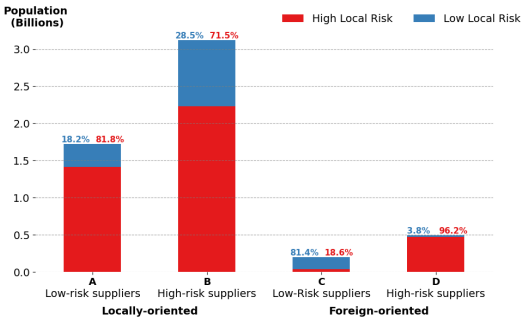


Figure 2.12: Share of Population Living in High or Low Local Risk Country in Each Quadrant of Figure 2.11

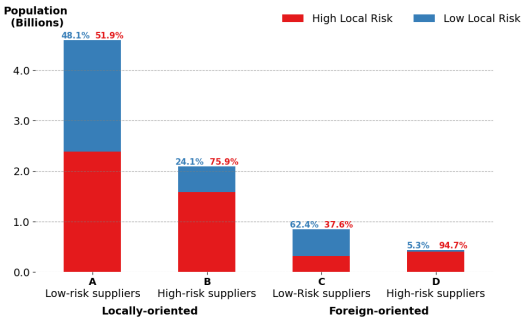
Panel (a-i)



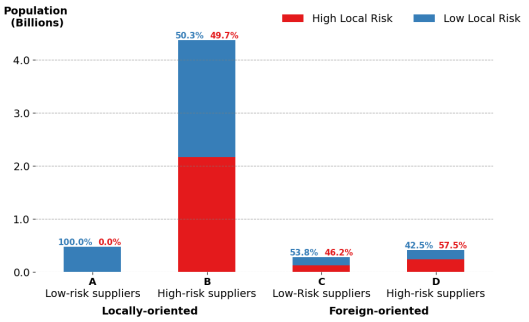
Panel (a-ii)



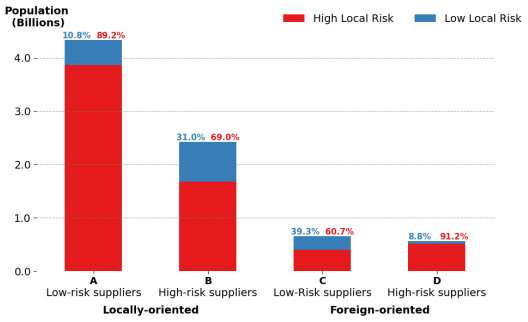
Panel (a-iii)



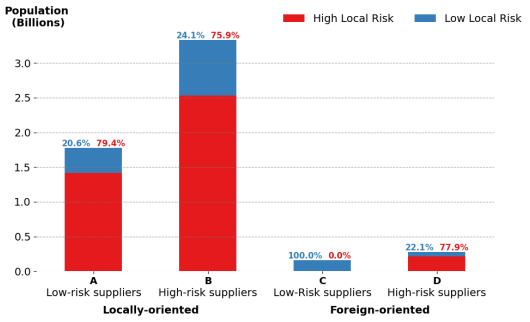
Panel (a-iv)



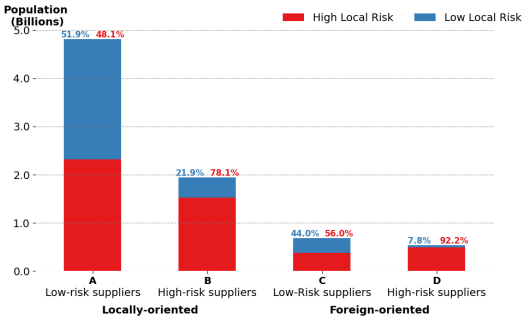
Panel (b-i)



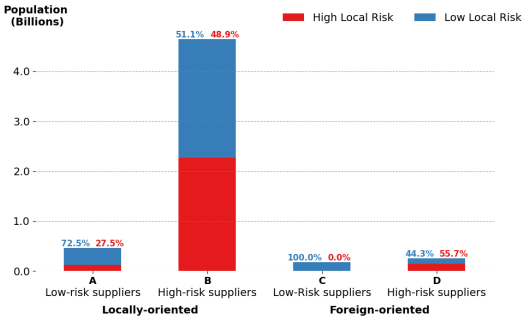
Panel (b-ii)



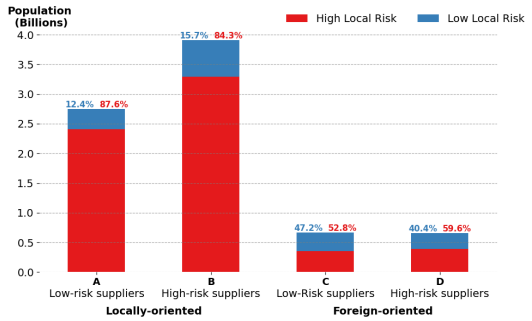
Panel (b-iii)



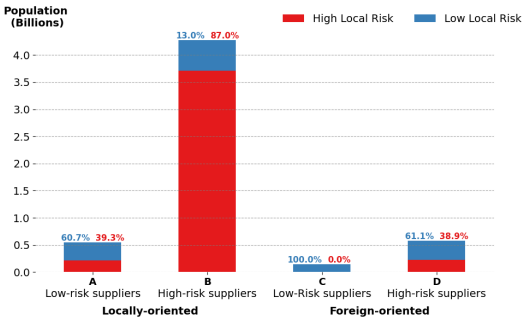
Panel (b-iv)



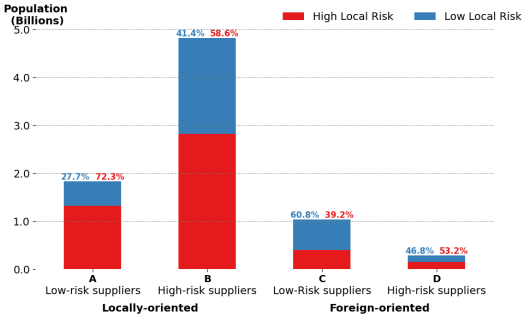
Panel (c-i)



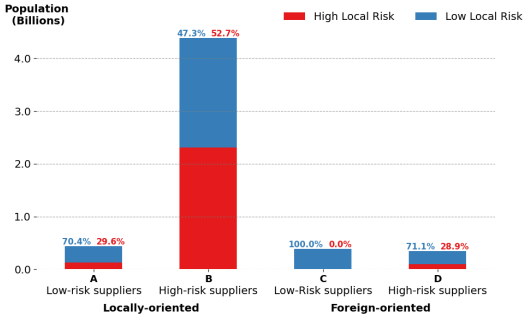
Panel (c-ii)



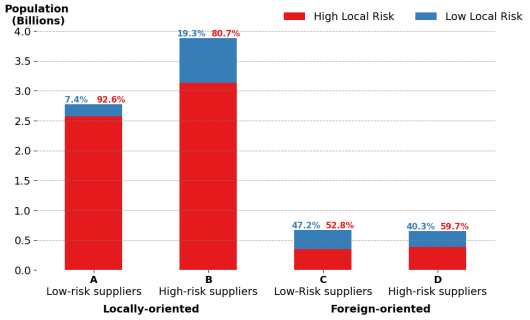
Panel (c-iii)



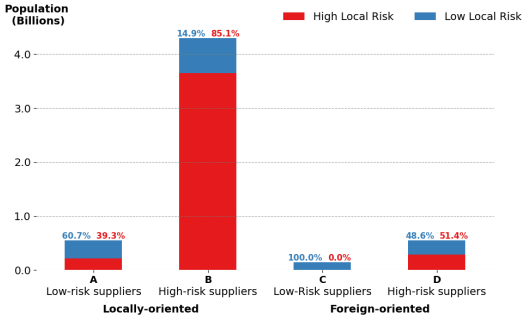
Panel (c-iv)



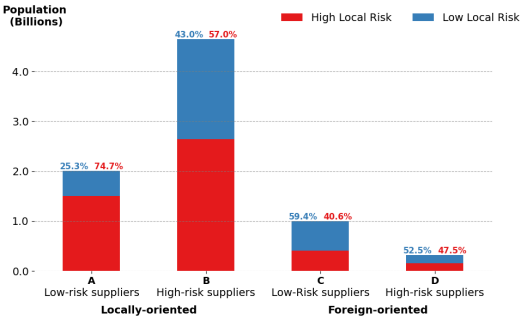
Panel (d-i)



Panel (d-ii)



Panel (d-iii)



Panel (d-iv)

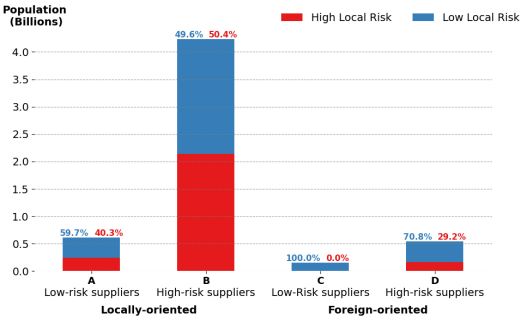
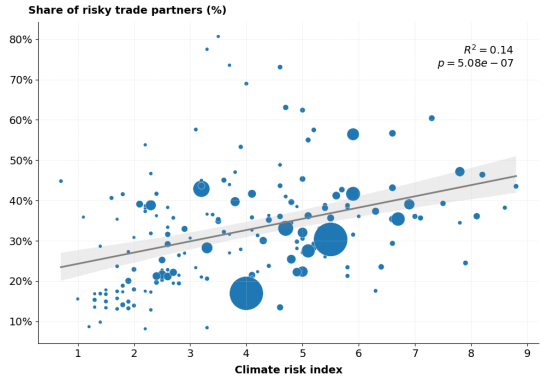
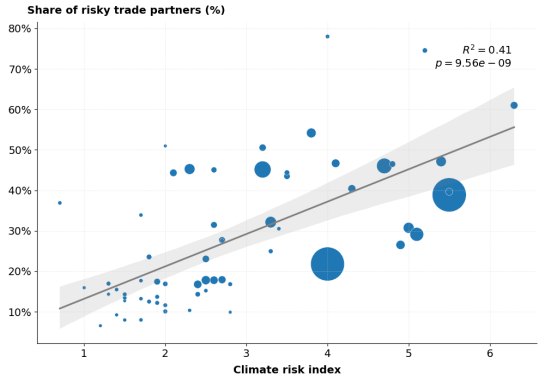


Figure 2.13: Regression of share of high climate risk trade partners on local climate risk

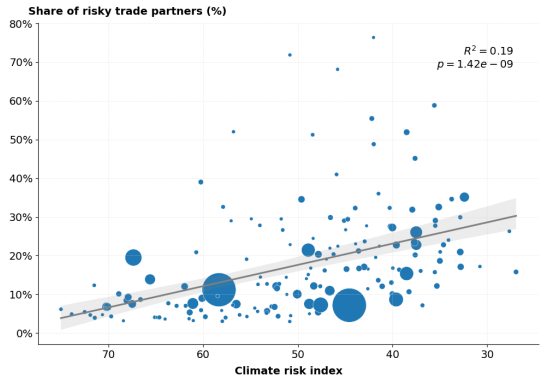
Panel (a-i) Imports of intermediate consumption (EORA26, INFORM).



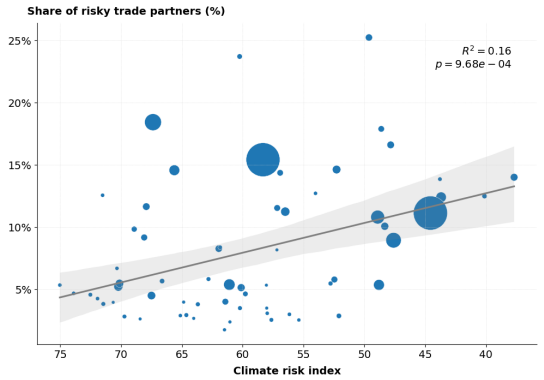
Panel (a-ii) Imports of intermediate consumption (ICIO, INFORM).



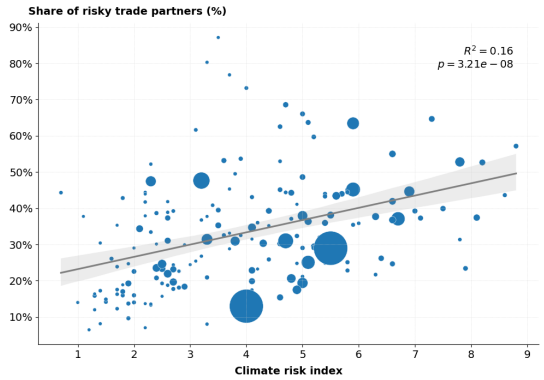
Panel (a-iii) Imports of intermediate consumption (EORA26, ND-GAIN).



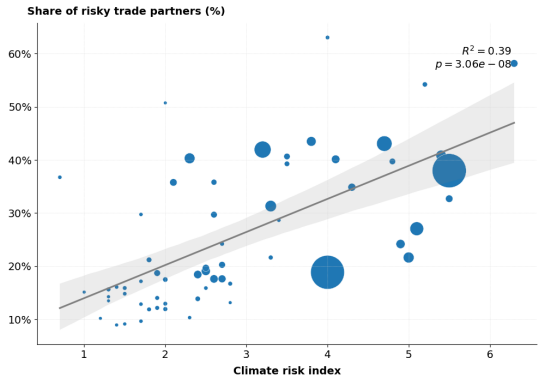
Panel (a-iv) Imports of intermediate consumption (ICIO, ND-GAIN).



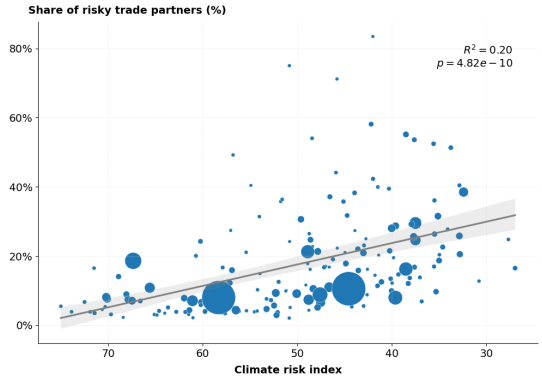
Panel (b-i) Imports of final consumption (EORA26, INFORM).



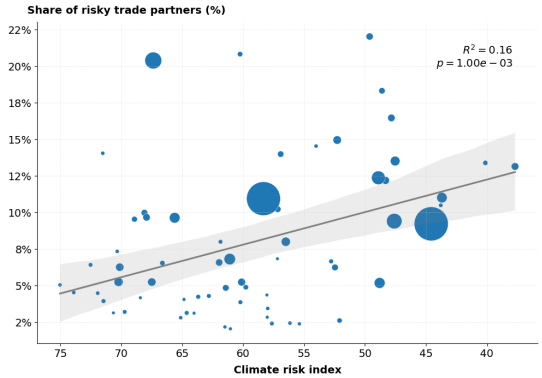
Panel (b-ii) Imports of final consumption (ICIO, INFORM).



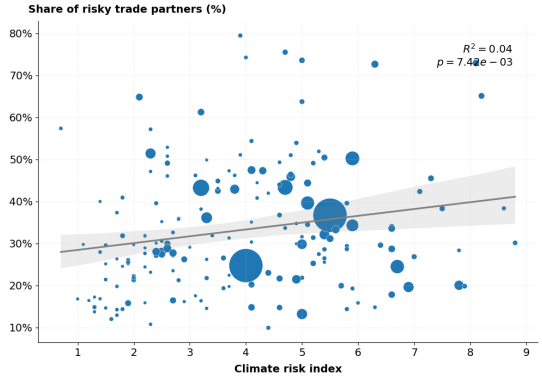
Panel (b-iii) Imports of final consumption (EORA26, ND-GAIN).



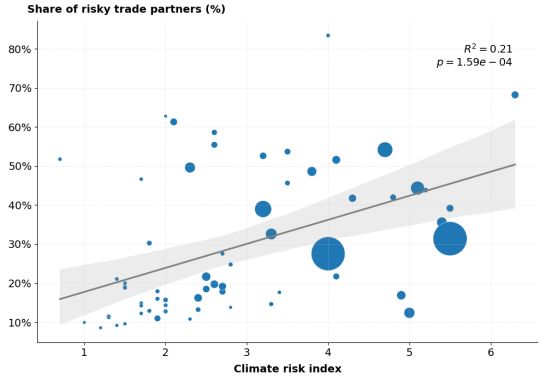
Panel (b-iv) Imports of final consumption (ICIO, ND-GAIN).



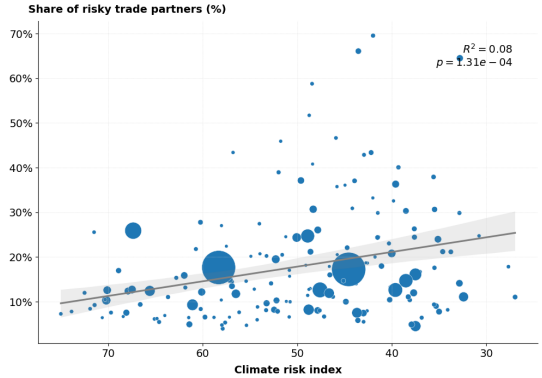
Panel (c-i) Exports of intermediate consumption (EORA26, INFORM).



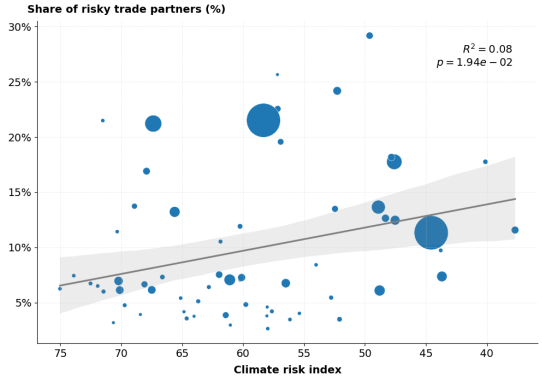
Panel (c-ii) Exports of intermediate consumption (ICIO, INFORM).



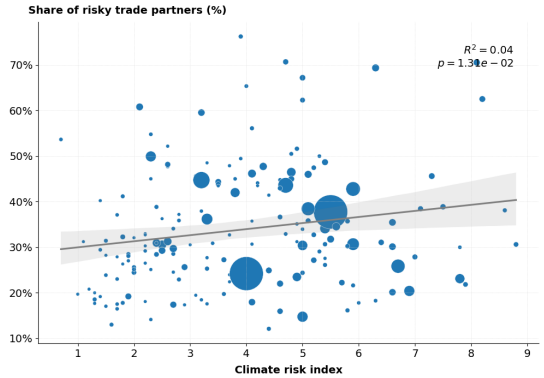
Panel (c-iii) Exports of intermediate consumption (EORA26, ND-GAIN).



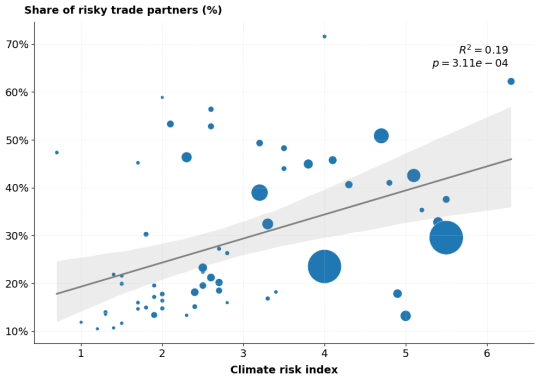
Panel (c-iv) Exports of intermediate consumption (ICIO, ND-GAIN).



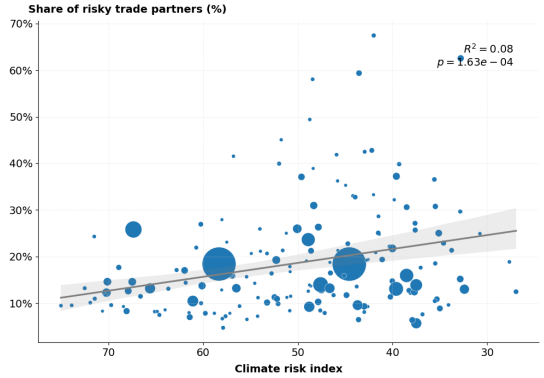
Panel (d-i) Exports of final consumption (EORA26, INFORM).



Panel (d-ii) Exports of final consumption (ICIO, INFORM).



Panel (d-iii) Exports of final consumption (EORA26, ND-GAIN).



Panel (d-iv) Exports of final consumption (ICIO, ND-GAIN).

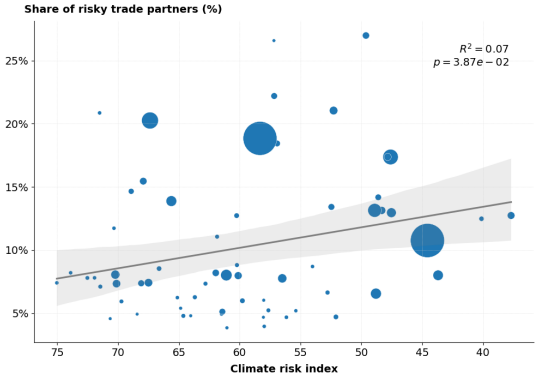
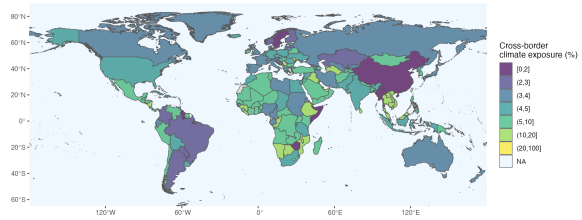
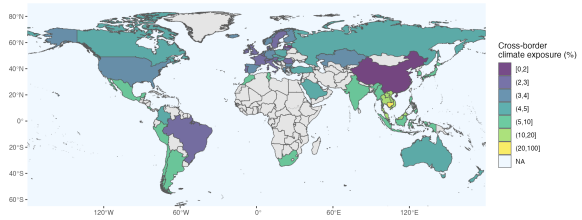


Figure 2.14: Maps of cross-border exposure

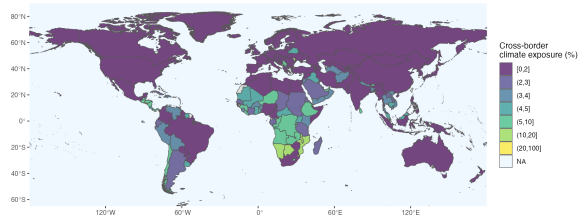
Panel (a-i)



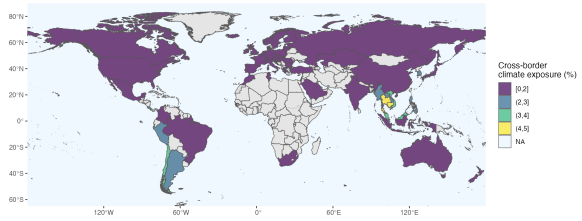
Panel (a-ii)



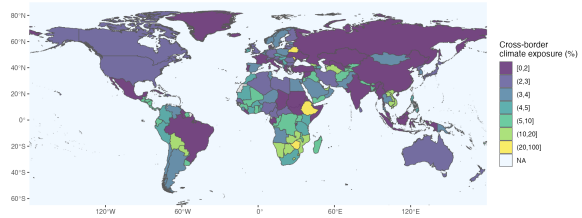
Panel (a-iii)



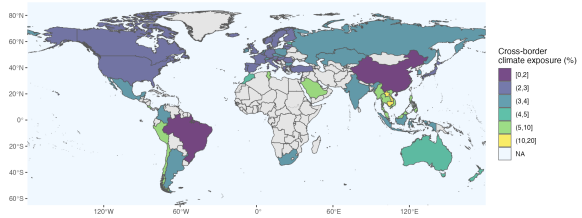
Panel (a-iv)



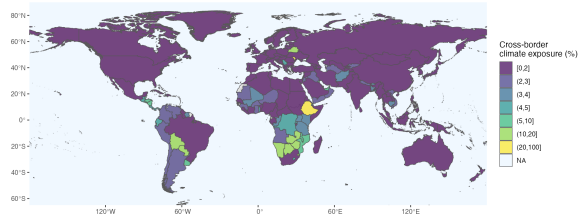
Panel (b-i)



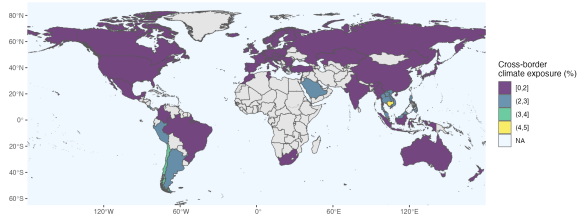
Panel (b-ii)



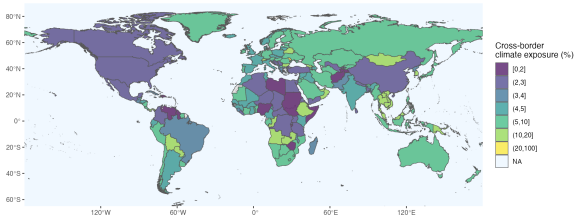
Panel (b-iii)



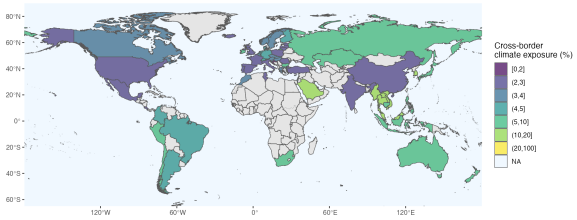
Panel (b-iv)



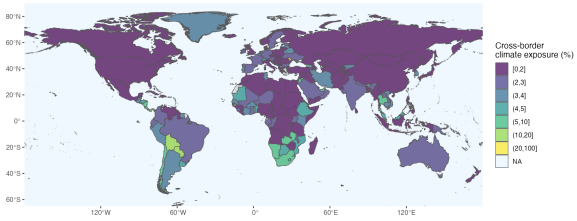
Panel (c-i)



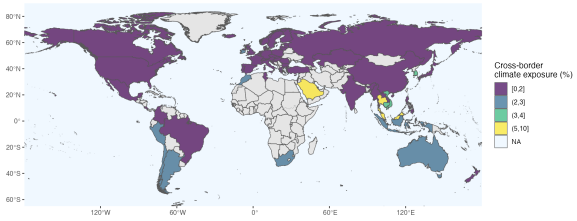
Panel (c-ii)



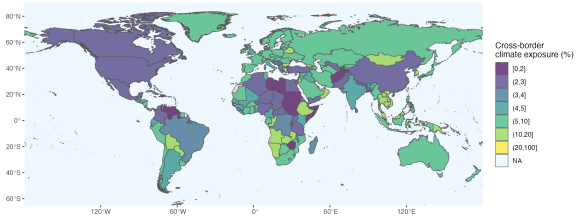
Panel (c-iii)



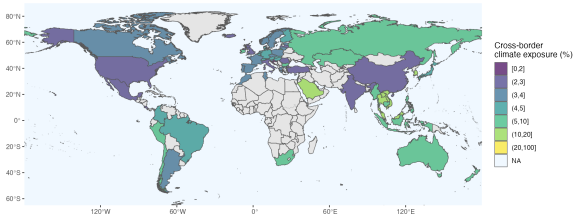
Panel (c-iv)



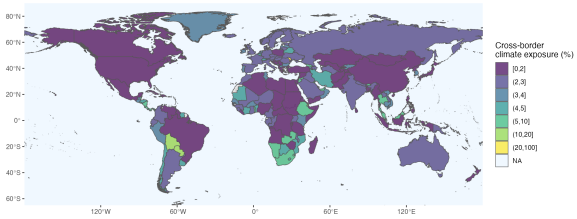
Panel (d-i)



Panel (d-ii)



Panel (d-iii)



Panel (d-iv)

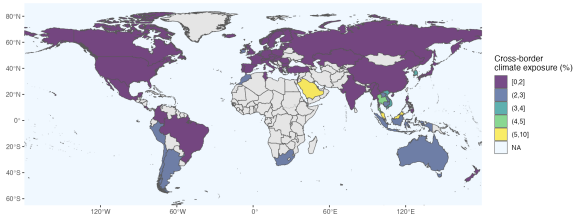
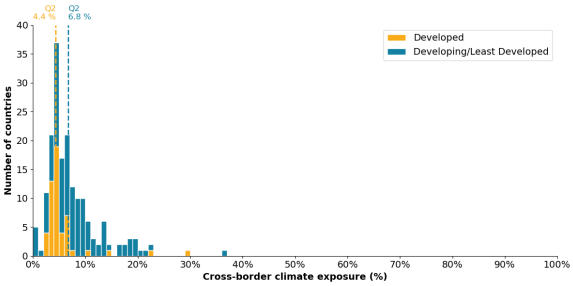
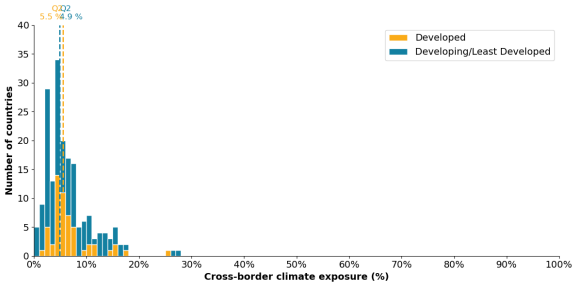


Figure 2.15: Cross-border trade exposure for imports and exports of intermediate and final consumption (EORA26, INFORM Climate Change)

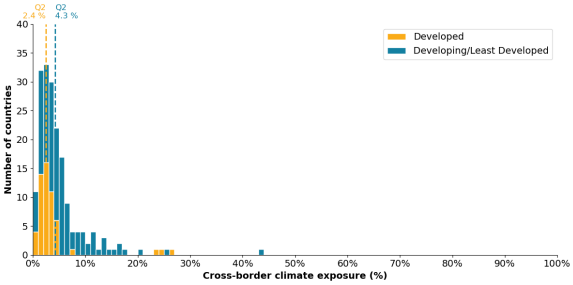
Panel (a) Imports of intermediate consumption



Panel (c) Exports for intermediate consumption



Panel (b) Imports of final consumption



Panel (d) Exports for final consumption

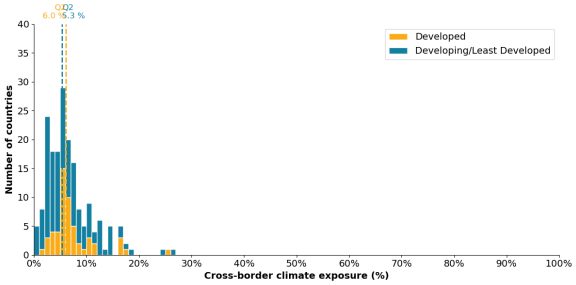


Table 2.1: Median of distributions of share of high risk trade partners, dependence on foreign countries and cross-border exposure for imports of intermediate consumption, final consumption, exports for intermediate and exports for final consumption, for both developed and developing/least developed countries (EORA26, INFORM Climate Change)

Panel (a) Share of high risk trade partners

	Developed	**Developing/least developed**
Imports of intermediate consumption	19.5%	35.4%
Imports of final consumption	19.3%	35.9%
Exports for intermediate consumption	25.5%	31.8%
Exports for final consumption	28.1%	32.8%

Panel (b) Dependence on foreign countries

	Developed	**Developing/least developed**
Imports of intermediate consumption	23.9%	21.4%
Imports of final consumption	14.2%	12.8%
Exports for intermediate consumption	26.4%	16.6%
Exports for final consumption	26.3%	16.6%

Panel (c) Cross-border exposure, compared with product of Panels (a) and (b) in parenthesis

	Developed	**Developing/least developed**
Imports of intermediate consumption	4.2% (4.6%)	6.2% (7.6%)
Imports of final consumption	2.4% (2.7%)	4.3% (4.6%)
Exports for intermediate consumption	5.5% (6.8%)	4.9% (5.3%)
Exports for final consumption	6.0% (7.4%)	5.3% (5.5%)

D Exposure by product among developed countries

In this section, exposure by product among developed countries is displayed for imports of both final (Figure 2.16) and intermediate (Figure 2.17) consumption. As can be seen:

(i) exposure varies widely between products,

(ii) for some products, product exposure is way higher than country exposure (dotted line, in the figures),

(iii) products with the largest exposure are generally similar for final and intermediate consumption (for ICIO: textile, electronic, electric equipment, for instance) with a few exceptions (firms are more exposed on 'mining, quarrying and non-energy producing product' or 'basic metals' than households).

Data are shown for INFORM Climate Change and both ICIO and EORA.

To better understand the issue posed by relying on high climate risk countries for certain goods, we calculate the concentration of suppliers for each product. For a given country c, concentration of suppliers of product s is measured by Herfindahl-Hirschman Index (HHI), as defined in Appendix A. The numerical value of the HHI depends on the number of countries that are represented in the chosen MRIOT. However, as can be seen on Figure 2.18, sectors with the highest exposure (for instance Textile, Electronic, Electrical Equipment) tend to have a concentration of suppliers above average. Concentration analysis displayed here is limited by the number of sectors in ICIO and EORA26, but shows that even at such an aggregate sector level, highest sector exposure could intersect with high concentration of suppliers. Besides, as can be seen in Panel (a) for instance, some sectors with equal exposure can face different levels of concentration of suppliers (like 'Motor vehicles' and 'Rubber and plastic products').

Finally, knowing which products s companies in country c source from high climate risk zones does not enable us to determine which economic sectors of country c are most to upstream shortages. However, this exposure could be measured by dividing, for each sector s in country c, intermediate consumption imported from high climate risk countries by (c, s) divided by total intermediate consumption of (c, s):

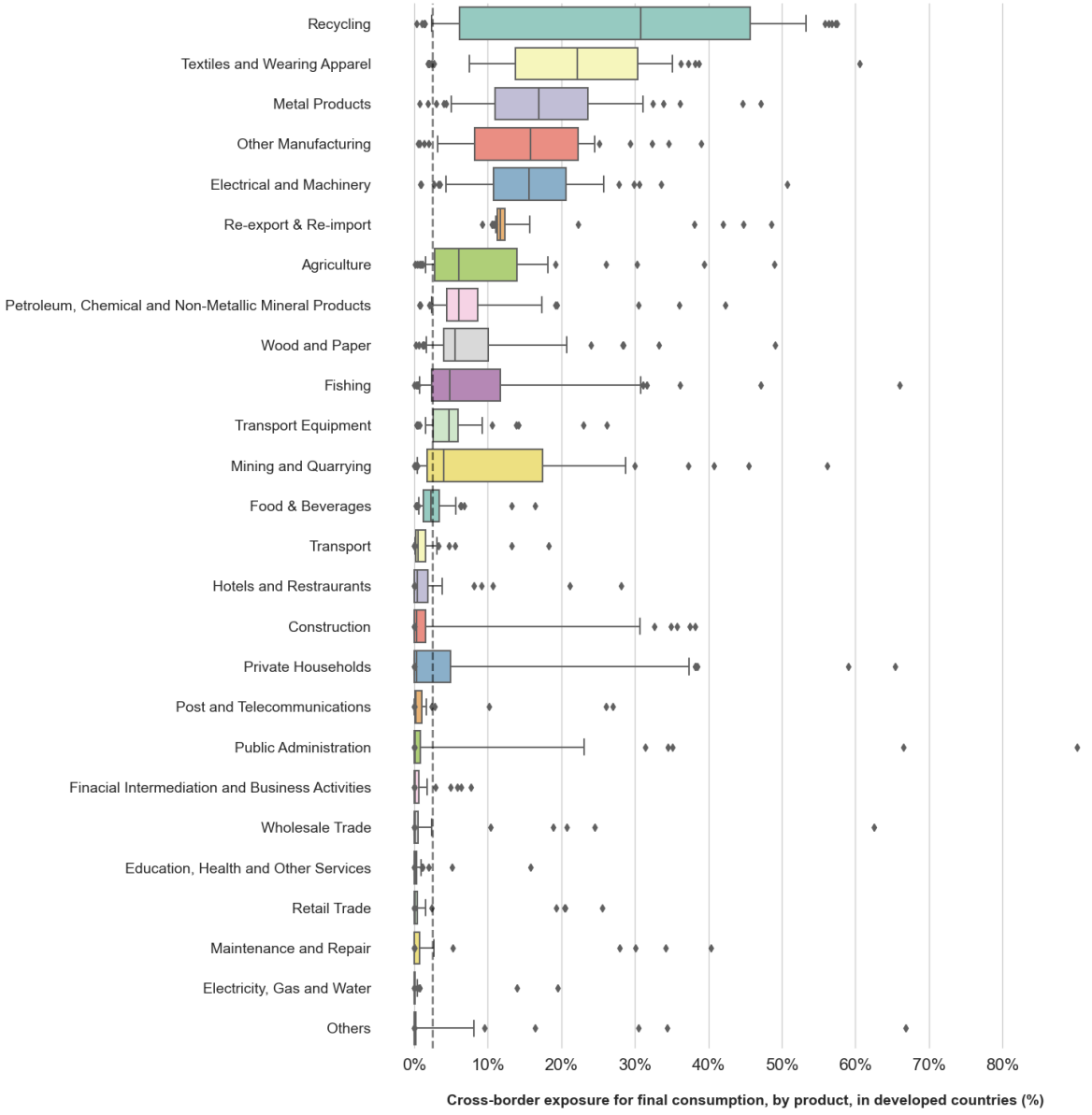
$$\frac{\sum_{(c',s'),\ c'\in R,\ c'\neq c} L_{(c',s'),(c,s)}\mathcal{Y}_{(c,s)}}{\sum_{(c',s')} L_{(c',s'),(c,s)}\mathcal{Y}_{(c,s)}}$$

This differs from what is depicted in Figure 2.16, as it focuses on the exposure of sector s in country c, rather than on how all firms in the country are exposed to imports of product s as intermediates. It appears that exposure is heterogeneous among sectors across developed countries, due to the fact that some imports are highly vulnerable, as shown in Figure 2.19. However, the highest sector exposure is lower than the highest exposure by product.

Figure 2.16: Exposure by product for imports of final consumption among developed countries [same figure as Fig. 2.4 of the main text]

(a) ICIO, INFORM Climate Change

(b) EORA, INFORM Climate Change

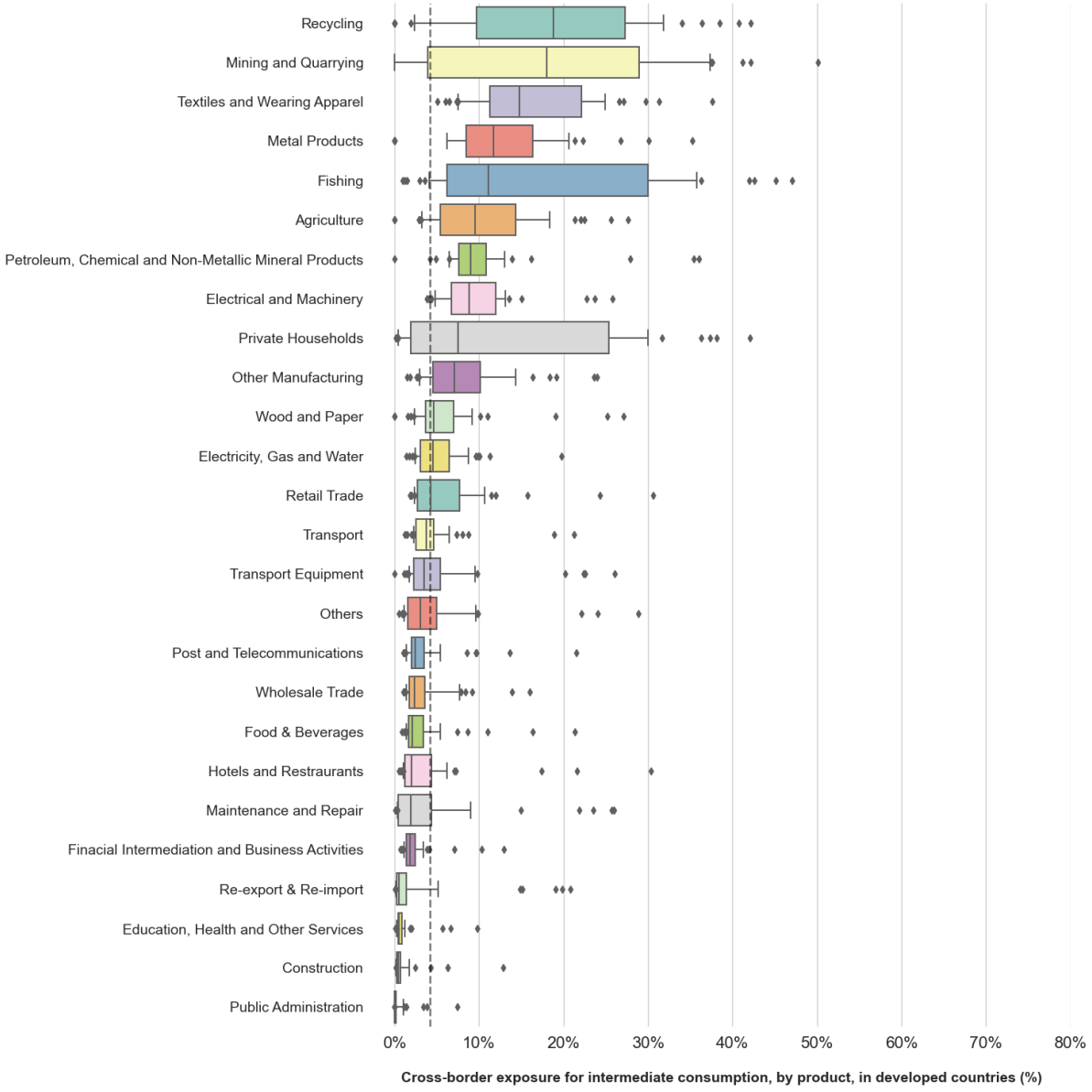


Lecture: For each sector of the ICIO (Panel (a)) or EORA26 (Panel (b)) tables, a boxplot represents the distribution of cross-border climate exposure on final consumption among developed countries. Boxplots indicate median, lower and upper quartiles while whiskers extend 1st and 9th deciles. The vertical dotted lines represent sector-aggregated median exposure for developed countries (2.6% for ICIO and 2.4% for EORA).

Figure 2.17: Exposure by product for imports of intermediate consumption among developed countries

(a) ICIO, INFORM Climate Change

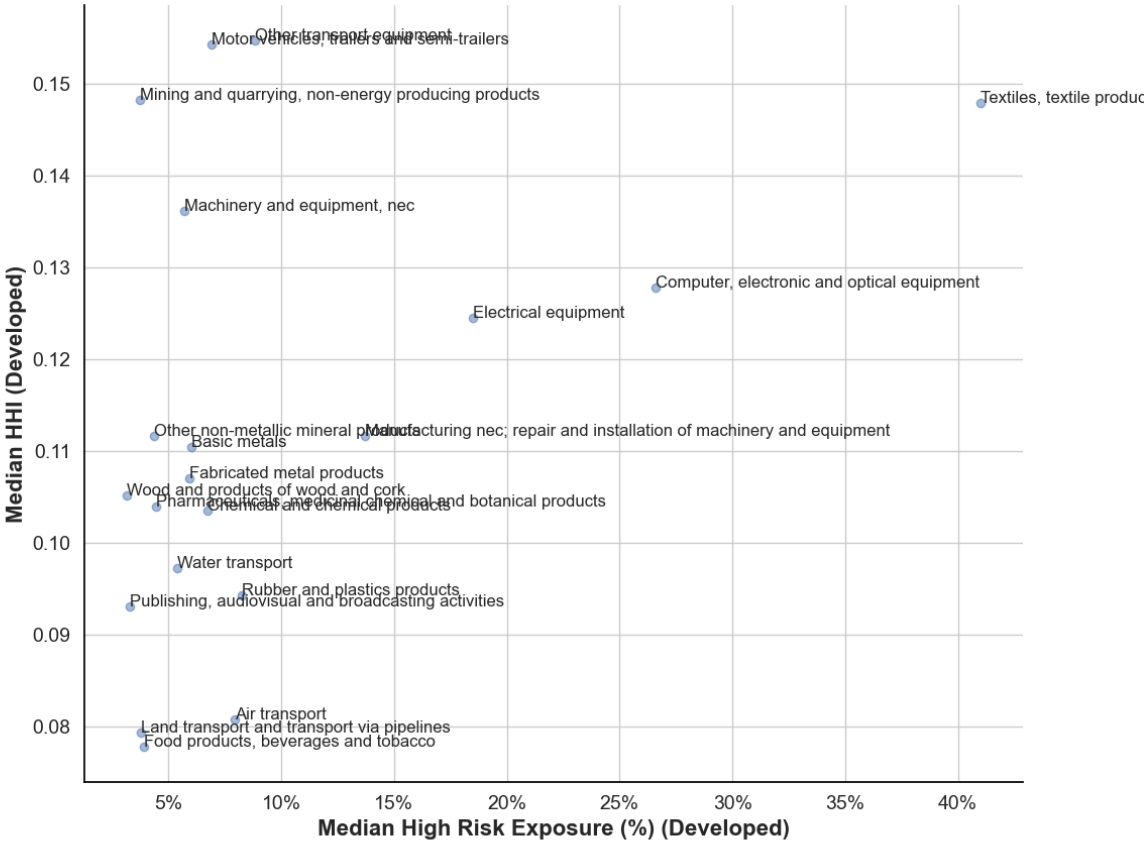
(b) EORA, INFORM Climate Change



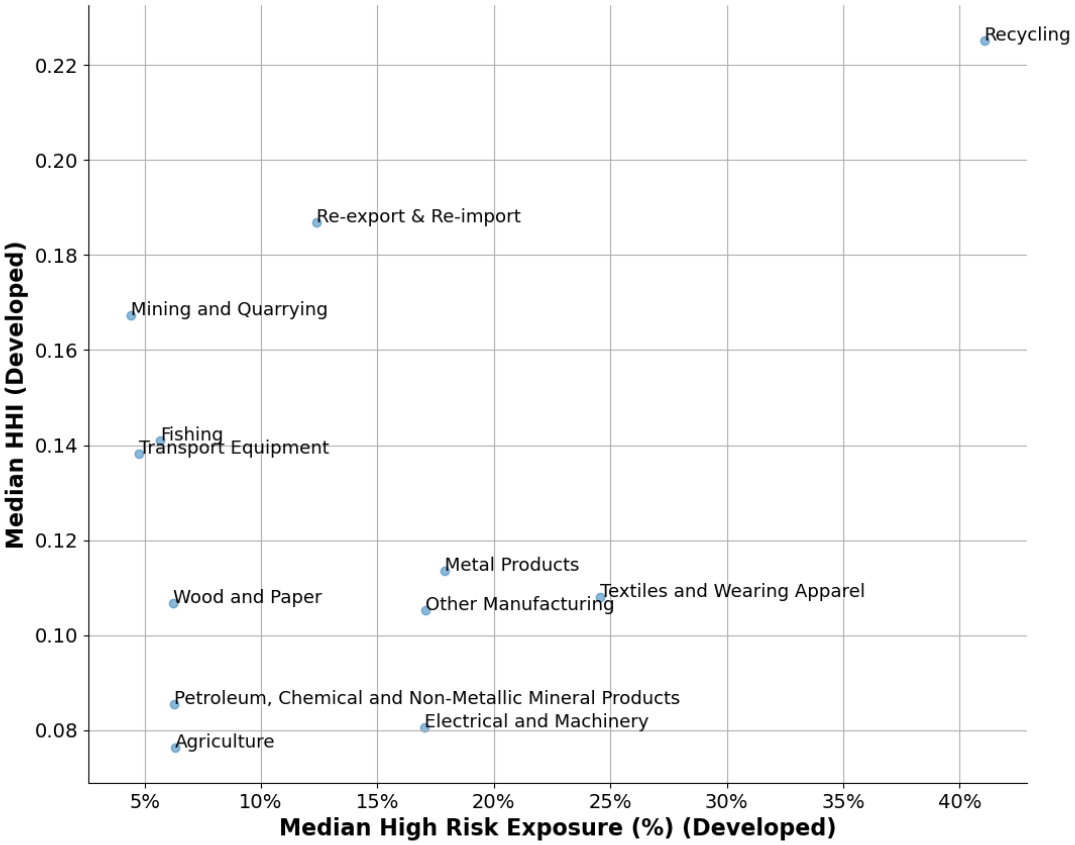
Lecture: For each sector of the ICIO (Panel (a)) or EORA26 (Panel (b)) tables, a box plot represents the distribution of cross-border climate exposure on intermediate consumption among developed countries. Boxplots indicate median, lower and upper quartiles while whiskers extend 1st and 9th deciles. The vertical dotted lines represent sector-aggregated median exposure for developed countries (3.1% for ICIO and 4.2% for EORA).

Figure 2.18: Exposure by product compared with concentration of suppliers, among developed countries

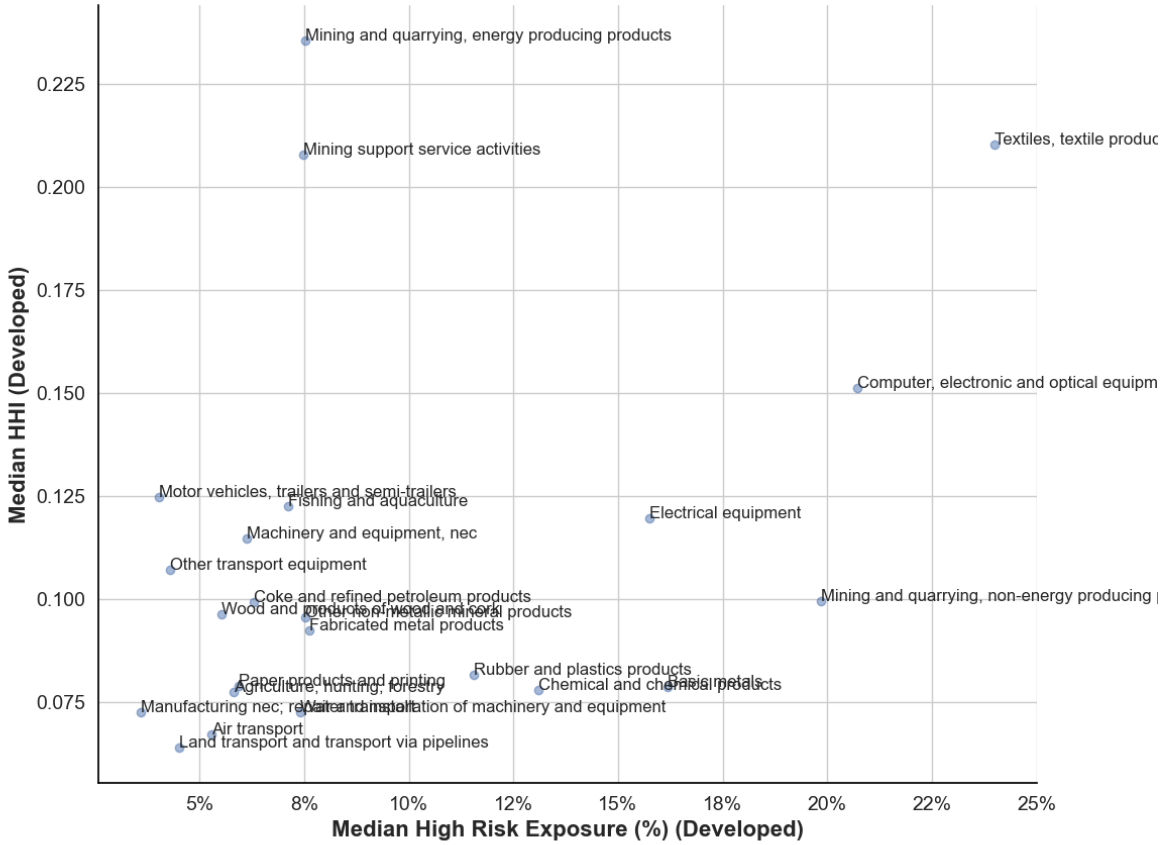
(a) Imports of final consumption (ICIO, INFORM Climate Change)



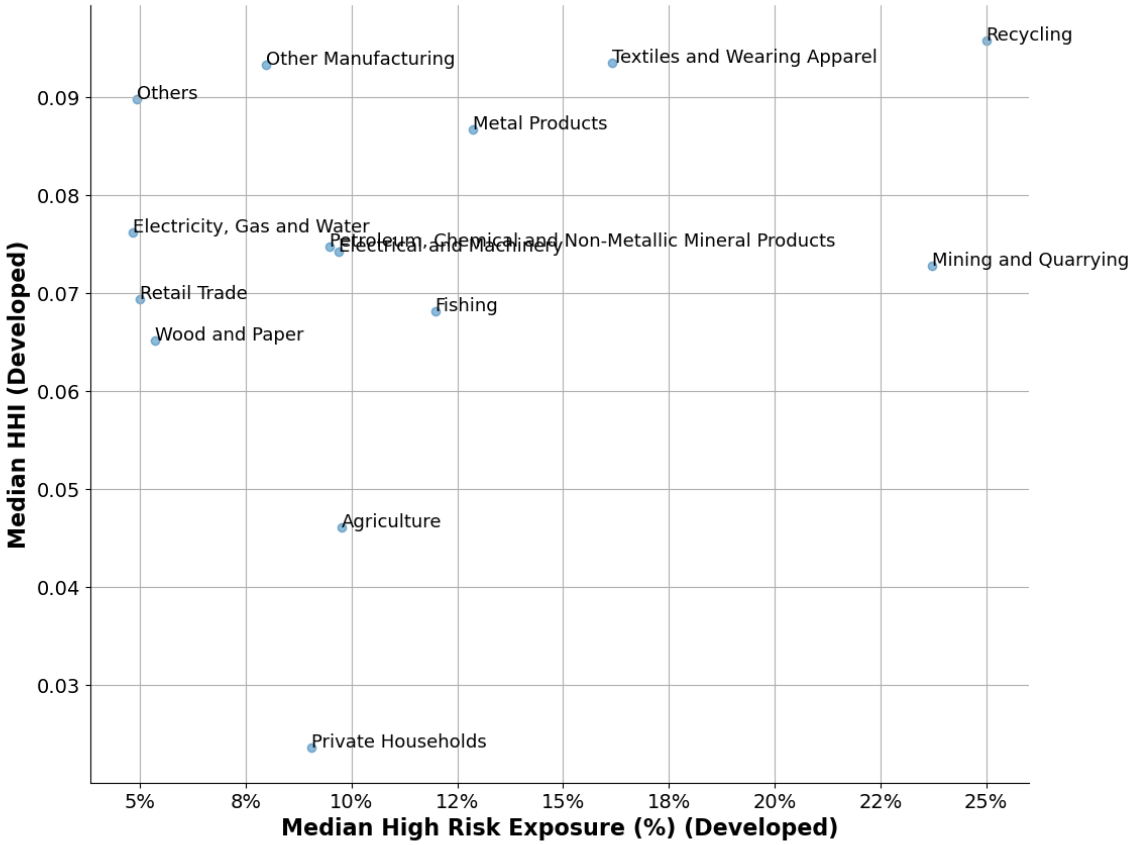
(b) Imports of final consumption (EORA, INFORM Climate Change)



(c) Imports of intermediate consumption (ICIO, INFORM Climate Change)



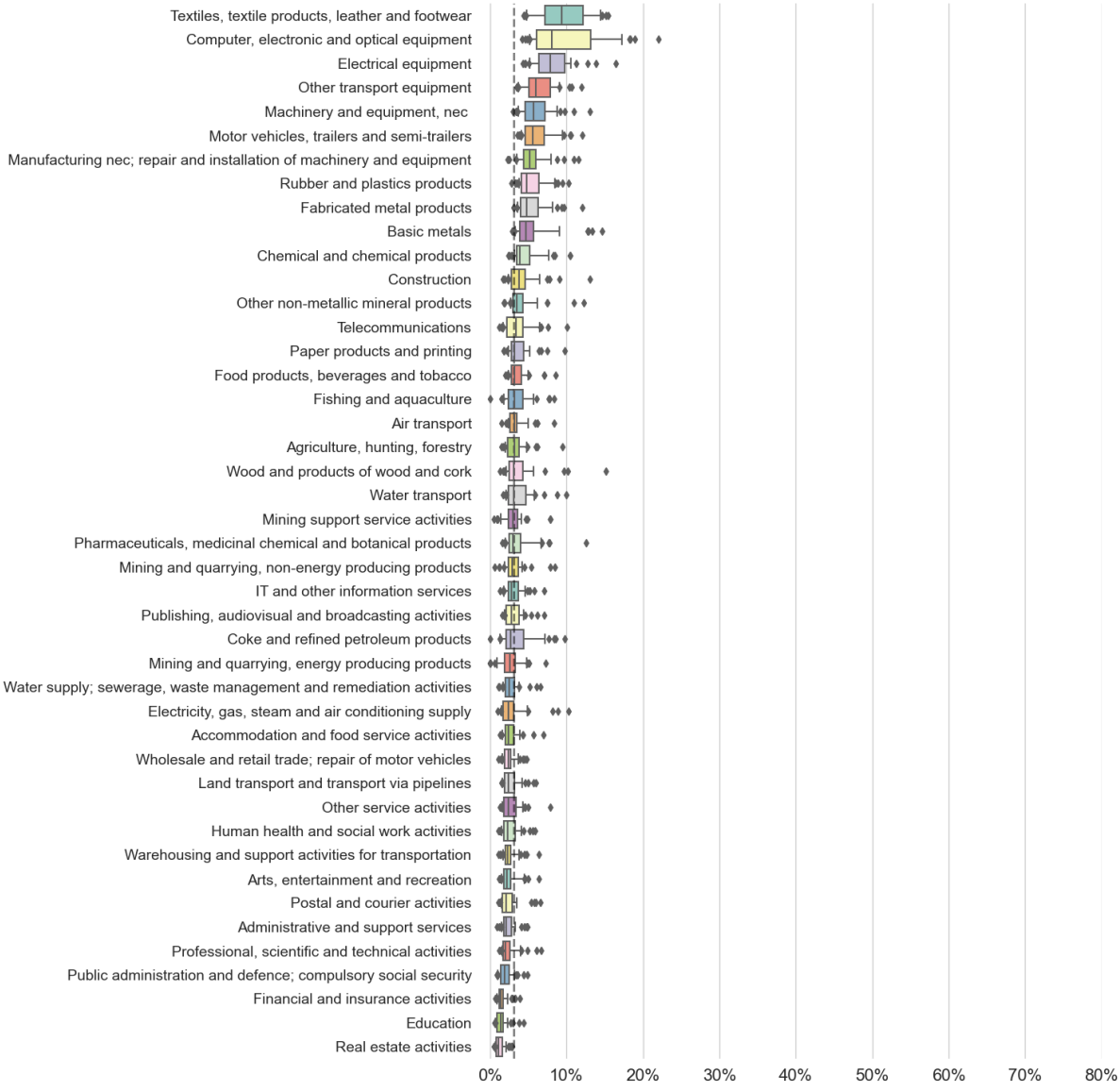
(d) Imports of intermediate consumption (EORA, INFORM Climate Change)



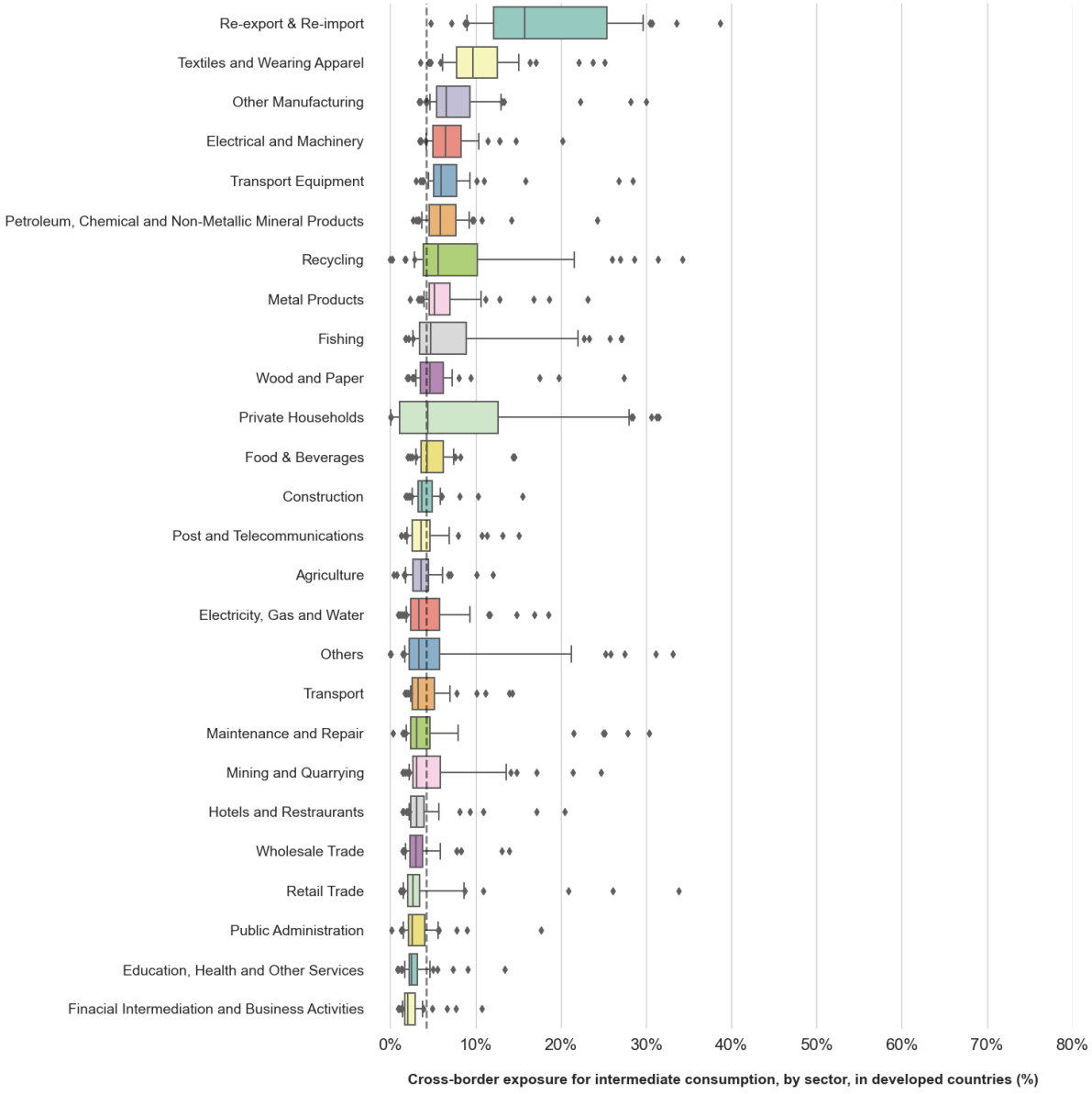
Lecture: For each sector of the ICIO (Panels (a) and (c)) or EORA26 (Panels (b) and (d)) tables, a point represents is located according to median high risk exposure across developed countries and median HHI index. Only sectors whose exposure is above country exposure are represented.

Figure 2.19: Sector exposure for imports of intermediate consumption among developed countries

(a) ICIO, INFORM Climate Change



(b) EORA, INFORM Climate Change



E Sensitivity analysis on risk classification

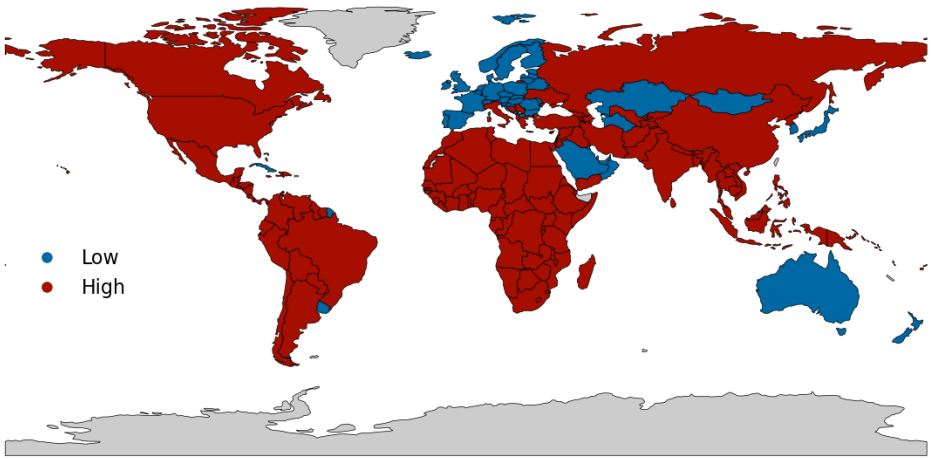
The qualitative results presented in the main text could be sensitive to the choice of a specific threshold separating countries between low and high climate risk. Below, we demonstrate that (1) adjusting the climate risk threshold for both indices and (2) removing a country for the high risk list does not alter the main conclusions.

E.1 Sensitivity analysis on risk threshold

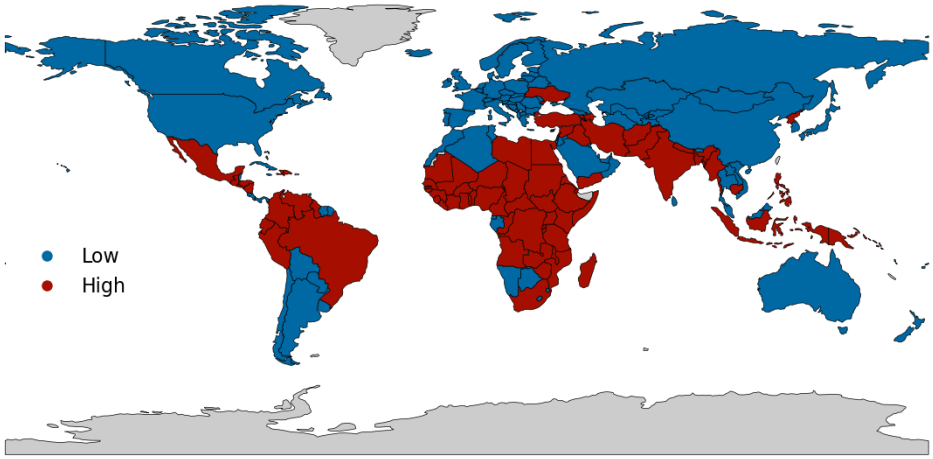
INFORM Climate Change already distinguishes five risk categories (very low, low, medium, high, and very high), based on a clustering method. We set the threshold at 3.5/10, that is between original low and medium risk categories. No risk classification is already available for ND-GAIN: 50/100 is chosen so that the list of high risk countries is generally consistent between both indices. These lists align well with both multidimensional risk analysis (Byers et al., 2018; Warren et al., 2022) and the literature on climate change impact on GDP (Burke et al., 2015; Kalkuhl et al., 2020) (Appendix F). However, to assess the robustness of our results, we check that our main conclusions remain valid for a wide range of threshold values, for both indices. More specifically, the 3.5 +/- 0.75 (INFORM Climate Change) and 50 +/- 10 (ND GAIN) ranges are explored below. Maps showing the distribution of countries between high and low risk at the extremes of the sensitivity analysis are presented in Figure 2.20.

Figure 2.20: Map of local climate risk for the bounds of the sensitivity analysis

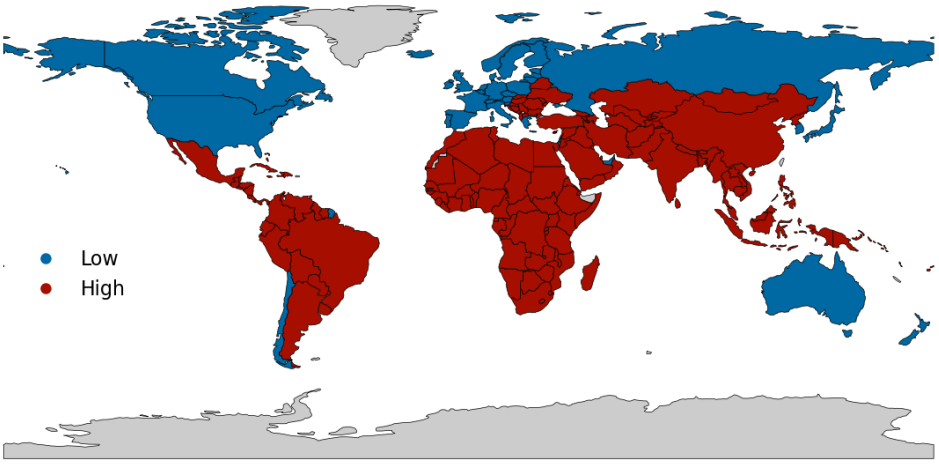
(a) INFORM Climate Change: threshold = 2.75



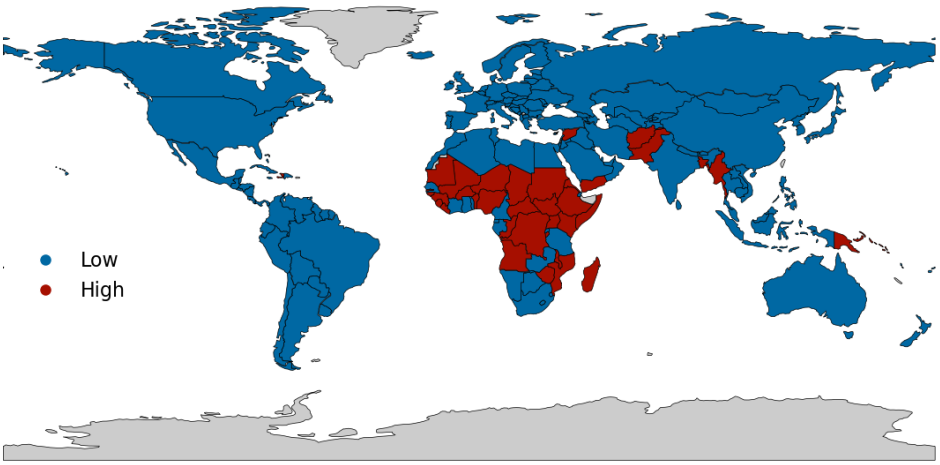
(b) INFORM Climate Change: threshold = 4.25



(c) ND-GAIN: threshold = 60



(d) ND-GAIN: threshold = 40



The robustness of three qualitative conclusions is assessed in the following, with EORA26.

First, Figure 2.3a, in the main text, showed that developed countries are among the least exposed to cross-border climate risk. Figure 2.21 displays for different thresholds the distribution of cross-border climate exposure for intermediate consumption in developed countries (blue dots) and all countries (orange dots). For both INFORM Climate Change (panel (a)) and ND-GAIN (panel (b)), developed countries generally exhibit lower exposure levels compared to all countries, across a large range of thresholds. For both INFORM Climate Change and ND-GAIN, except for some extreme threshold values (60/100 and 2.75/10, that is few low risk countries), the 70% quantile of exposure of developed countries is under the median exposure of all countries (note that, at the chosen threshold in the main text, the 85th percentile for developed countries falls below the median for all countries).

Second, Figure 2.3b, in the main text, shows that people exposed to the highest cross-border risk (4th column) mainly live in high local risk countries. Figure 2.22 displays how the share of people exposed to the highest cross-border risk living in high local risk countries changes when the risk threshold is changed. For INFORM Climate Change, the share is systematically high (more than 81%), except for threshold = 4.0 (where it is 68.9%), due to some countries, (e.g. Vietnam) switching from high to low risk status, but still being highly connected to high risk countries. For ND-GAIN, the share is high (more than 94%), except when too few countries are labelled high risk (for threshold = 40/100 and 45/100, share is respectively 55% and 65%), which stems from the fact that Asia is not high risk anymore.

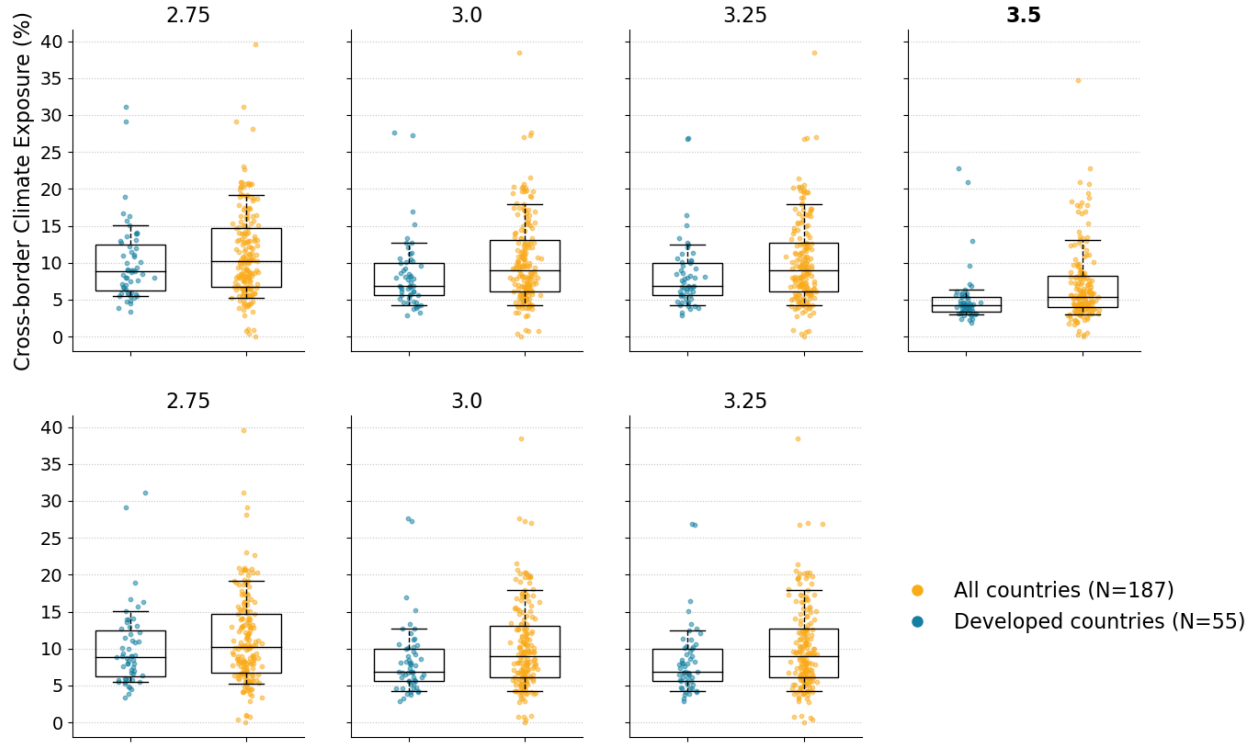
Finally, Figure 2.3c, in the main text, indicates that the relationship between local risk index and the share of high risk trade partners is significant. Figure 2.23 shows that regression is still significant across a wide range of thresholds for both INFORM Climate Change (Panel (b)) and ND-GAIN (Panel (d)) and that correlation is stronger for ND-GAIN (comparison of Panel (a) and (c)). R-squared is lower for threshold extreme values (e.g. t=2.75 for INFORM Climate Change), as more and more countries are labelled as high climate risk.

E.2 Do the results depend on only one country?

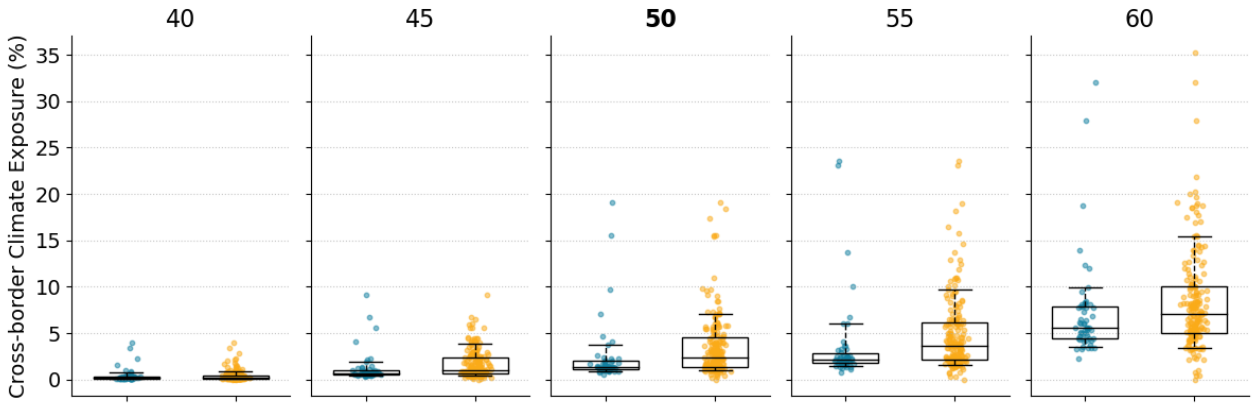
Finally, we wanted to check that the above results did not depend on the presence or absence of a country on the list of high risk countries, so that our results are not driven by only one country. We did so using INFORM Climate Change and EORA26. Figure 2.24 shows how distribution (median, 1st and 3rd quartile) of cross-border exposure for developed (blue) and developing/least developed (red) change when one country is removed from the high risk list. The blue distribution is systematically at the bottom of the red one, even though the level of exposure can be substantially lower: in particular, removing China from the high risk country lowers substantially the median level of exposure among developed (from 4.4% to 2.3%) and developing/least developed (from 6.8% to 4.8%). Figure 2.25 displays that correlation between local risk and share of high risk suppliers is significant whatever the country being removed from the high risk list. Figure 2.26 shows that, whatever the country removed from the high risk list, the share of people exposed to a high local climate risk among those living in a country with high cross-border exposure is higher than 90%, except for 4 countries: Ethiopia, Vietnam, Thailand, Ghana. This is due to the fact that these countries are the most populated countries with both high local and high cross-border risk. In these cases, a sharp decrease in share of people exposed to high local risk among those exposed to high cross-border risk is simply due to these countries leaving the high risk country list.

Figure 2.21: Distribution of cross-border climate exposure for developed and developing or least developed countries, for different risk thresholds (EORA26)

(a) INFORM Climate Change



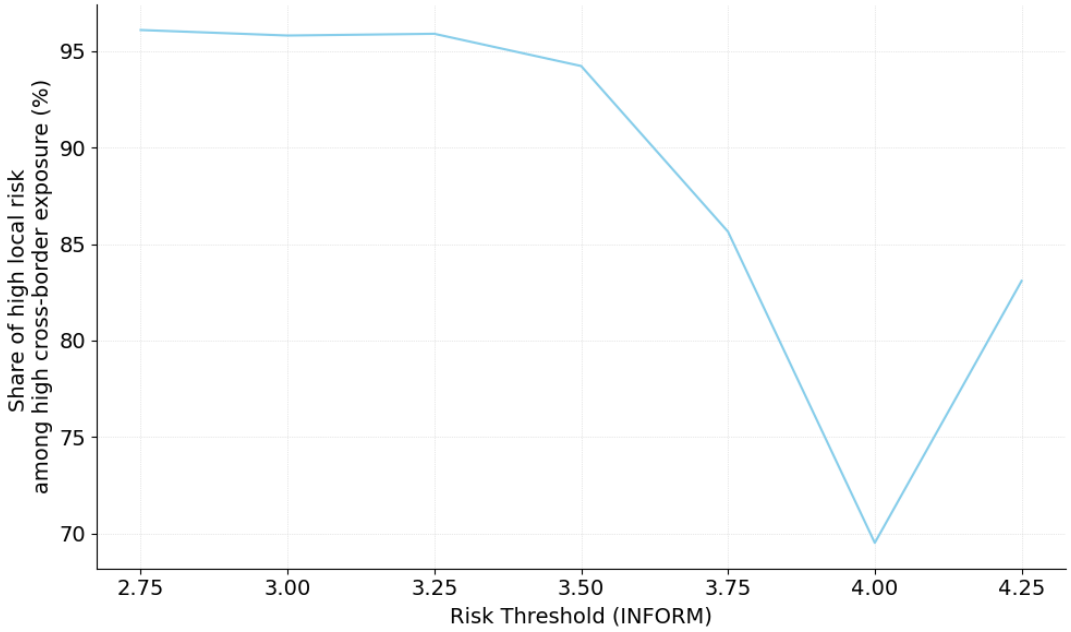
(b) ND-GAIN



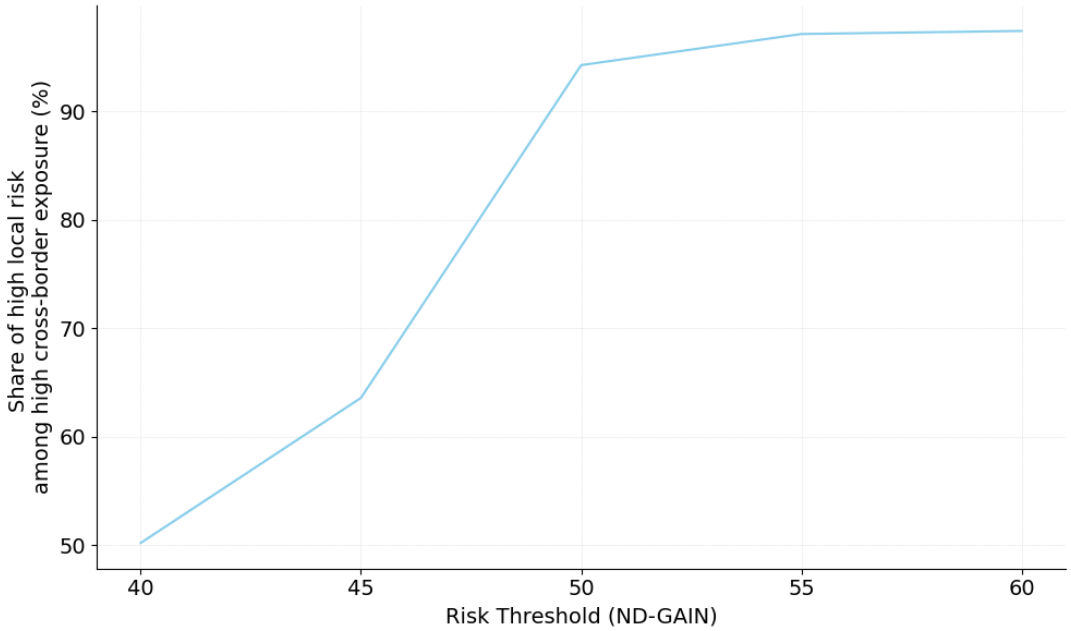
Lecture: distribution of cross-border climate exposure for developed (blue dots) and developing or least developed (yellow dots) countries is displayed for different risk thresholds. Boxplots indicate median, lower and upper quartiles while whiskers extend 1st and 9th deciles. Threshold values used in the main analysis are in bold font (3.5/10 and 50/100).

Figure 2.22: Total number of people living in countries with both a high cross-border exposure and a high local climate risk divided by the total number of people living in a country with a high cross-border exposure (EORA26)

(a) INFORM Climate Change

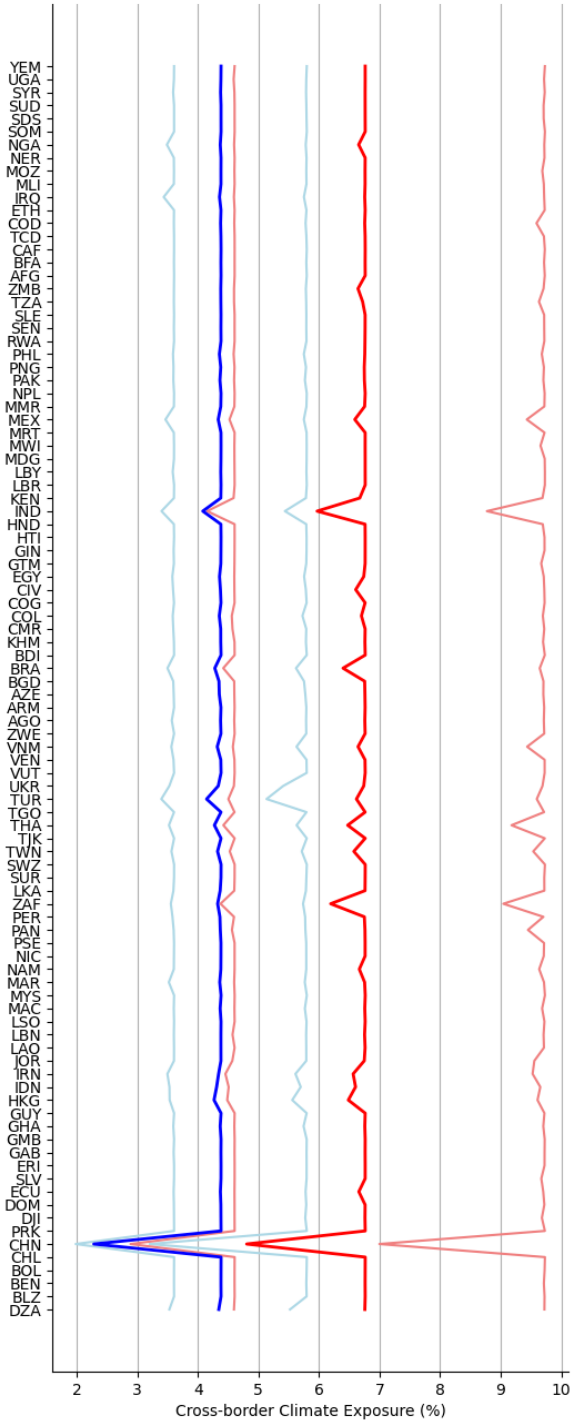


(b) ND-GAIN



Lecture: Among the people living in a country with high cross-border climate exposure, share of those exposed to a high local climate risk. Across the range of threshold explored, this share is high but is lowered when the number of high climate risk countries is lowered (high threshold for INFORM and low threshold for ND-GAIN).

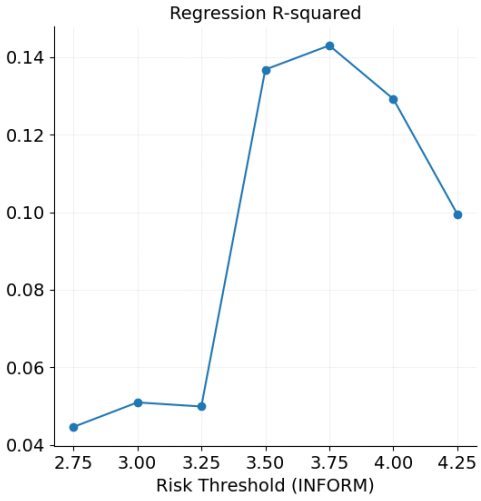
Figure 2.24: Distribution of cross-border climate exposure for developed and developing/least developed countries, one country is removed from the high risk list at a time (EORA26, INFORM Climate Change)



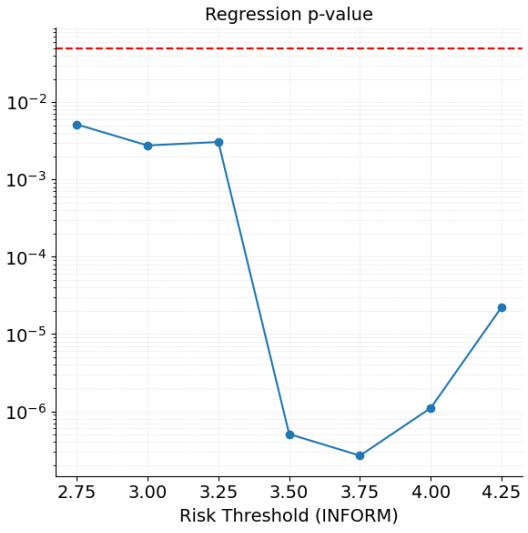
Lecture: distribution of cross-border climate exposure for developed (median dark blue, 1st and 3rd quartile in light blue) and developing/least developed (median dark red, 1st and 3rd quartile in light red) countries. Each line corresponds to a country taken out of the high risk countries risk. Distribution for developed countries' exposure is systematically in the lower half of the developing/least developed countries' distribution.

Figure 2.23: Regression of Share of High Risk Trade Partners on Local Climate Risk (EORA26)

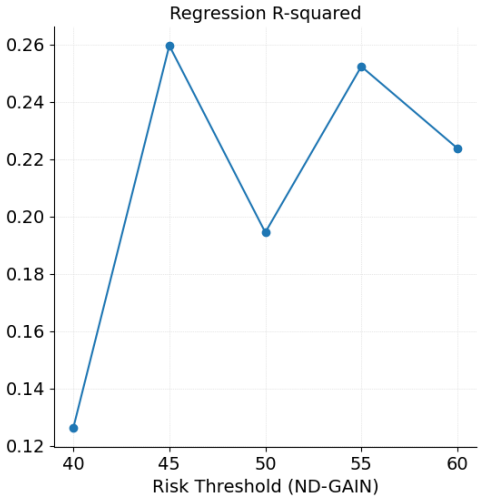
(a) INFORM Climate Change R^2



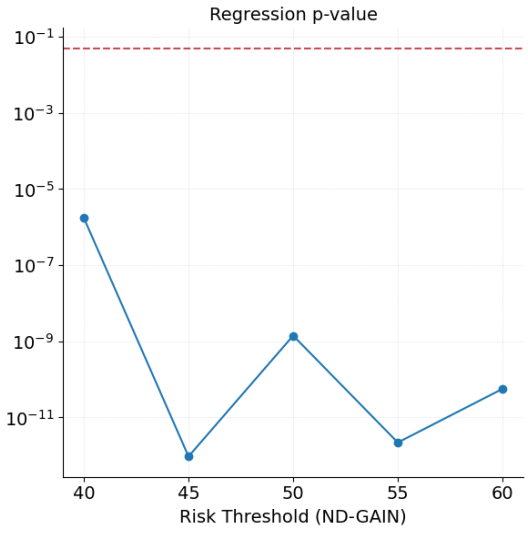
(b) INFORM Climate Change p-value



(c) ND-GAIN R^2

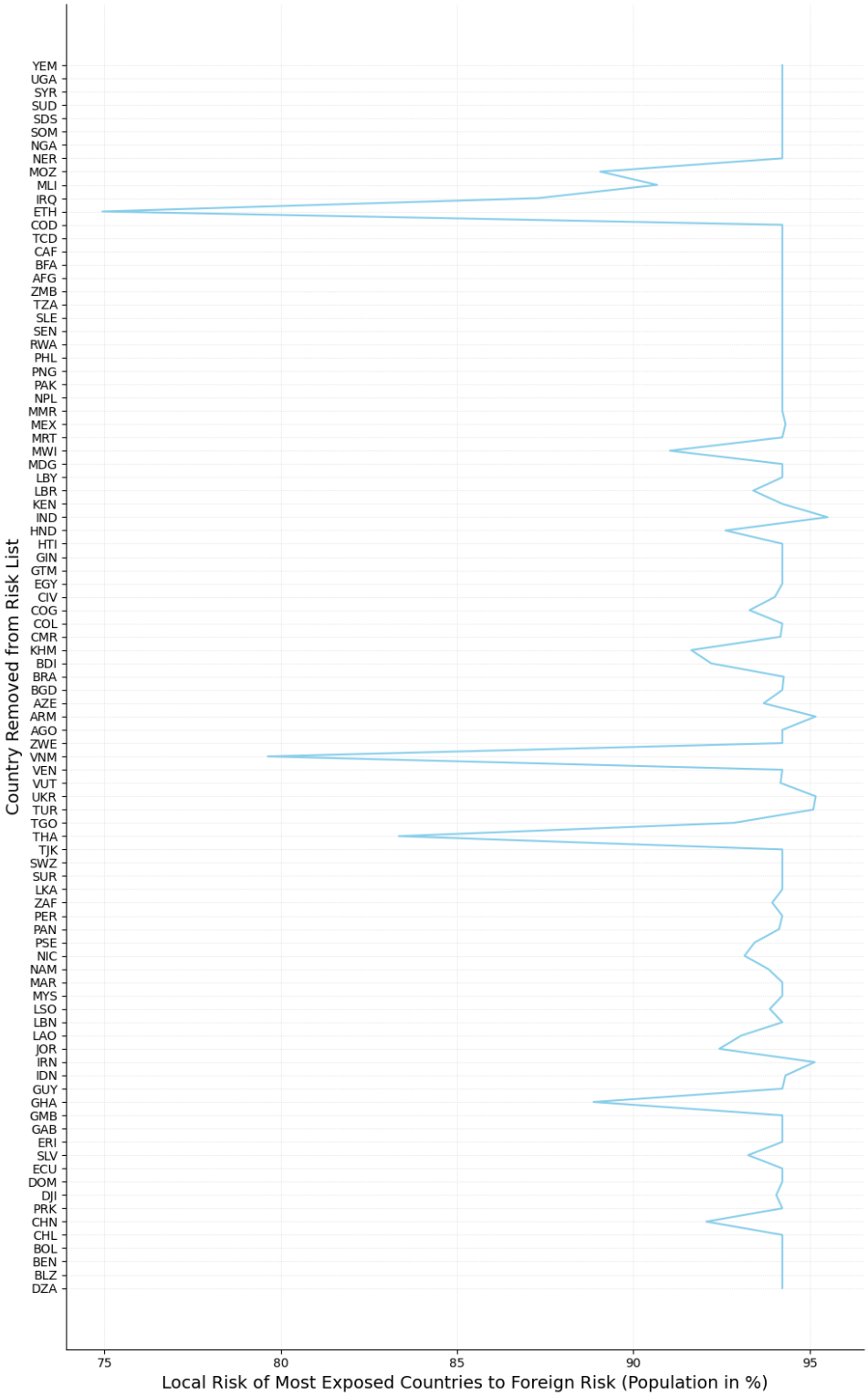


(d) ND-GAIN p-value



Lecture: Panel (a) and (b) indicate R-squared coefficient for correlation between local climate risk and share of high risk trade partners using respectively INFORM Climate Change and ND-GAIN. Panel (c) and (d) shows p-value, systematically less than 0.05 (red dotted line).

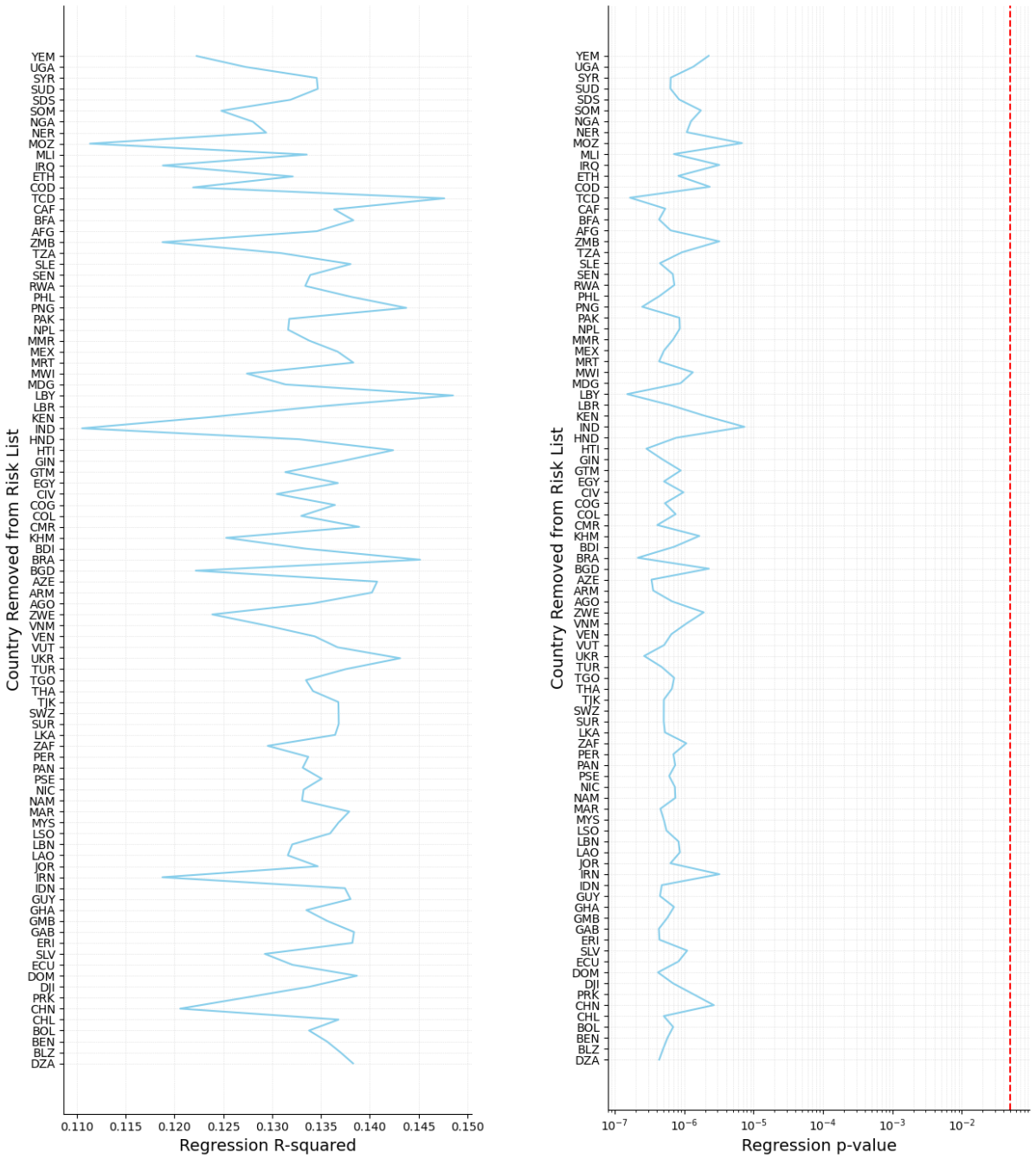
Figure 2.26: Total number of people living in countries with both a high cross-border exposure and a high local climate risk divided by the total number of people living in a country with a high cross-border exposure, one country is removed from the high risk list at a time (EORA26, INFORM Climate Change)



Lecture: Among the people living in a country with high cross-border climate exposure, share of those exposed to a high local climate risk, one country being removed from the high risk list at a time. Whatever the country removed from the high risk list, the share remains higher than 90%, with exception of 4 countries (Ethiopia, Vietnam, Thailand, Ghana).

Figure 2.25: Regression of Share of High Risk Trade Partners on Local Climate Risk, one country is removed from the high risk list at a time (EORA26, INFORM Climate Change)

(a) R^2 **(b)** p-value



Lecture: Panel (a) indicates R-squared coefficient for correlation between local climate risk and share of high risk trade partners, one country being removed from the high risk list at a time. Panel (b) shows p-value, systematically less than 0.05 (red dotted line).

F Robustness of the spatial distribution of local climate risk

The spatial distribution of climate change impacts can be assessed through various methods. Below, we present climate risk maps generated through: (1) composite indicators aggregating multiple biophysical and vulnerability dimensions of climate impacts, or (2) the assessment of climate change impact on GDP. As indicated by the studies mentioned (University of Notre Dame Adaptation Initiative, 2023; European Commission. Joint Research Centre., 2022; Byers et al., 2018; Warren et al., 2022; Burke et al., 2015; Kalkuhl et al., 2020), the identification of the most vulnerable areas—Africa and Southeast Asia—is consistent across all studies, although the classification of certain regions, such as the southern USA and parts of China, varies. Developing and least developed countries are generally considered more at risk from climate change than developed countries, due to both hazard spatial distribution and vulnerability levels.

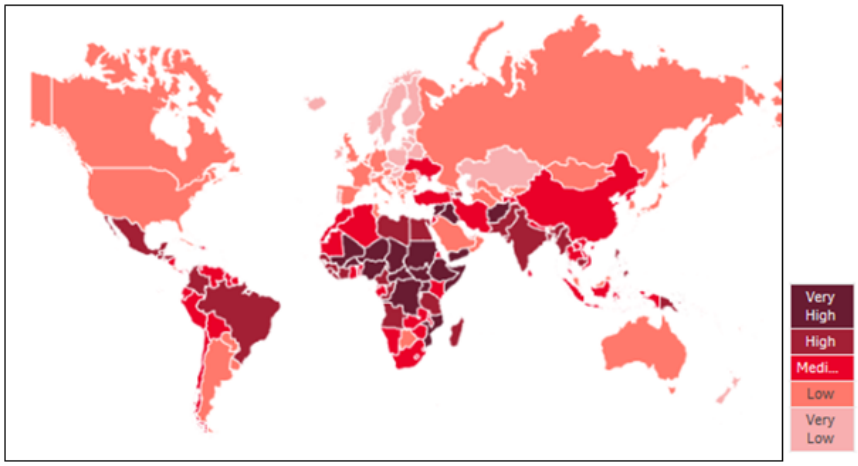
F.1 Aggregating biophysical and vulnerability indicators

Climate risk indices have been developed to identify climate risk hotspots. To our knowledge, INFORM Climate Change and ND-Gain are the only ones to integrate future climate hazards, exposure and vulnerability. They are used in this paper to identify countries with high climate risk and original maps of climate risk can be found in Figure 2.27.

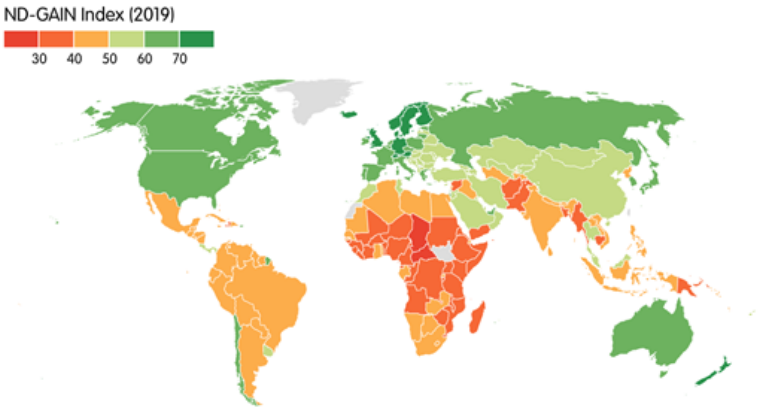
Academic literature has also focused on the identification of climate hotspots. Byers et al. 2018 and Warren et al. 2022 are the most recent examples, and their results are shown in Figure 2.28, even though their raw data are not publicly available.

Figure 2.27: Spatial distribution of climate risk according to publicly available climate risk indices

(a) INFORM Climate Change



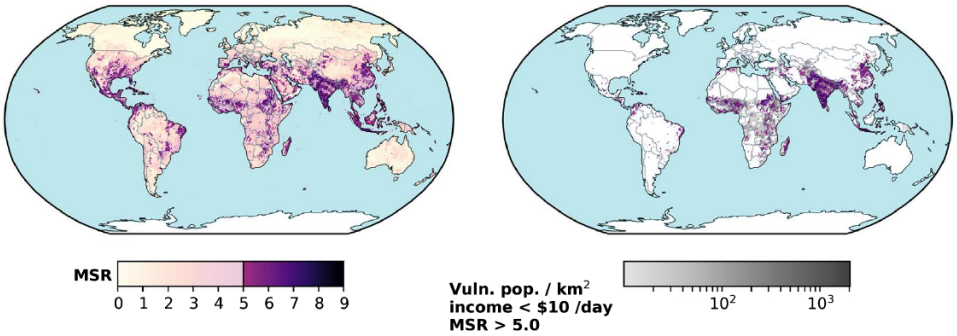
(b) ND-Gain



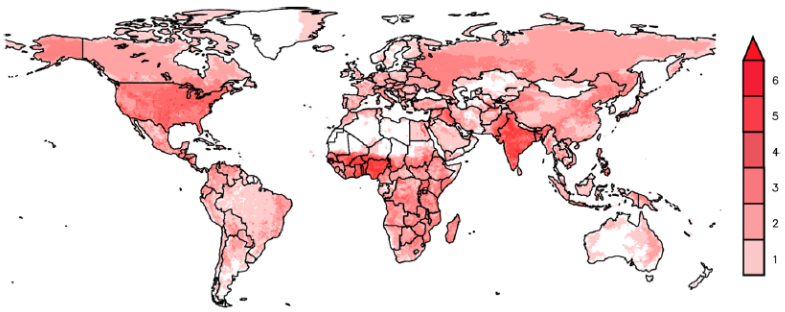
Lecture - Panel (a) Risk level by 2050 under RCP8.5 according to INFORM Climate Change. Panel (b) Risk level due to climate change according to ND-GAIN.

Figure 2.28: Spatial Distribution of Climate Risk according to Byers et al. 2018 and Warren et al. 2022 (Reprinted from Byers et al. 2018. Copyright © 2018 IOPScience and Warren et al. 2022 Copyright © 2022 Springer Nature)

(a) Byers et al. 2018



(b) Warren et al. 2022



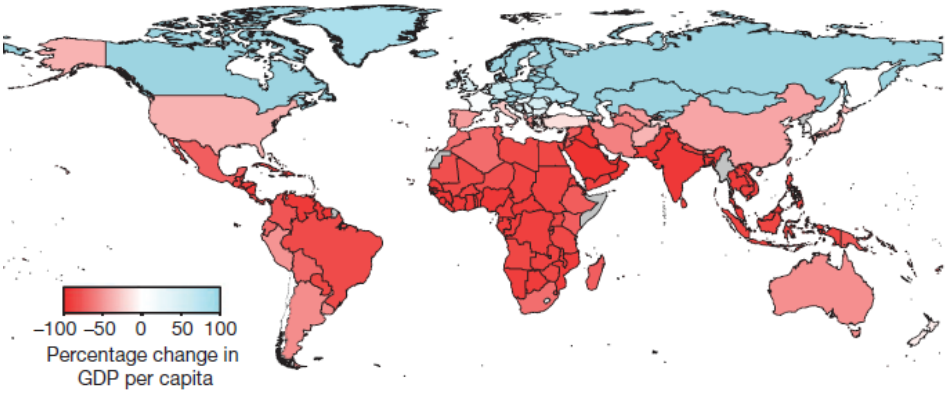
Lecture - Panel (a): multi-sector risk (MSR) map for 3.0°C climate. Left map indicates MSR level and the right map combines high climate risk (MSR>5) and high exposure and vulnerability (number of people living on less than $10 a day). Panel (b) : hotspots of multi-sectoral additional climate change risk at 1.5°C (SSP2).

F.2 Climate change impact on GDP

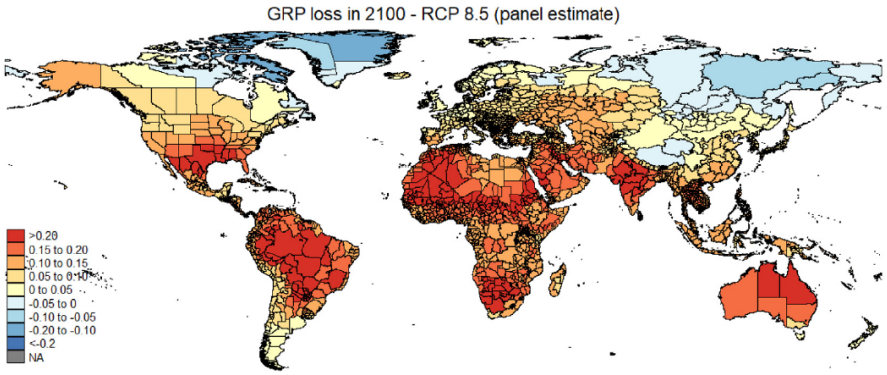
Assessing the impact of climate change on GDP has generated a vast literature. It has been reported that the impacts are likely to be regressive, in the sense that they affect poorer countries more (Piontek et al., 2021). We reproduce below (Figure 2.29), by way of illustration, two maps showing the spatial distribution of impacts on GDP (Burke et al., 2015; Kalkuhl et al., 2020): as can be seen, patterns identical to those illustrated by aggregating biophysical and vulnerability indicators emerge.

Figure 2.29: Spatial heterogeneity in climate change impact on GDP (Reprinted from Burke et al. 2016. Copyright © 2020 Springer Nature and Kalkuhl and Wenz 2020 Copyright © 2020 Elsevier)

(a) Burke et al. 2016



(b) Kalkuhl and Wenz 2020



Lecture - Panel (a): Change in Gross Domestic Product in 2100 under RCP8.5 SSP5 according to Burke et al. 2016. Panel(b): Change in Gross Regional Product in 2099 under RCP8.5 according to Kalkuhl and Wenz 2020.

Chapter 3

Trading for resilience: assessing the impact of extreme events in the context of climate change across various trade scenarios

Working paper
Joint work with Samuel Juhel (ETH),
Timothé Beaufils (PIK) and Vincent Viguié (CIRED).

Abstract

Countries can suffer important economic losses when they are hit by extreme events. As climate risks are expected to increase in the future, climate-related economic disruptions are also likely to become more frequent and severe. One possible adaptation strategy is to further integrate national economies into international trade, thereby reducing exposure to local shocks and smoothing consumption. However, greater trade integration also increases vulnerability to shocks originating in other countries. Here, we propose a quantitative framework to investigate this trade-off by combining a database of thousands of river floods under current and future climate conditions, an input-output cost propagation model, and a set of diversely integrated international trade networks. As a first step, we explore the effect of a uniform increase in trade integration across the world and find that increasing trade openness creates both winners and losers, with more losers than winners. However, Nevertheless, from the perspective of a global social planner, greater trade openness would be desirable, since countries heavily hit, directly and indirectly, by floods get a significant gain from trade integration. Having low directly impacted countries isolate highly directly impacted ones would significantly worsen the situation of the latter group.

Keywords: Climate change, Climate impacts, Resilience, Trade, Extreme events, Floods.

Contents

1 Introduction **131**
2 Methods **133**
2.1 Flood data 133
2.2 Trade scenarios 134
2.3 Cross-border impact propagation 135
3 Results **136**
3.1 Capital and consumption losses due to floods are heterogeneously distributed across the globe 136
3.2 Increasing trade openness creates both winners and losers, with more losers than winners 140
3.3 From the perspective of a global social planner, greater trade openness would be desirable 142
3.4 Isolating high local risk countries would significantly worsen their situation 144
4 Discussion and conclusion **146**
5 References **149**
A Supplementary Methods **153**
A.1 Floods database 153
A.2 Trade networks 155
A.3 ARIO 160

1 Introduction

Climate change is already underway and is expected to intensify by 2050, even in the absence of additional greenhouse gas emissions. This will lead to an increase in the frequency and intensity of extreme events (IPCC, 2023b), which is particularly concerning due to their significant economic impacts that may affect population well-being. To reduce the economic damages, several adaptation measures can be implemented, such as strengthening the resilience of infrastructure (Hallegatte et al., 2019). It has been proposed that further integrating countries into international trade can also play a role, as it allows countries to compensate for local production losses through imports and thus both facilitate continuous business operations safeguarding people's access to goods after a natural disaster (Janssens et al., 2021).

However, the validity of this proposition is not obvious, as greater integration also exposes economies to external shocks (Wenz et al., 2016). This vulnerability is all the more problematic since extreme events are already disrupting, and will increasingly disrupt, global supply chains. For example, the global semiconductor shortage between 2020 and 2023 was partly attributed to the drought that occurred in Taiwan in 2021 (Barbiroglio, 2021). Similarly, the sharp increase in global food prices since 2022 has been linked to the fact that recent years have been among the driest on record worldwide (Ryan, 2023). Risks associated with trade integration in the context of climate change are referred to as trade cross-border climate risks (Carter et al., 2021; Hedlund et al., 2018). From this perspective, trade openness could also be seen as a form of maladaptation (Magnan et al., 2016; Schipper, 2020).

Overall, for a given country or for the world as a whole, it is not clear whether greater

economic integration helps mitigate the adverse economic effects of climate change-related extreme events, or rather contributes to amplifying them. While an existing literature generally quantifies the economic gains from trade for countries (Costinot et al., 2014), this study focuses on a more specific question: the role of trade integration in shaping countries' exposure to climate-related risks.

Two main types of approaches have explored the interactions between international trade and the impacts of climate change. One body of literature relies on long-term economic models—such as computable general equilibrium (CGE) or quantitative trade models—and investigates how gradual climate damages—so-called slow-onset impacts—progressively reshape trade networks (Schenker, 2013; Schenker and Stephan, 2014; Gouel et al., 2021; Cruz et al., 2024; Constant et al., 2019). One key insight from Schenker and Stephan (2014) and Constant et al. (2019) is that countries that are less directly affected by climate impacts still experience welfare losses. This occurs because climate damages reduce the long-term growth of affected countries, thereby lowering the gains from trade for unaffected ones—to the point that they may have an economic interest in financing adaptation in the most vulnerable regions. However, these models focus on a specific category of climate impacts—namely gradual damages—and overlook extreme events, whose accurate assessment requires a less adaptive framework than CGE models. In addition, the international trade scenarios considered in these models typically assume that economic agents respond optimally and spontaneously to climate impacts. Yet global trade trajectories can be much more diverse: they may involve non-optimal reactions to shocks—such as the exclusion of the most affected regions (Adaptation Without Borders, 2023; Bednar-Friedl et al., 2022)—or be shaped by geopolitical dynamics and non-economic considerations (Aiyar et al., 2023). Another strand of the literature, based on input–output models—such as ARIO (Hallegatte, 2014), MRIA (Koks and Mark Thissen, 2016), or Acclimate (Otto et al., 2017)—, assesses the short-term consequences of fast-onset events triggered by climate change. However, this approach has so far only been applied to current or past trade networks (Wenz et al., 2016; Willner et al., 2018), and has not been used to assess how impact propagation across trade networks may vary with different levels of trade integration or, more broadly, with alternative future evolutions of trade networks.

In this study, we develop a quantitative framework that allows for comparing, across countries, the costs and benefits of trade integration in the face of extreme events and their intensification due to climate change. To this end, we use a dataset on floods under both current and future climate conditions (Alfieri et al., 2017). Using the ARIO model—an input–output model widely employed in the literature (Hallegatte, 2014; Inoue et al., 2019; Guan et al., 2020; Sun et al., 2024)—we assess the indirect economic consequences of these floods, both for the directly affected countries and for the rest of the world, through their propagation across multiple trade networks, each reflecting a distinct scenario of future trade integration. In particular, using the SPIN method (Beaufils et al., 2022), we project current trade networks to the year 2050 based on gross domestic product (GDP) trajectories from the Shared Socioeconomic Pathways scenarios (SSPs) (Dellink et al., 2017; O'Neill et al., 2017). We then explore alternative versions of these networks, depending on whether countries are more or less commercially integrated than today.

We also consider more complex scenarios involving the formation of trade blocs, including as a response to climate change impacts. Our objective is to examine different possible evolutions of the global trade system, thereby extending the existing SSP scenarios with explicit trade projections. In this study, we focus on a single type of extreme event, namely floods. Floods are among the costliest natural disasters, as illustrated by the 2021 floods in Germany, which caused damages estimated at €33 billion (AON, 2021). However, the methodology we propose can be applied to other types of climate-related extreme events as well.

Studying the propagation of the economic consequences of extreme events under different international trade scenarios is all the more important given that historical transformations of trade networks have been shown to either amplify or mitigate the transmission of economic shocks, depending on the context (Wenz et al., 2016; Willner et al., 2018). Moreover, several factors suggest that these networks are likely to undergo significant changes in the coming decades. On the one hand, long-term economic growth could lead some countries—particularly those most exposed to climate risks—to increase their share in global trade. On the other hand, trade networks could also be profoundly reshaped by geopolitical dynamics, such as the ongoing tariff policies.

2 Methods

Our methodological framework builds on the agent-based model ARIO, which simulates the propagation of shocks along the global trade network. We model alternative states of the global trade network using the SPIN method and incorporate floods using simulated data from climate change projections.

2.1 Flood data

We use a database of projected continental floods in the 21st century (Alfieri et al., 2017). This database provides an assessment of the impact of floods in terms of productive capital losses, a metric particularly suited to assess their wider economic impact, and has already been used in the economic climate impact literature (Koks, Thissen, et al., 2019). It is composed of hundreds of thousands of individual flood events ranging from 2016 to 2130, generated by seven different global climate models over the period. All climate projections used are based on Representative Concentration Pathway 8.5 (RCP 8.5) (IPCC, 2014). For each flood event, capital damages are assessed in the original data across different impact categories. In our implementation, only infrastructure, industrial and commercial capital losses are considered, as damages to residential buildings cannot be directly attributed to specific economic sectors in our input-output framework.

We select a subset of all flood events by focusing on those occurring around 2020 (i.e., between 2015 and 2025), around 2050 (i.e., between 2045 and 2055) and around 2100 (i.e., between 2095 and 2105), which correspond to global warming levels of +1.1 °C, +2.4 °C, and +4.3 °C above pre-industrial levels. Due to climate change, flood events are projected to cause

substantially higher damages by 2050, and even greater damages by 2100, holding the economic structure constant, as events become more frequent and more intense. While floods in the original database are spatially explicit at a 1-km grid resolution, the input-output tables we rely on are national in scope; as a result, each shock is interpreted as a reduction in productive capital at the level of the whole economy. Shocks are expressed in relative terms based on current input-output tables, so that they can be applied both to current and future trade networks (see Supplementary Material A for detailed calculations).

2.2 Trade scenarios

Here, trade networks are represented through input-output tables that describe economic interdependencies between sectors across countries. We use EORA26, as it covers over 180 countries, enabling us to capture trade flows involving as many countries as possible (Lenzen et al., 2012). EORA26 provides data for 26 sectors in each country. Our baseline input-output table is the 2016 version of EORA26, which is the most recent version that is publicly accessible. We rely on GDP projections from the SSPs. The latest year available in the most recent release of SSP GDP projections is 2020: as a consequence, to describe current trade networks, we construct a set of input–output tables based on 2020 GDP levels, using the 2016 Eora26 table as the underlying structure. To this end, we use the SPIN algorithm, which takes an input-output table as a baseline and projects future tables under aggregate GDP and trade constraints (Beaufils et al., 2022). SPIN aims to generate input-output tables that preserve the original technological structure—defined by the technical coefficients of domestic economies—while meeting updated GDP and trade volume constraints. GDP levels for 2020 are sourced from the SSP database (IIASA, 2024), while trade constraints are set to preserve the trade-to-GDP ratios observed in the 2016 input-output table.

Alongside this table representing current trade networks, we also construct tables reflecting future trade networks by 2050. The trade scenarios are designed to encompass a broad range of plausible future developments. Regarding GDP constraints, we consider three SSP scenarios: SSP2 (business-as-usual), SSP3 (low growth), and SSP5 (high growth). Regarding trade constraints, we consider two main types of scenarios. First, we consider a uniform opening or closing of international trade, by imposing trade-to-GDP ratios that decrease by 50 % ("Low trade"), remain constant ("Constant trade"), or increase by 50 % ("High trade"). Combining GDP and trade scenarios leads to 9 distinct scenarios. In the following, for clarity, all results are presented for SSP2 and for year 2050. Second, we explore a trade bloc scenario in which countries highly exposed to floods on their own territory are cut off from global trade and consequently compelled to trade among themselves. More specifically, countries are divided into two categories: those experiencing limited flood events on their national territory during the period in the flood database ('Low local floods'), and those facing higher flood impact ("High local floods"). We define the least exposed countries as those with the lowest cumulative capital losses over 2045–2055, selected in ascending order until they together account for 75 % of world GDP. Those with high flood impact therefore correspond to the remaining 25 % of world GDP. We define a "Isolation" scenario where inter-zone trade volume is reduced by 50 % while interna-

tional trade volume is kept constant. We keep the "Constant trade" scenario of the first set. We define an "Integration" scenario where inter-zone trade is increased by 50 % while international trade volume is kept constant (see Supplementary Material A for a step-by-step description of how the projected input-output tables are constructed).

Table 3.1 synthesizes the various scenarios considered. It is possible to analyze the input–output tables produced in order to examine how trade openness modifies them. In the uniform scenarios, the resulting input–output tables show relatively little change in the composition of each country's trade partners. However, trade specialization tends to increase in sectors that are more integrated into global trade, for a given level of GDP. In contrast, in the club scenarios, there are not only changes in sectoral specialization, but also, by construction, shifts in trading partners.

Table 3.1: Trade scenarios considered in the simulations

Scenario	**Constraints compared to 2020 baseline**
Low trade	Future GDPs For every country, trade openness = –50% compared to baseline
Constant trade	Future GDPs For every country, trade openness = same as baseline
High trade	Future GDPs For every country, trade openness = +50% compared to baseline
Isolation	Future GDPs Trade volume between low-risk and high-risk countries is diminished by 50% compared to baseline, but overall trade is constant
Integration	Future GDPs Trade volume between low-risk and high-risk countries is increased by 50% compared to baseline, but overall trade is constant

2.3 Cross-border impact propagation

To capture the cascading effects of flood-induced losses across sectors and countries, we rely on the ARIO model, a widely used model in the literature to simulate these effects (Hallegatte, 2014; Juhel, 2024; Inoue et al., 2019; Guan et al., 2020; Sun et al., 2024). As an input-output framework, it is particularly appropriate for capturing the short-term economic impacts of extreme events (Botzen et al., 2019): as a result of capital destruction, affected economic sectors are forced to reduce their production, which in turn impacts other firms—they stop ordering from their suppliers (upstream propagation) and are unable to deliver to their clients (downstream propagation)—as well as final consumers, who are deprived of goods and services (Vasco M. Carvalho et al., 2019). Given that economic sectors are integrated into global trade, any shock also propagates to sectors and consumers in other countries. Because ARIO is an input-output model, sectors are unable to substitute trading partners when disruptions occur, reflecting the limited flexibility of trade networks in the short run (Koks, Carrera, et al., 2016). In addition, ARIO includes realistic features related to the aftermath of extreme events. First, destroyed capital must be rebuilt, which diverts resources from the rest of the economy. Second, economic

sectors hold inventories, which allow them to absorb part of the shock (Lafrogne-Joussier et al., 2023) (see Supplementary Material A for details regarding model parametrization).

3 Results

3.1 Capital and consumption losses due to floods are heterogeneously distributed across the globe

Before looking at the economic consequences of trade openness on flood-related losses, it is useful to first highlight the main characteristics of the losses that we simulate in the central scenario, namely the SSP2 2050 "Constant Trade" scenario, combined with the warming level of the 2045–2055 period.

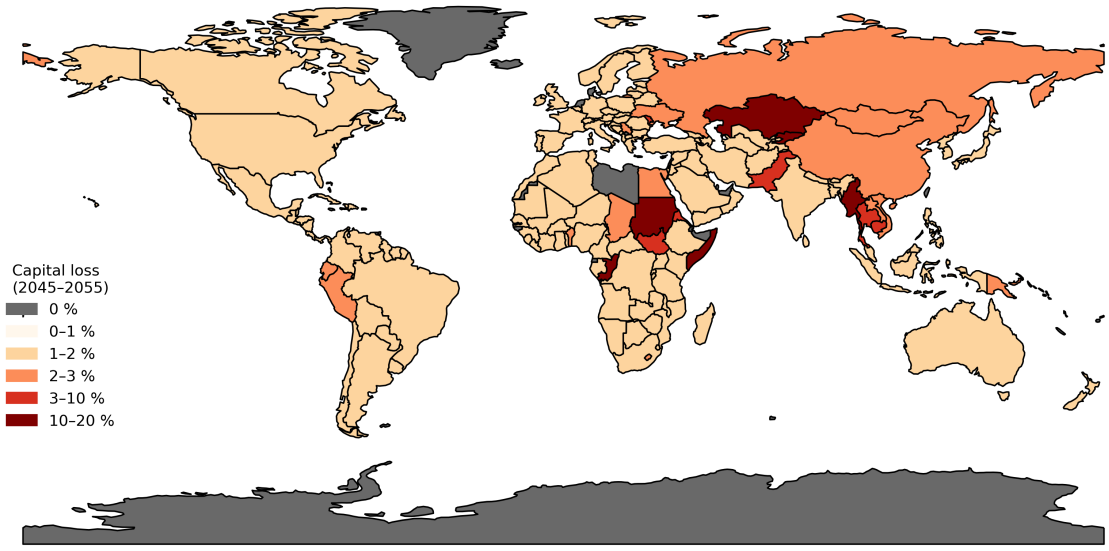
Figure 3.1a shows the level of annualized capital loss related to floods over the period 2045–2055, for each country, expressed relative to the country's productive capital, common to all scenarios. Out of the 188 countries covered in the EORA26 dataset, only 147 experience at least one flood event within their own territory in the database. Among these, the first quartile corresponds to a loss of 0.02% of their productive capital, the median is a 0.10% loss, and the third quartile is a 0.48% loss. The three most severely affected countries are Kazakhstan (9.14%), Somalia (6.46%) and Sudan (5.29%). This illustrates that, even when measured relative to the size of national economies, countries are not equally exposed to floods, even under the current level of warming.

Flood events are capital shocks that generate consumption losses, both in the country of the flood and in other countries through supply chain linkages. Figure 3.1b shows the annualized aggregation of consumption losses across countries, capturing the impact of all floods that occur between 2045 and 2055. All countries are affected, since even those with no recorded floods over 2045–2055 experience losses through supply chain propagation. The first quartile loss is 0.16%, the median 0.60%, and the third quartile 2.33%. The difference in magnitude compared to capital losses arises from the fact that the capital reconstruction process itself absorbs resources that would otherwise be devoted to final consumption, and because it is not instantaneous but can last for more than a year (Hallegatte, 2008).

Total consumption losses for a given country can be decomposed into those stemming from floods occurring domestically (Figure 3.1c), referred to as local consumption losses, and those stemming from floods occurring abroad, referred to as losses due to cross-border events, or even cross-border consumption losses (Figure 3.1d). Local consumption losses are strongly correlated with the magnitude of floods in the country, i.e. capital losses (the correlation coefficient is 0.92). However, the geographical patterns of cross-border consumption losses are widely different: the countries most directly affected by floods during this period are not necessarily those most affected through cross-border propagation (the correlation coefficient between local and cross-border losses is 0.14, as shown in Figure 3.2). As a consequence, total consumption losses are less correlated to capital losses than losses due to local floods (0.60 vs 0.92).

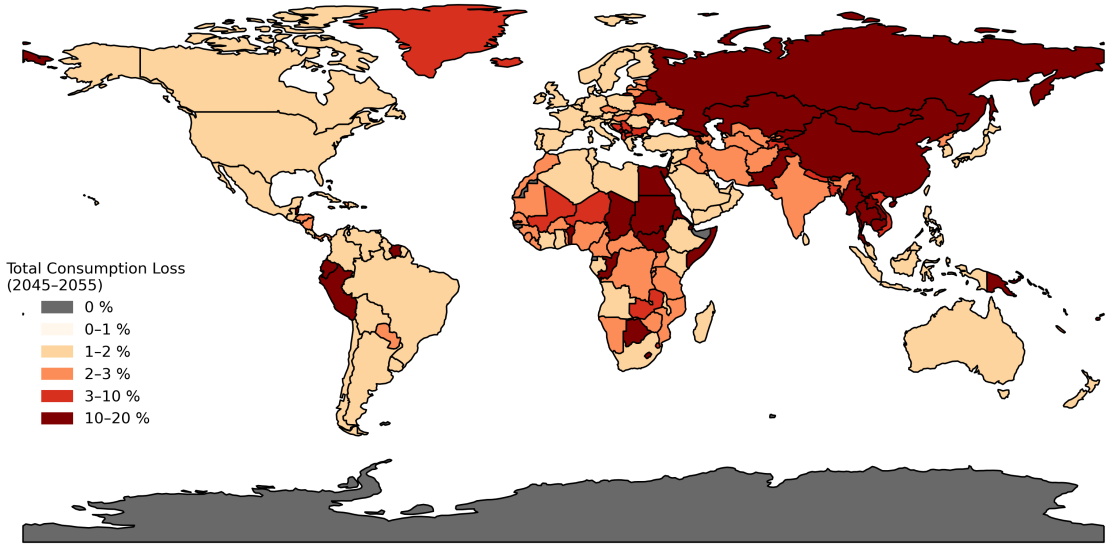
Figure 3.1: Maps of initial capital loss and its local and cross-border consequences with future floods (2045-2055) in the SSP2 2050 "Constant trade" scenario

(a) Capital losses due to local floods (%), based on the database by Alfieri et al. (2017)



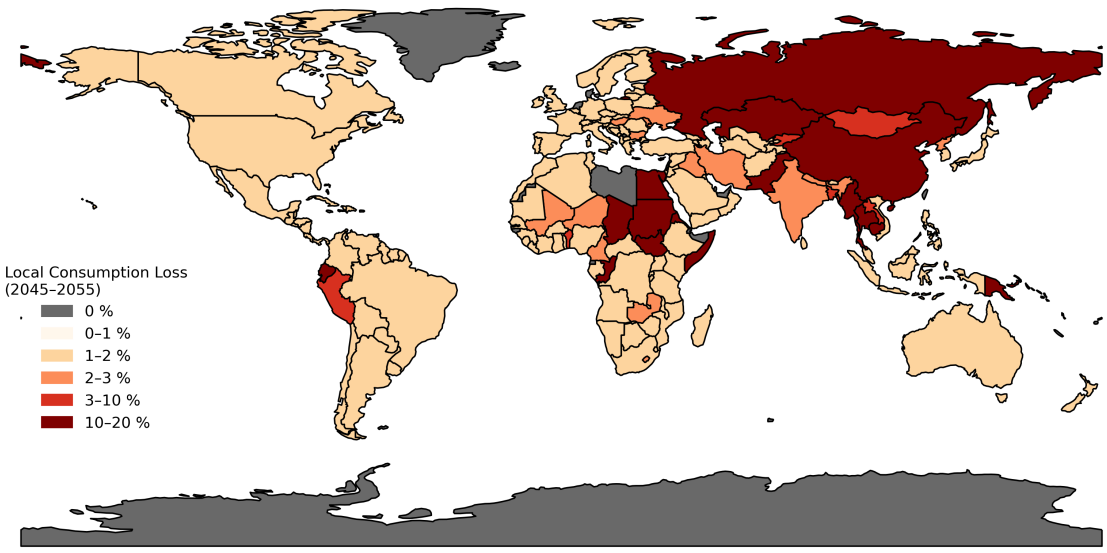
Lecture - Panel (a): We aggregate and annualize, for each country, the annualized capital losses from floods occurring in this country between 2045 and 2055, expressed relative to the productive capital stock of the country as reported in the input-output 2050 SSP2 "Constant trade" table.

(b) Total consumption loss due to floods (%)



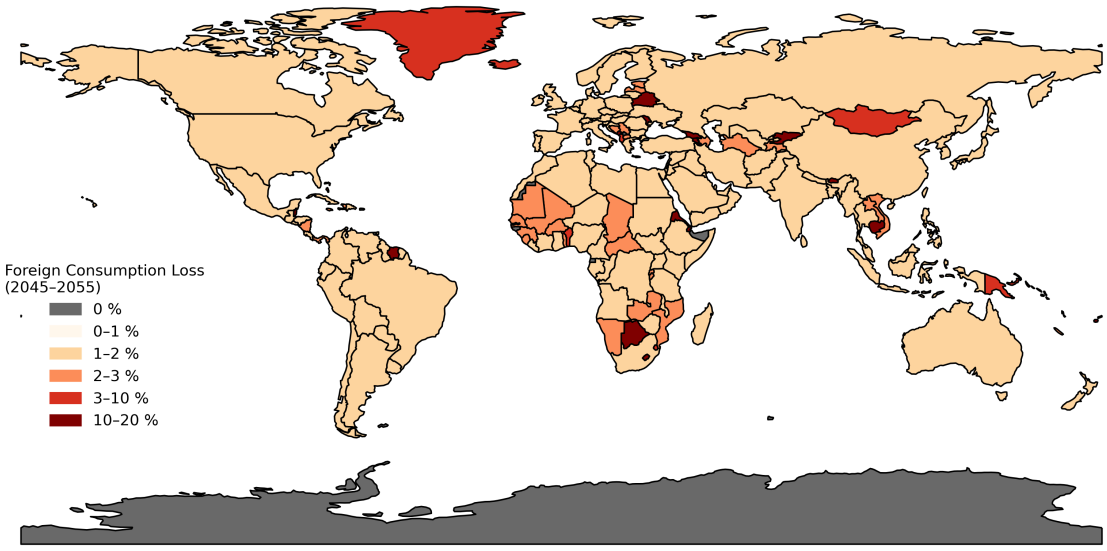
Lecture - Panel (b): We aggregate and annualize, for each country, the consumption losses due to both local and foreign floods occurring between 2045 and 2055, expressed relative to one year of final consumption in this country, as reported in the input-output 2050 SSP2 "Constant trade" table.

(c) Share of consumption losses due to local floods (%)



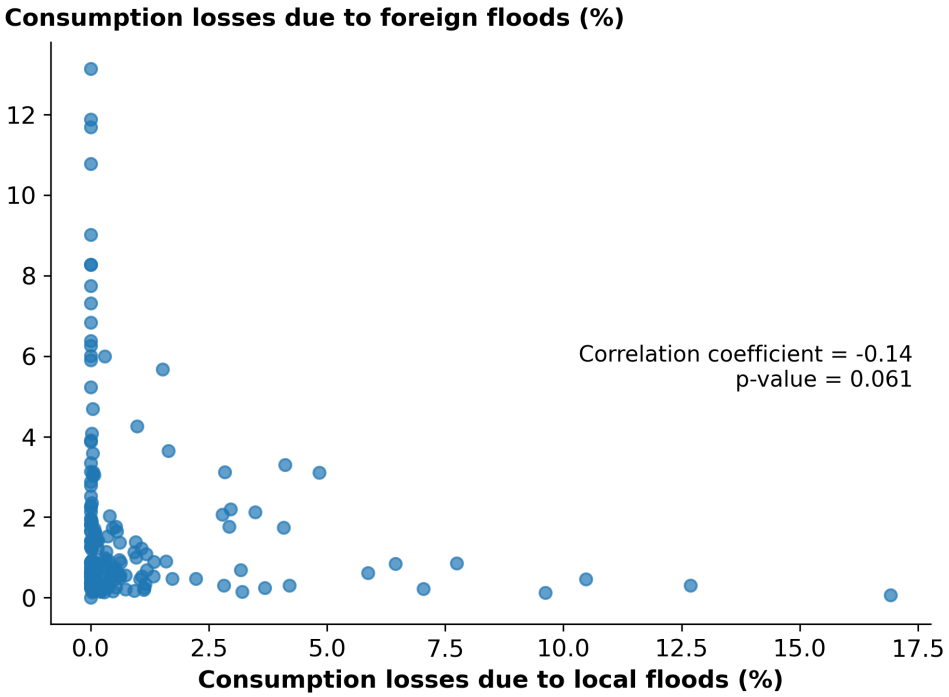
Lecture - Panel (c): We aggregate and annualize, for each country, the consumption losses due to floods occurring in this country between 2045 and 2055, expressed relative to one year of final consumption in this country, as reported in the input-output 2050 SSP2 "Constant trade" table.

(d) Share of consumption losses due to foreign floods (%)



Lecture - Panel (d): We aggregate, for each country, the consumption losses due to floods occurring in all other countries between 2045 and 2055, expressed relative to one year of final consumption in this country, as reported in the input-output 2050 SSP2 "Constant trade" table.

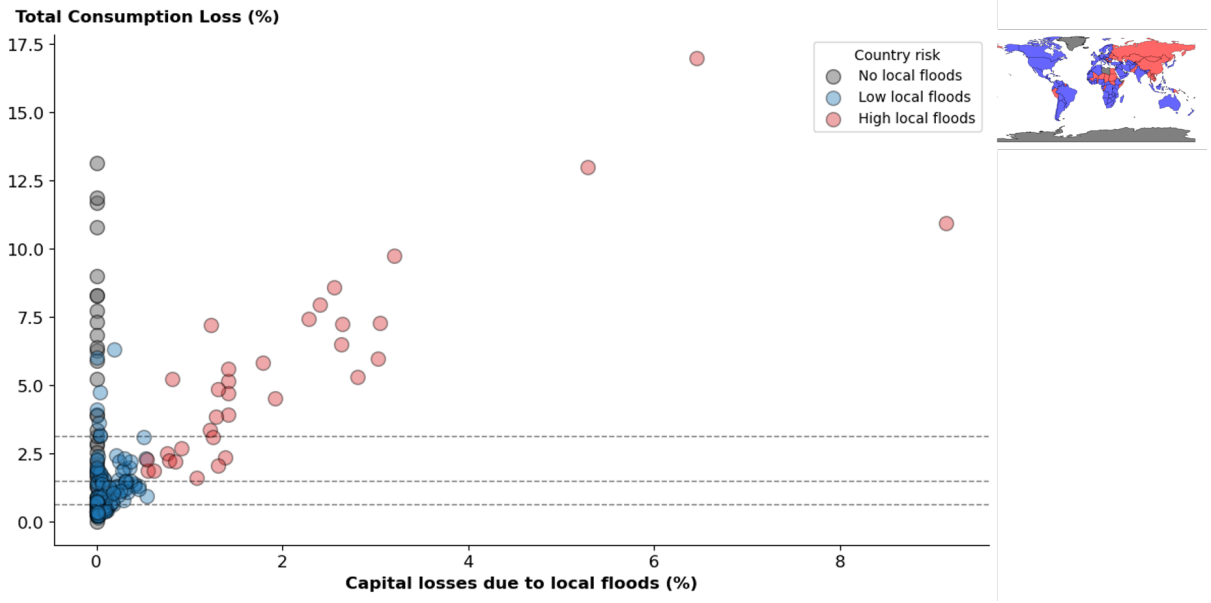
Figure 3.2: Relation between consumption losses induced by local and foreign floods



Lecture - Each point represents a country and indicates both the annualized level of consumption losses—stemming both from local (x-axis) and foreign floods (y-axis)—during the period 2045–2055. The scenario is 2050 SSP2 "Constant trade".

Figure 3.3 shows how total consumption losses and capital losses over the 2045–2055 period are related across countries. Countries are divided into three categories: those with no floods recorded on their national territory during the period in the flood database, those experiencing limited flood events, and those facing high flood events. We define the least exposed countries as those with the lowest cumulative capital losses over 2045–2055, selected in ascending order until they together account for 75% of world GDP. Those with high flood impact therefore correspond to the remaining 25% of world GDP. As can be seen, total consumption losses tend to be correlated with cumulative capital losses from local floods, except for countries with no floods. By definition, these countries incur zero capital loss over the period, but they can still experience very large consumption losses—up to more than 15% of annual final consumption—driven by floods occurring abroad.

Figure 3.3: Distribution of countries into zero, low, and high flood groups, with their associated capital losses and total consumption losses



Lecture - Each point represents a country and indicates both the level of consumption losses relative to one year of final consumption—stemming both from local and foreign floods—incurred in that country (y-axis), and the level of capital loss from local floods relative to the country's productive capital, during the period 2045–2055. The scenario is 2050 SSP2 "Constant trade". The horizontal lines indicate the first quartile, the median, and the third quartile of the distribution of aggregate total consumption losses across countries over the period. Quartile numbers are indicated on the right of the figure. Countries are divided into three categories: those with no floods recorded on their national territory during the period in the flood database (Zero Floods in grey), those experiencing limited flood events, and those facing higher flood impact. We define the least exposed countries as those with the lowest cumulative capital losses over 2045–2055, selected in ascending order until they together account for 75% of world GDP (Low Floods in blue). Those with high flood impact therefore correspond to the 25% of world GDP most at risk from floods (High Floods in red). A map is displayed next to the legend to show the countries classified as "No local floods", "Low local floods", and "High local floods".

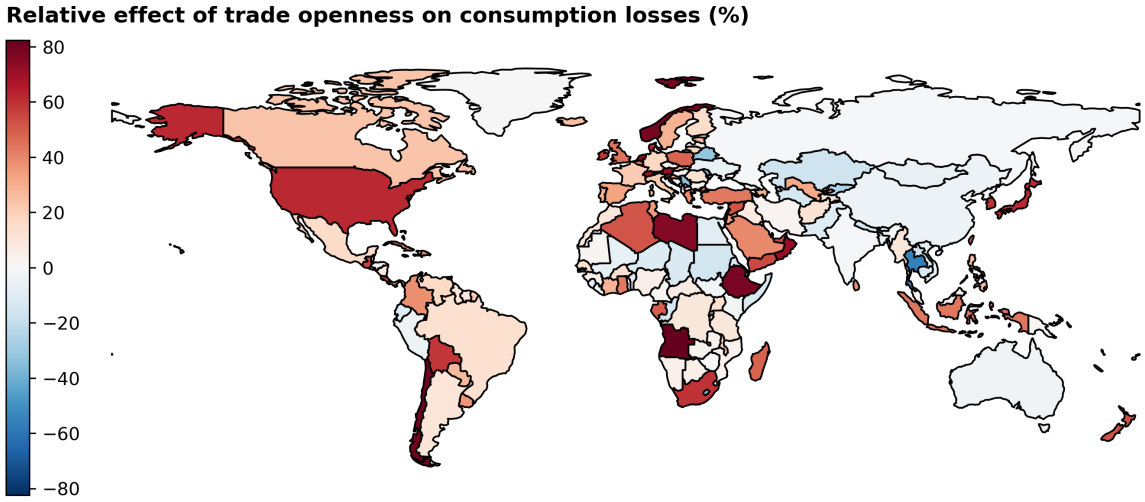
3.2 Increasing trade openness creates both winners and losers, with more losers than winners

As stated in the introduction, increasing trade openness could a priori have opposite effects on the total consumption losses due to floods. We find in the simulations that the effect in indeed sometimes positive and sometimes negative, depending on the country. This can be seen in Figure 3.4a, which shows, for each country, whether total consumption losses increase or decrease under a uniform rise in trade openness ("High trade" scenario vs "Low trade" scenario). It appears that the regions benefiting from trade openness are mainly those most affected by floods on their own territory, as shown in Figure 3.1a—namely Asia and the equatorial African countries. This is logical since, in these countries, most flood damages originate from local floods; therefore, greater trade openness tends to decouple final consumption from local production. Conversely, countries that are less exposed to floods domestically tend to experience a larger share of damages stemming from foreign floods. As a result, higher trade integration—while

maintaining a similar profile of trade partners—tends to increase the foreign contribution to their consumption losses.

Figure 3.4: Change in total consumption losses from "Low trade" to "High trade" scenario – 2050 SSP2 and 2045-2055 warming level

(a) Map of change in total consumption losses



Lecture - Panel (a): Reddish colors (respectively bluish) indicate an increase (respectively a decrease) in consumption losses due to higher trade openness.

(b) Histogram of change in total consumption losses

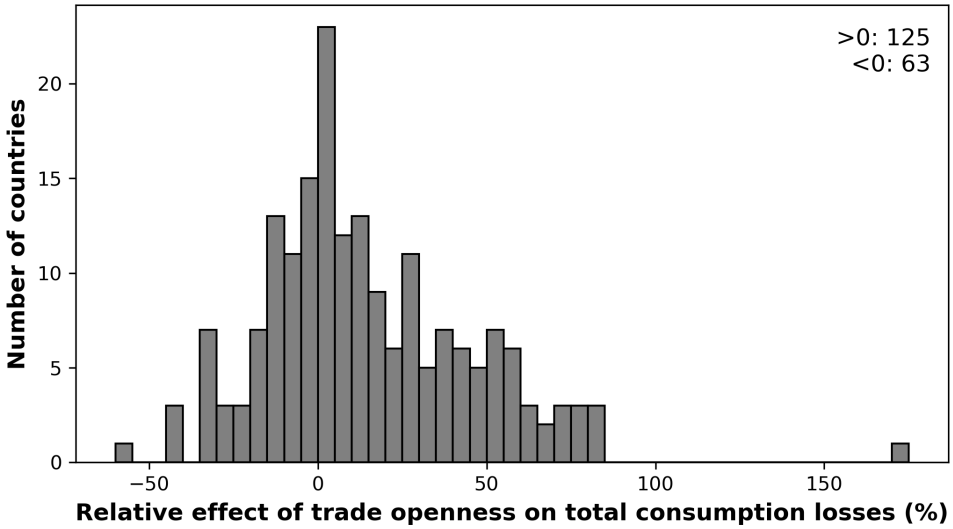


Figure 3.4b provides a quantitative assessment of the effect of trade openness. By construction, moving from the "Low trade" scenario (trade openness reduced by 50% compared to "Constant trade") to the High Trade scenario (trade openness increased by 50% compared to "Constant trade") implies a threefold increase in trade openness. For the median country,

trade openness appears negative, as it increases consumption losses by 8.9%. For countries in the first quartile, the effect is a reduction of at least 5.4%, while for those in the third quartile it is an increase of at least 33.6%. It also shows that a majority of countries would benefit more from trade closure (125 versus 63 countries). This highlights that, based on the available data, uniform trade openness generates both winners and losers, with substantially more losers than winners.

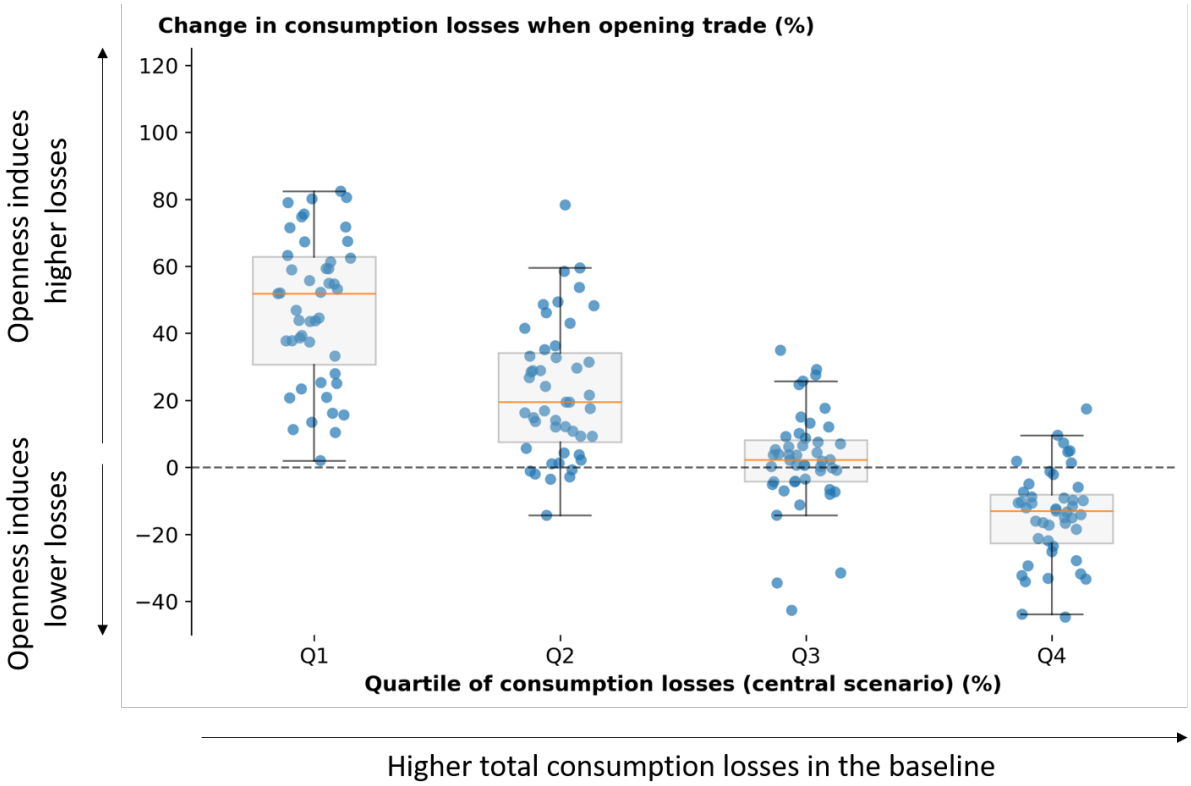
3.3 From the perspective of a global social planner, greater trade openness would be desirable

While a majority of countries do not benefit from trade openness, the most affected countries (in the central scenario) are those that would gain the most from it. Figure 3.5 shows the effect of trade openness on countries according to their total loss of final consumption in the central scenario. The higher the total loss in the central scenario, the more trade openness leads to a reduction in the total loss. Quantitatively, the countries in the quartile least exposed to floods—directly or through supply chains—in the central scenario experience a median increase in total losses of more than 40%, while the most exposed quartile shows a median decrease of about 10%.

Due to this, when looking at the entire world population, higher trade openness tends to reduce the total consumption losses. This can be seen in Figure 6, which shows how global consumption losses evolve with trade openness, at different levels of warming. The "High trade" scenario leads to higher global consumption losses than the "Low trade" scenario, and the gap widens with the level of warming, from a difference of 0.15 p.p. at +1,1°C to +1.04 p.p. at 4.3°C. The fact that a majority of countries would lose from higher trade openness does not necessarily imply that it is not globally optimal: following the majority's outcome differs from minimizing aggregate world losses, as global welfare gains from openness appear to outweigh the losses overall.

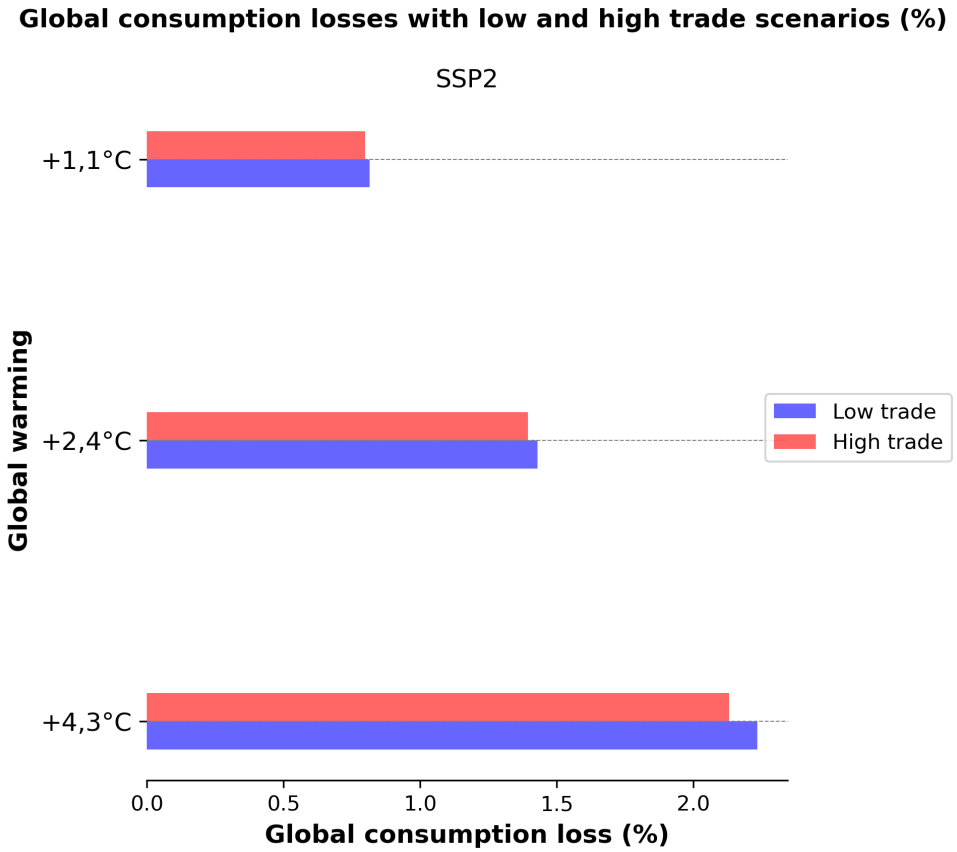
It should be noted, however, that climate warming has a quantitatively much stronger effect on global consumption losses (about +4 p.p. between +1.1 °C and +2.3 °C, and about +8 p.p. between +2.3 °C and +4.3 °C) than changes in trade (difference between the "Low trade" and "High trade" scenarios is at most +1.04 p.p.). As a consequence, in our study, mitigation appears as a much more effective strategy to reduce consumption losses than changes in international trade which would be specifically implemented to reduce the cost of climate change impacts.

Figure 3.5: Change in total consumption losses from "Low trade" to "High trade" scenario (2050 SSP2 and 2045-2055 warming level), by quartile



Lecture - Each point is a country and countries are divided into quartiles according to their total consumption losses from floods over 2045–2055 in the 2050 SSP2 "Constant trade" scenario. For each country, we show the change in final consumption losses when moving from the low-trade to the high-trade scenario. For each quartile, a box plot of the change in consumption losses is shown. Boxplots indicate the median, the first and third quartiles; whiskers extend to the most extreme data points within 1.5 times the interquartile range.

Figure 3.6: Global consumption losses in 2050 SSP2 tables, but with different level of warming and different trade scenarios

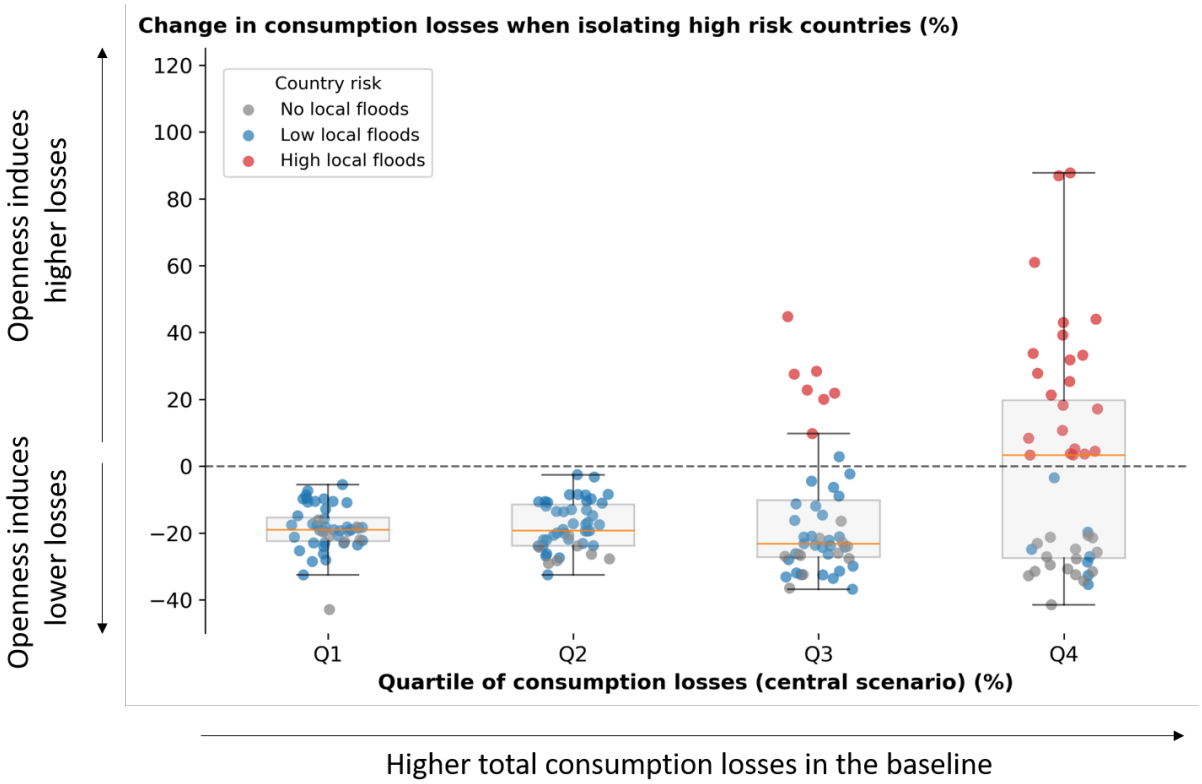


Lecture - Global final consumption losses are given for SSP2 in 2050, for different level of warming and two different trade scenarios ("Low trade" and "High trade").

3.4 Isolating high local risk countries would significantly worsen their situation

While the majority of countries, especially those with the lowest initial flood-related costs, benefit from trade closure, such closure would also entail drawbacks. In particular, international trade generates a wide range of gains from trade (Costinot et al., 2014), which are not accounted for in the present analysis. One way for these countries to avoid losing the gains from trade while protecting themselves from the increasing floods in the most exposed countries is to form a trade club, thereby maintaining the same level of trade integration as in the baseline scenario but with trade partners located in low-flood-risk countries. As a consequence, this would force low-risk countries to trade more with each other, if we want to hold the volume of international trade constant. Such selective and adverse trade integration scenarios are already explored in some scenario-analysis exercises (Talebian, Lager, et al., 2025).

Figure 3.7: Change in total consumption losses from "Constant" to "Isolation" trade scenario (2050 SSP2 and 2045-2055 warming level), by quartile



Lecture - Each point is a country and countries are divided into quartiles according to their total consumption losses from floods over 2045–2045 in the central 2050 SSP2 "Constant trade" scenario. For each country, we show the change in final consumption losses when moving from the central 2050 SSP2 "Constant trade" scenario to the "Isolation" scenario. We define "Low floods" countries as those with the lowest cumulative capital losses over 2045–2055, selected in ascending order until they together account for 75% of world GDP. Those with "High floods" therefore correspond to the remaining 25% of world GDP. For each quartile, a box plot of the change in consumption losses is shown. Boxplots indicate the median, the first and third quartiles; whiskers extend to the most extreme data points within 1.5 times the interquartile range.

Figure 3.7 is analogous to Figure 3.5, but in the context of these club scenarios. Countries are classified according to their level of local flooding over the period 2045–2055: none, low floods, and high floods, as in Figure 3.3. Countries with high local floods are found only in Q3 and Q4 of the distribution of total losses. Whereas under uniform trade openness the least exposed countries experienced higher consumption losses and the most exposed countries saw their losses decrease, the formation of a trade club changes this pattern. In this scenario, countries with low local flood risk trade preferentially among themselves, thereby reducing their exposure to climate-related shocks transmitted through trade. As a result, these low flood members (blue points in Figure 3.7) see their consumption losses fall by about 20% (in relative terms). Conversely, countries with high local flood risk (red points in Figure 3.7) become increasingly excluded from trade with safer partners, which amplifies their exposure and raises their consumption losses by roughly +20%. When aggregated at the global level, this selective

"Isolation" scenario leads to higher total consumption losses — by about +0.06 percentage points at +1.2°C and +0.4 percentage points at +4.3°C — indicating that such fragmentation may benefit low floods countries individually but worsens global welfare and that of high floods countries.

4 Discussion and conclusion

Trade openness can help countries heavily hit by floods, either directly and indirectly, to reduce their economic losses by decoupling final consumption from local production. However, it comes at a cost for other countries, which experience higher exposure to foreign shocks and greater dependence on flood-affected trade partners, thereby increasing their own consumption losses. In our simulations, direct exposition to floods appear heterogeneously distributed across the globe: trade integration has therefore ambiguous effects, depending on each country, and creates both winners and losers. A difficulty arises from the fact that, in terms of the number of countries, there are more losers than winners. However, from a global perspective, trade openness appears beneficial, as the gains of the winners more than offset the losses of the losers. Besides, isolating the countries most directly hit by floods would significantly worsen their situation, while improving that of other countries — but not enough to generate a positive global welfare effect. While our study focuses on a single type of extreme event, namely continental floods, the methodological framework provided in this study can directly be applied to other extreme events, using for instance the CLIMADA database (Aznar-Siguan et al., 2019; Bresch et al., 2021).

In our study, we have focused on understanding the fundamental mechanisms underlying the role of trade openness for climate-induced trade resilience. To do so, we used the best available trade network data that offer global coverage. However, even these data display relatively low granularity, offering spatial resolution only at the country level and sectoral resolution across 26 sectors — a limitation that may affect the results. For instance, in our setting, the shocks consist of capital losses that are relatively modest compared to the size of the entire economy—often involving losses of less than 1 % of national capital. From the perspective of shock propagation, a small uniform loss is not at all equivalent to a geographically or firm-level concentrated loss: a concentrated loss that can trigger much stronger amplification dynamics and make capital re-accumulation considerably more difficult and prolonged (Vasco M Carvalho et al., 2021; Henriet et al., 2012). Still, the methods used here can also apply to more detailed trade network data, although it raises numerical and interpretation challenges. The growing availability of firm-level network data should make it possible in the future to improve the representation of shock propagation (Pichler et al., 2023).

Regarding our modeling choices, to project input–output tables we use the SPIN method, which identifies the tables that best match new GDP and trade constraints while minimizing changes to countries' technical coefficients. An alternative approach would have been to project IO tables using more structural models—such as computable general equilibrium or quantitative trade models—which explicitly represent the drivers of international trade (Fontagné et al.,

2017). However, these tools have limitations of their own: they are not necessarily better suited to modeling long-term technological change, leading to potentially misleading assessments of long-term transitions (Mercure et al., 2019). Indeed, these models typically rely on fixed functional forms (e.g. constant elasticity of substitution production functions) and parameters calibrated on historical data, which constrain how production technologies can evolve over time. The chosen method allows us to explore a wide range of possible future scenarios by varying the two main drivers—GDP and trade openness—in the spirit of the SSPs. In doing so, we offer an original way to develop the quantitative dimension of SSP trade projections, which have so far remained mostly qualitative (O'Neill et al., 2017; Talebian, Carlsen, et al., 2021). Moreover, many other types of scenarios could be explored using this set-up — for instance, by varying the composition of countries forming the club, by considering multiple clubs, or by assuming GDP trajectories that follow differentiated North–South post-growth pathways, all of which would influence the cross-border propagation of the physical impacts of climate change. More specifically, the qualitative scenarios of global trade evolution developed by various institutions to assess cross-border climate risks could gain a quantitative foundation if brought to numbers with our framework (Adaptation Without Borders, 2023; Talebian, Lager, et al., 2025).

Finally, our cost–benefit analysis of trade—regarding resilience to extreme events—does not capture all relevant dimensions. First, our analysis does not account for one key benefit of trade: the long-term gains from trade that arise when countries are more economically integrated. This omission stems from our methodology, which projects input–output tables by imposing future values of GDP and trade volume independently. However, economic theory suggests that higher trade integration should lead to higher GDP levels (Costinot et al., 2014). This is not a concern, as we do not claim that trade openness should be determined solely by its implications for exposure to extreme events. Our objective is simply to illustrate that, when short-term consequences are considered, trade integration can play either a positive or negative role. Examining how this cost–benefit analysis would change when accounting for long-term gains from trade, and the associated potential variation in vulnerability to climate change impacts, is subject of future research. Second, the trade scenarios we consider are exogenous and, in particular, are not shaped by firm's own responses to climate impacts. Indeed, our uniform scenarios do not account for the fact that, knowing which countries are particularly vulnerable, firms could gradually adjust their trade partners over the course of the century. Our approach simply aims at shedding light on the relationship between trade openness and the amplification or attenuation of the indirect effects of extreme events. In this respect, we follow a logic similar to that of the SSP framework, which defines a set of baseline scenarios independently of climate change impacts. However, in a way, we do capture part of this feedback effect through the club-based scenarios. Yet, this is not the result of an endogenous decision by economic agents: we imposed the formation of two relatively distinct trade clubs, grouping respectively the countries most and least exposed to floods.

In conclusion, our results suggest that trade openness can play an important role in global adaptation to climate change by mitigating part of the economic losses induced by physical impacts. This finding is consistent with a growing body of literature highlighting how openness

can facilitate adaptation, whether through agricultural market integration—which allows for the reallocation of production and buffering of local shocks (Gouel et al., 2021; Janssens et al., 2020; Janssens et al., 2021)—or through migration flows that help redistribute labor and reduce exposure to climate risks (Benveniste et al., 2020; Desmet et al., 2024). Yet, our analysis also shows that these benefits are not evenly distributed: while more open economies may experience smaller losses on average, the global outcome depends on how trade linkages transmit shocks across borders. In this sense, our framework emphasizes that cooperation among countries remains a key dimension of climate adaptation (Bednar-Friedl et al., 2022; Talebian, Carlsen, et al., 2021)—as it is for mitigation (IPCC, 2023a)—and that a fragmented world divided into competing trade blocs would likely exacerbate global welfare losses rather than reduce them.

5 References

Adaptation Without Borders (2023). *The Global Transboundary Climate Risk Report*. Tech. rep. URL: https://www.iddri.org/sites/default/files/PDF/Publications/Catalogue%20Iddri/Rapport/the_global_transboundary_climate_risk_report.pdf.

Aiyar, Shekhar, Anna Ilyina, Jiaqian Chen, Alvar Kangur, Juan Trevino, Christian Ebeke, et al. (2023). "Geo-Economic Fragmentation and the Future of Multilateralism". *Staff Discussion Notes* 2023.001, p. 1. URL: https://elibrary.imf.org/openurl?genre=journal&issn=2617-6750&volume=2023&issue=001 (visited on 11/21/2024).

Alfieri, Lorenzo, Berny Bisselink, Francesco Dottori, Gustavo Naumann, Ad De Roo, Peter Salamon, et al. (2017). "Global projections of river flood risk in a warmer world". *Earth's Future* 5.2, pp. 171–182. URL: https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016EF000485 (visited on 09/06/2024).

AON (2021). *2021 Weather, Climate and Catastrophe Insight*. Tech. rep. URL: https://www.aon.com/weather-climate-catastrophe/2021.

Aznar-Siguan, Gabriela and David N. Bresch (2019). "CLIMADA v1: a global weather and climate risk assessment platform". *Geoscientific Model Development* 12.7, pp. 3085–3097. URL: https://gmd.copernicus.org/articles/12/3085/2019/ (visited on 05/19/2025).

Barbiroglio, Emanuela (2021). "No Water No Microchips: What Is Happening In Taiwan?" *Forbes*.

Beaufils, Timothé and Leonie Wenz (2022). "A scenario-based method for projecting multi-regional input–output tables". *Economic Systems Research* 34.4, pp. 440–468. URL: https://www.tandfonline.com/doi/full/10.1080/09535314.2021.1952404 (visited on 11/07/2023).

Bednar-Friedl, Birgit, Nina Knittel, Joachim Raich, and Kevin M. Adams (2022). "Adaptation to transboundary climate risks in trade: Investigating actors and strategies for an emerging challenge". *WIREs Climate Change* 13.2. URL: https://onlinelibrary.wiley.com/doi/10.1002/wcc.758 (visited on 08/08/2023).

Benveniste, Hélène, Michael Oppenheimer, and Marc Fleurbaey (2020). "Effect of border policy on exposure and vulnerability to climate change". *Proceedings of the National Academy of Sciences* 117.43, pp. 26692–26702. URL: https://www.pnas.org/content/117/43/26692 (visited on 11/05/2020).

Botzen, W. J. Wouter, Olivier Deschenes, and Mark Sanders (2019). "The Economic Impacts of Natural Disasters: A Review of Models and Empirical Studies". *Review of Environmental Economics and Policy* 13.2, pp. 167–188. URL: https://www.journals.uchicago.edu/doi/10.1093/reep/rez004 (visited on 12/09/2022).

Bresch, David N. and Gabriela Aznar-Siguan (2021). "CLIMADA v1.4.1: towards a globally consistent adaptation options appraisal tool". *Geoscientific Model Development* 14.1, pp. 351–363. URL: https://gmd.copernicus.org/articles/14/351/2021/ (visited on 05/19/2025).

Carter, Timothy R., Magnus Benzie, Emanuele Campiglio, Henrik Carlsen, Stefan Fronzek, Mikael Hildén, et al. (2021). "A conceptual framework for cross-border impacts of climate change". *Global Environmental Change* 69, p. 102307. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378021000868 (visited on 08/08/2023).

Carvalho, Vasco M, Makoto Nirei, Yukiko U Saito, and Alireza Tahbaz-Salehi (2021). "Supply Chain Disruptions: Evidence from the Great East Japan Earthquake*". *The Quarterly Journal of Economics* 136.2, pp. 1255–1321. URL: https://academic.oup.com/qje/article/136/2/1255/6030033 (visited on 03/09/2023).

Carvalho, Vasco M. and Alireza Tahbaz-Salehi (2019). "Production Networks: A Primer". *Annual Review of Economics* 11.1, pp. 635–663. URL: https://www.annualreviews.org/doi/10.1146/annurev-economics-080218-030212 (visited on 08/14/2023).

Constant, Karine and Marion Davin (2019). "Unequal Vulnerability to Climate Change and the Transmission of Adverse Effects Through International Trade". *Environmental and Resource Economics* 74.2, pp. 727–759. URL: http://link.springer.com/10.1007/s10640-019-00345-8 (visited on 08/22/2023).

Costinot, Arnaud and Andrés Rodríguez-Clare (2014). "Trade Theory with Numbers: Quantifying the Consequences of Globalization". *Handbook of International Economics*. Vol. 4. Elsevier, pp. 197–261. URL: https://linkinghub.elsevier.com/retrieve/pii/B9780444543141000045 (visited on 10/04/2025).

Cruz, José-Luis and Esteban Rossi-Hansberg (2024). "The Economic Geography of Global Warming". *Review of Economic Studies* 91.2, pp. 899–939. URL: https://academic.oup.com/restud/article/91/2/899/7107009 (visited on 05/06/2025).

Dellink, Rob, Jean Chateau, Elisa Lanzi, and Bertrand Magné (2017). "Long-term economic growth projections in the Shared Socioeconomic Pathways". *Global Environmental Change* 42, pp. 200–214. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378015000837 (visited on 05/07/2021).

Desmet, Klaus and Esteban Rossi-Hansberg (2024). "Climate Change Economics over Time and Space". *Annual Review of Economics* 16.1, pp. 271–304. URL: https://www.annualreviews.org/content/journals/10.1146/annurev-economics-072123-044449 (visited on 10/05/2025).

Fontagné, Lionel, Jean Fouré, and Alexander Keck (2017). "Simulating World Trade in the Decades Ahead: Driving Forces and Policy Implications". *The World Economy* 40.1, pp. 36–55. URL: https://onlinelibrary.wiley.com/doi/10.1111/twec.12479 (visited on 07/15/2024).

Gouel, Christophe and David Laborde (2021). "The crucial role of domestic and international market-mediated adaptation to climate change". *Journal of Environmental Economics and Management* 106, p. 102408. URL: https://linkinghub.elsevier.com/retrieve/pii/S0095069620301315 (visited on 09/01/2022).

Guan, Dabo, Daoping Wang, Stephane Hallegatte, Steven J. Davis, Jingwen Huo, Shuping Li, et al. (2020). "Global supply-chain effects of COVID-19 control measures". *Nature Human Behaviour* 4.6, pp. 577–587. URL: https://www.nature.com/articles/s41562-020-0896-8 (visited on 01/26/2023).

Hallegatte, Stéphane (2008). "An Adaptive Regional Input-Output Model and its Application to the Assessment of the Economic Cost of Katrina". *Risk Analysis* 28.3, pp. 779–799. URL: https://onlinelibrary.wiley.com/doi/10.1111/j.1539-6924.2008.01046.x (visited on 11/28/2022).

— (2014). "Modeling the Role of Inventories and Heterogeneity in the Assessment of the Economic Costs of Natural Disasters: Modeling the Role of Inventories and Heterogeneity". *Risk Analysis* 34.1, pp. 152–167. URL: https://onlinelibrary.wiley.com/doi/10.1111/risa.12090 (visited on 11/28/2022).

Hallegatte, Stéphane, Jun Rentschler, and Julie Rozenberg (2019). *Lifelines: The Resilient Infrastructure Opportunity*. The World Bank. URL: http://elibrary.worldbank.org/doi/book/10.1596/978-1-4648-1430-3 (visited on 05/26/2023).

Hedlund, Johanna, Stephen Fick, Henrik Carlsen, and Magnus Benzie (2018). "Quantifying transnational climate impact exposure: New perspectives on the global distribution of climate risk". *Global Environmental Change* 52, pp. 75–85. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378017312505 (visited on 02/29/2024).

Henriet, Fanny, Stéphane Hallegatte, and Lionel Tabourier (2012). "Firm-network characteristics and economic robustness to natural disasters". *Journal of Economic Dynamics and Control* 36.1, pp. 150–167. URL: https://linkinghub.elsevier.com/retrieve/pii/S0165188911001825 (visited on 08/13/2023).

IIASA (2024). *SSP Database (Shared Socioeconomic Pathways) - Version 3.0*. URL: https://data.ece.iiasa.ac.at/ssp/.

Inoue, Hiroyasu and Yasuyuki Todo (2019). "Firm-level propagation of shocks through supply-chain networks". *Nature Sustainability* 2.9, pp. 841–847. URL: https://www.nature.com/articles/s41893-019-0351-x (visited on 07/27/2023).

IPCC (2014). *Climate Change 2013: The Physical Science Basis*. Tech. rep.

"Ch. 14 International Cooperation" (2023a). *Climate Change 2022 - Mitigation of Climate Change*. Ed. by IPCC. 1st ed. Cambridge University Press, pp. 1451–1546. URL: https://www.cambridge.org/core/product/identifier/9781009157926%23c14/type/book_part (visited on 10/05/2025).

IPCC (2023b). *Climate Change 2023 – Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Tech. rep. Intergovernmental Panel on Climate Change (IPCC). URL: https://www.ipcc.ch/report/ar6/syr/ (visited on 06/27/2025).

Janssens, Charlotte, Petr Havlík, Tamás Krisztin, Justin Baker, Stefan Frank, Tomoko Hasegawa, et al. (2020). "Global hunger and climate change adaptation through international trade". *Nature Climate Change* 10.9, pp. 829–835. URL: https://www.nature.com/articles/s41558-020-0847-4 (visited on 08/22/2023).

— (2021). "International trade is a key component of climate change adaptation". *Nature Climate Change* 11.11, pp. 915–916. URL: https://www.nature.com/articles/s41558-021-01201-8 (visited on 11/09/2022).

Juhel, Samuel (2024). "BoARIO: A Python package implementing the ARIO indirecteconomic cost model". *Journal of Open Source Software* 9.98, p. 6547. URL: https://joss.theoj.org/papers/10.21105/joss.06547 (visited on 05/18/2025).

Koks, Elco E., Lorenzo Carrera, Olaf Jonkeren, Jeroen C. J. H. Aerts, Trond G. Husby, Mark Thissen, et al. (2016). "Regional disaster impact analysis: comparing input–output and computablegeneral equilibrium models". *Natural Hazards and Earth System Sciences* 16.8, pp. 1911–1924. URL: https://nhess.copernicus.org/articles/16/1911/2016/ (visited on 04/03/2023).

Koks, Elco E., M Thissen, L Alfieri, H De Moel, L Feyen, B Jongman, et al. (2019). "The macroeconomic impacts of future river flooding in Europe". *Environmental Research Letters* 14.8, p. 084042. URL: https://iopscience.iop.org/article/10.1088/1748-9326/ab3306 (visited on 08/09/2023).

Koks, Elco E. and Mark Thissen (2016). "A Multiregional Impact Assessment Model for disaster analysis". *Economic Systems Research* 28.4, pp. 429–449. URL: https://www.tandfonline.com/doi/full/10.1080/09535314.2016.1232701 (visited on 08/23/2023).

Lafrogne-Joussier, Raphael, Julien Martin, and Isabelle Mejean (2023). "Supply Shocks in Supply Chains: Evidence from the Early Lockdown in China". *IMF Economic Review* 71.1, pp. 170–215. URL: https://link.springer.com/10.1057/s41308-022-00166-8 (visited on 08/11/2023).

Lenzen, Manfred, Keiichiro Kanemoto, Daniel Moran, and Arne Geschke (2012). "Mapping the Structure of the World Economy". *Environmental Science & Technology* 46.15, pp. 8374–8381. URL: https://pubs.acs.org/doi/10.1021/es300171x (visited on 03/27/2024).

Magnan, A. K., E.L.F. Schipper, M. Burkett, S. Bharwani, I. Burton, S. Eriksen, et al. (2016). "Addressing the risk of maladaptation to climate change". *WIREs Climate Change* 7.5, pp. 646–665. URL: https://wires.onlinelibrary.wiley.com/doi/10.1002/wcc.409 (visited on 05/19/2025).

Mercure, Jean-Francois, Florian Knobloch, Hector Pollitt, Leonidas Paroussos, S. Serban Scrieciu, and Richard Lewney (2019). "Modelling innovation and the macroeconomics of low-carbon transitions: theory, perspectives and practical use". *Climate Policy* 19.8, pp. 1019–1037. URL: https://www.tandfonline.com/doi/full/10.1080/14693062.2019.1617665 (visited on 10/05/2025).

O'Neill, Brian C., Elmar Kriegler, Kristie L. Ebi, Eric Kemp-Benedict, Keywan Riahi, Dale S. Rothman, et al. (2017). "The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century". *Global Environmental Change* 42, pp. 169–180. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959378015000060 (visited on 03/06/2022).

Otto, C., S.N. Willner, L. Wenz, K. Frieler, and A. Levermann (2017). "Modeling loss-propagation in the global supply network: The dynamic agent-based model acclimate". *Journal of Economic Dynamics and Control* 83, pp. 232–269. URL: https://linkinghub.elsevier.com/retrieve/pii/S0165188917301744 (visited on 08/09/2023).

Pichler, Anton, Christian Diem, Alexandra Brintrup, François Lafond, Glenn Magerman, Gert Buiten, et al. (2023). "Building an alliance to map global supply networks". *Science* 382.6668, pp. 270–272. URL: https://www.science.org/doi/10.1126/science.adi7521 (visited on 10/24/2023).

Ryan, Carol (2023). "Where Heat Waves Lead, Food Inflation Will Follow". *The Wall Street Journal*.

Schenker, Oliver (2013). "Exchanging Goods and Damages: The Role of Trade on the Distribution of Climate Change Costs". *Environmental and Resource Economics* 54.2, pp. 261–282. URL: http://link.springer.com/10.1007/s10640-012-9593-z (visited on 08/22/2023).

Schenker, Oliver and Gunter Stephan (2014). "Give and take: How the funding of adaptation to climate change can improve the donor's terms-of-trade". *Ecological Economics* 106, pp. 44–55. URL: https://linkinghub.elsevier.com/retrieve/pii/S0921800914002080 (visited on 08/22/2023).

Schipper, E. Lisa F. (2020). "Maladaptation: When Adaptation to Climate Change Goes Very Wrong". *One Earth* 3.4, pp. 409–414. URL: https://linkinghub.elsevier.com/retrieve/pii/S2590332220304838 (visited on 05/19/2025).

Scussolini, Paolo, Jeroen C. J. H. Aerts, Brenden Jongman, Laurens M. Bouwer, Hessel C. Winsemius, Hans de Moel, et al. (2016). "FLOPROS: an evolving global database of flood protection standards". *Natural Hazards and Earth System Sciences* 16.5, pp. 1049–1061. URL: https://nhess.copernicus.org/articles/16/1049/2016/ (visited on 06/03/2025).

Sun, Yida, Shupeng Zhu, Daoping Wang, Jianping Duan, Hui Lu, Hao Yin, et al. (2024). "Global supply chains amplify economic costs of future extreme heat risk". *Nature*. URL: https://www.nature.com/articles/s41586-024-07147-z (visited on 03/21/2024).

Talebian, Sara, Henrik Carlsen, Oliver Johnson, Jan Volkholz, and Elvine Kwamboka (2021). "Assessing future cross-border climate impacts using shared socioeconomic pathways". *Climate Risk Management* 32, p. 100311. URL: https://linkinghub.elsevier.com/retrieve/pii/S2212096321000401 (visited on 01/15/2024).

Talebian, Sara, Frida Lager, and Stockholm Environment Institute (2025). "Navigating a changing world order: The future of geopolitical and geoeconomic fragmentation".

Wenz, Leonie and Anders Levermann (2016). "Enhanced economic connectivity to foster heat stress–related losses". *Science Advances* 2.6, e1501026. URL: https://www.science.org/doi/10.1126/sciadv.1501026 (visited on 09/29/2023).

Willner, Sven Norman, Christian Otto, and Anders Levermann (2018). "Global economic response to river floods". *Nature Climate Change* 8.7, pp. 594–598. URL: https://www.nature.com/articles/s41558-018-0173-2 (visited on 08/09/2023).

Appendices

A Supplementary Methods

We present here the details of the calculations and transformations carried out to link three elements: (1) the floods database, (2) the input-output tables and their future projections, and (3) the ARIO cost propagation model.

A.1 Floods database

The original database

We use a river floods dataset established by Alfieri et al. (2017). This dataset provides daily time series of simulated floods for both a historical (1970-2005) and future period (2006-2125) and for seven different climate forcing models under RCP8.5, detailing each flooded cell on a 0.5° resolution grid, at the global scope. It includes the number of affected people and the amount of damaged assets per cell. The study takes into account existing flood protections through the FLOPROS dataset (Scussolini et al., 2016). The rationale used to account for the effect of flood protection is to assume that floods with return periods lower than the protection capacity do not cause any damage. It is important to note that the study does not incorporate any projections of socioeconomic change; therefore, all asset damage estimates are expressed in €2010 at purchasing power parity (PPP) for all events.

Spatio-temporal clustering

While the original database is a time series of global damage maps, the ARIO model requires individual shocks as input. We assume that flooded cells that are close in space and time can be grouped into the same 'flood event' rather than being treated separately. To do so, we apply a spatio-temporal clustering algorithm. As a first step, we assign each flooded cell to its corresponding economic region based on the multi-regional input-output tables (MRIOT) used, Eora26 (Lenzen et al., 2012), and group the flooded cells accordingly by region. Next, we assign a temporal cluster to each flooded 'day-cell' pair based on the day of occurrence, using the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm. We then refine these temporal clusters spatially to obtain spatio-temporal clusters, by applying a second run of the DBSCAN algorithm, this time on the geographical coordinates of the cells. Once each flooded 'day-cell' is assigned to a unique spatio-temporal cluster, we define the corresponding flood events by aggregating damages across cells. Damages from different cells within the same event are summed, while damages occurring in the same cell on different dates are represented by the maximum value, reflecting the assumption that assets cannot be destroyed more than once and that initial damage estimates are independent.

This process results in a dataset of 1,450,565 flood events spanning the period from 2016 to 2130. This total combines the results from seven models, meaning that, on average, each

model yields approximately 207,223 flood events over the period. We focus in particular on floods occurring around 2020 (i.e., between 2016 and 2025) and around 2050 (i.e., between 2045 and 2055). Each flood event is characterized by its central latitude and longitude, date, and the associated damages to different types of capital—residential, industrial, commercial, and infrastructure—expressed in €2010 PPP. The basic geographical unit in EORA26 is the country: each flood event is assigned to one of the 188 EORA26 countries, based on the average latitude and longitude of the shock.

From absolute to relative damage values

Since the projected MRIOTs are expressed in $2017 at market exchange rates (MER), damages are converted from €2010 PPP to $2017 MER. To do so, we use the conversion rate provided in the original paper: 1€2010 = 0.77$2010 PPP. We then convert from $2010 PPP to $2017 MER using the World Bank GDP deflator data[1].

In our study, only industrial, commercial and infrastructure capital losses are considered. Indeed, damages to residential buildings cannot be directly attributed to specific economic sectors in our input-output framework. Industrial, commercial and infrastructure capital losses are added up and expressed as a share of the total capital stock of each country. These total capital stocks are estimated following the method of Hallegatte (2014), using sectoral value added by country and conversion coefficients between value added and productive capital. Since flood damages in the original paper are estimated based on the 2010 economy, we use the 2010 version of EORA26 (expressed in $2017 MER) to compute sectoral productive capital stocks. This allows us to convert absolute capital damages into relative terms.

Representative events and interpolation

An ARIO simulation is computationally demanding. Running the model on 97,240 events for years around 2020 and 140,523 events for years around 2050, across several trade scenarios, would be computationally too costly. Moreover, numerous events exhibit similar direct damages, leading to analogous results. To address this, we define a collection of representative events for each economic region based on the direct damages incurred. For every region, we identify events with the minimum and maximum direct damages (in terms of capital loss), along with those closest to the subsequent percentiles: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%. Since events in our global set differ solely in their region of occurrence and the extent of direct damages (given that the distribution of direct damages to industries is contingent on the affected region), and we can assume that indirect impacts are a monotonic function of direct impacts, linear interpolation of our results based on these two variables proves to be an effective way to estimate indirect impacts for the complete set of events. Thus, we run BoARIO simulations on all representative events and interpolate the results for the remaining flood events in the dataset. This is done by taking a linear combination of the results from the representative floods in the same country whose estimated impacts are just above and just below those of the actual event.

[1] See https://data.worldbank.org/indicator/NY.GDP.DEFL.KD.ZG?end=2017&start=2010.

A.2 Trade networks

ARIO simulates the propagation of a shock within a given multi-regional input-output table (MRIOT), which captures the supply and demand linkages between economic sectors and final consumers within and across countries. As a result, an MRIOT reflects a specific configuration of global trade networks.

In this study, we use EORA26 because it covers over 180 countries, enabling us to capture trade flows involving a broad range of economies (Lenzen et al., 2012). EORA26 provides data for 26 sectors in each country. Our baseline input-output table is the 2016 version of EORA26, which is the most recent publicly accessible release. The process of moving from the original 2016 table to the 2020 table and to the 2050 tables representing future trade patterns involves first a balancing step, and then a projection step.

Balancing of the original EORA26 (2016) table

As a first step, we address several issues present in the original EORA26 (2016) table.

First, the original EORA26 (2016) table includes an outdated country, the Soviet Union, whose economic sectors are all producing close to zero. As noted in the EORA26 documentation, this is a remnant of the database's coverage starting in 1990, prior to the dissolution of the USSR in 1991. We therefore remove all rows and columns corresponding to this country from the data. In the end, the dataset contains 188 countries.

Second, the original EORA26 (2016) table, as provided on the EORA26 website, is not balanced—i.e., for a given sector in a given country, total resources do not match total uses. In practice, this means that for a given country and sector, the sum of the corresponding row does not equal the sum of the corresponding column, as it should be in an input-output table. Given that both SPIN and ARIO rely on balanced input-output tables, we adjust the value added for each sector–country pair to ensure that the sum of inputs (column) matches the sum of outputs (row) for that pair.

Third, the balanced EORA26 (2016) table includes negative values in value added (VA) or final consumption (Y) for some sector-country pairs. Since SPIN and ARIO must be given an MRIOT with only positive values, we set all these negative VA (resp. Y) to zero and add its absolute value to the corresponding Y (resp. VA) to keep a balanced table.

In the end, we get a balanced and positive EORA26 (2016) table.

Projections to 2020 and 2050

We use the balanced EORA26 (2016) as an input into SPIN, a multi-regional input-output table projection algorithm. SPIN aims to generate input-output tables that preserve the original technological structure—defined by the technical coefficients of domestic transactions—while meeting updated aggregate country-level Gross Domestic Product (GDP) and trade volume constraints (Beaufils et al., 2022). In short, the 2020 table is obtained by using 2020 GDP levels from the Shared Socioeconomic Pathways (SSP) database (historical data), while trade constraints are set to preserve the trade-to-GDP ratios observed in the 2016 input-output table.

For their part, the 2050 tables are generated by using 2050 SSP GDP levels and diverse trade constraints, as explained below.

GDP constraints. We use the GDP projections from the SSPs to project input-output tables into the future (IIASA, 2024; O'Neill et al., 2017). Specifically, we rely on the most recent release of these projections (February 2024), and select those generated using the OECD-ENV economic model, as it covers the widest range of countries (for the original method, see Dellink et al., 2017). 15 of the 188 countries of EORA26 do not have a GDP trajectory in the SSP data. We chose to give those countries the same growth rate as other countries next to them, as indicated in Table 3.2. We consider only three SSP scenarios: SSP2 (business-as-usual), SSP3 (low growth), and SSP5 (high growth), because our objective is to span a broad space of potential developments.

Trade constraints. We build two types of trade scenarios: (i) uniform increase or decrease of trade ration and (ii) formation of trade blocs.

(i) Uniform trade scenarios. First, we consider projections of trade networks in which trade openness—defined as the ratios of imports and exports to GDP—is uniformly either decreased (low trade scenario), kept constant (constant trade scenario) or increased (high trade scenario).

More specifically, in the low trade scenario, all trade ratios are reduced by 50% by 2050; in the constant trade scenario, they are held at their 2016 levels; and in the high trade scenario, they are increased by 50% by 2050. To give a concrete example, in 2016, Thailand's imports represent approximately 40% of its GDP. In the low trade scenario, this ratio decreases to around 20% by 2050, while in the high trade scenario, it increases to around 60%.

Generating trade constraints trajectory for country c means obtaining imports $M_{c,t}$ and exports $X_{c,t}$ volumes for each period from 2016 and 2050 (that is 2020, 2025, 2030, 2035, 2040, 2045 and 2050). We proceed in to steps.

Step 1 – Projecting trade. We already have GDP constraints and we define, for each country c and period t, its GDP value $GDP_{c,t}$ and its GDP growth $g(GDP)_{c,t}$ by:

$$GDP_{c,t+1} = e^{g(GDP)_{c,t}} GDP_{c,t}$$

Similarly, we denote imports $M_{c,t}$ and exports $X_{c,t}$ and we define imports and exports growths $g(M)_{c,t}$ and $g(X)_{c,t}$ by:

$$M_{c,t+1} = e^{g(M)_{c,t}} M_{c,t} \qquad X_{c,t+1} = e^{g(X)_{c,t}} X_{c,t}$$

Our objective is to obtain $g(X)_{c,t}$ and $g(M)_{c,t}$ so that:

$$\frac{M_{c,2050}}{GDP_{c,2050}} = k \cdot \frac{M_{c,2016}}{GDP_{c,2016}}$$

where k is 0.5 for low trade, 1 for constant trade and 1.5 for high trade.

We can show that this can be done by setting:

$$g(M)_{c,t} = g(X)_{c,t} = g(GDP)_{c,t} \left(1 + \frac{\ln(k)}{\sum_{t=2016}^{2050} g(GDP)_{c,t}} \right)$$

Step 2 – Balancing trade. However, since all aggregate trade volumes are increased/decreased independently for each country, there is no reason to have a balanced trade overall (that is $\sum_c X_{c,t} = \sum_c M_{c,t}$ for all t). To balance trade, we correct imports from $M_{c,t} \rightarrow \mathrm{M}'_{c,t}$ by a common factor α_t so that:

$$\sum_c X_{c,t} = \sum_c M'_{c,t} = \sum_c M_{c,t}\, \alpha_t$$

That is:

$$\alpha_t = \frac{\sum_c X_{c,t}}{\sum_c M_{c,t}}$$

Balancing trade has only a negligible effect on the trade-to-GDP ratios.

(ii) Formation of trade blocs. Second, we consider projections of trade networks in which countries are grouped into two trade blocs (denoted T1 and T2, where T stands for "Trade zone"), which either isolate themselves ("Isolation" scenario) or further integrate ("Integration" scenario). More precisely, we take as a baseline scenario one that is identical to the "Constant" uniform scenario described above, i.e., such that the ratios $X_{c,t}/GDP_{c,t}$ and $M_{c,t}/GDP_{c,t}$ remain constant for all countries c, despite the increase in $GDP_{c,t}$ over time. We then consider an "Isolation" scenario in which the total sum of intra-bloc and inter-bloc trade volumes is the same as in the baseline scenario, but distributed differently: inter-bloc trade volumes are reduced by 50%, while intra-bloc trade volumes are increased by 50%. In this configuration, the two blocs become more like independent islands, even though a non-negligible residual trade remains. In the "Integration" scenario, inter-bloc trade is increased by 50%, while intra-bloc trade is reduced by 50% in exchange.

For uniform scenarios, it was sufficient to provide SPIN with GDP constraints ($GDP_{c,t}$ for all lines t and countries c) and aggregated trade constraints, i.e., exports X_c and imports M_c for all t and c. In the case of trade blocs, more detail is required: one must provide aggregated trade constraints by destination trade zone, namely $X_{c\rightarrow IN}$, $X_{c\rightarrow T2}$, $M_{c\leftarrow IN}$, $M_{c\leftarrow T2}$. More specifically, SPIN requires $X_{T_x\rightarrow T_y}$, $M_{T_x\leftarrow T_y}$, where IN denotes the trade zone of c and OUT denotes the other.

In practice, we follow the steps below.

Step 1 – Obtaining $X_{c\rightarrow IN}$ and $X_{c\rightarrow OUT}$ for all countries c. For each year, we take the value obtained in the "Constant" uniform scenario, described in the previous section.

Step 2 – Obtaining trade zones' aggregate trade volumes. The trade volumes aggregated at

the trade zone level are defined by:

$$X_{T_1 \to T_1} = \sum_{c \in T_1} X_{c \to IN}$$

$$X_{T_1 \to T_2} = \sum_{c \in T_1} X_{c \to OUT}$$

$$X_{T_2 \to T_1} = \sum_{c \in T_2} X_{c \to OUT}$$

$$X_{T_2 \to T_2} = \sum_{c \in T_2} X_{c \to IN}$$

Step 3 – Compute the "Isolation" and "Integration" trade zones aggregate trade volumes. Denoting $\Delta_r(A) = \frac{\Delta A}{A}$ the relative change between the "Constant" scenario and either the "Isolation" or "Integration" scenario, we compute the new trade zones aggregate trade volumes as follows.

For "Isolation":

$$\Delta_r(X_{T_1 \to T_2}) = -50\%$$

$$\Delta_r(X_{T_2 \to T_1}) = -50\%$$

$$\Delta_r(X_{T_1 \to T_1}) = +50\%$$

$$\Delta_r(X_{T_2 \to T_2}) = +50\%$$

For "Integration":

$$\Delta_r(X_{T_1 \to T_2}) = +50\%$$

$$\Delta_r(X_{T_2 \to T_1}) = +50\%$$

$$\Delta_r(X_{T_1 \to T_1}) = -50\%$$

$$\Delta_r(X_{T_2 \to T_2}) = -50\%$$

However, since we want to keep the sum of inter- and intra-trade zone trade volumes constant ($X_{T_1 \to T_1} + X_{T_1 \to T_2} + X_{T_2 \to T_1} + X_{T_2 \to T_2}$), we must renormalize each $X_{T_x \to T_y}$ by:

$$\frac{(X_{T_1 \to T_1} + X_{T_1 \to T_2} + X_{T_2 \to T_1} + X_{T_2 \to T_2})_0}{X_{T_1 \to T_1} + X_{T_1 \to T_2} + X_{T_2 \to T_1} + X_{T_2 \to T_2}}$$

Step 4 – Use the $X_{T_x \to T_y}$ values obtained to get the $M_{T_x \to T_y}$. We have the following correspondence:

$$M_{T_1 \to T_1} = X_{T_1 \to T_1}$$

$$M_{T_2 \to T_2} = X_{T_2 \to T_2}$$

$$M_{T_1 \to T_2} = X_{T_2 \to T_1}$$

$$M_{T_2 \to T_1} = X_{T_1 \to T_2}$$

Step 5 – Use the "trade zone" aggregated trade volumes to obtain "country-level" aggregated trade volumes. We use the proportions of the "country-level" aggregated trade volumes within the "trade-zone" aggregated trade volumes at the same date t in the "Constant" scenario to perform this downscaling.

These country-level flows already satisfy the aggregated constraints and can therefore be used directly.

We aim to explore retreat scenarios in which the least risky countries—i.e., those expected to experience the smallest capital losses over a ten year period in our dataset—turn inward, thereby forcing the riskiest countries to trade primarily among themselves. Countries are divided into two categories: those experiencing limited flood events on their national territory during the period in the flood database ('Low local floods'), and those facing higher flood impact ("High local floods"). We define the least exposed countries as those with the lowest cumulative capital losses over 2045–2055, selected in ascending order until they together account for 75% of world GDP. Those with high flood impact therefore correspond to the remaining 25% of world GDP. We define a "Isolation" scenario where inter-zone trade volume is reduced by 50% while international trade volume is kept constant. We keep the "Constant trade" scenario of the first set. We define an "Integration" scenario where inter-zone trade is increased by 50% while international trade volume is kept constant.

Table 3.2: List of EORA26 countries without SSP projections and their assigned neighbor proxy countries)

Country lacking SSP projection	**Proxy neighbor country**
Greenland	Denmark
Syria	Iraq
Bermuda	Antigua and Barbuda
Cayman Islands	Antigua and Barbuda
Netherlands Antilles	Antigua and Barbuda
Virgin Islands (British)	Antigua and Barbuda
Venezuela	Colombia
Afghanistan	Pakistan
Palestine, State of	Jordan
South Sudan	Sudan
Sudan	Sudan
Liechtenstein	Austria
Monaco	France
Andorra	France
San Marino	Italy

A.3 ARIO

Parameters

To capture the cascading effects of flood-induced productive capital losses across sectors and countries, we rely on the ARIO model, a widely used input-output framework in the literature. ARIO is parametrized as is standard in the ARIO literature, see Table 3.3. Simulations are conducted over 1,000 days, which is long relative to the characteristic time of rebuilding—one year, that is 365 days.

Table 3.3: Parameters used for the simulations

Parameter	**Parameter value**
Inventories	
Heterogeneity parameter (ψ)	0.8
Inventory size	90 days
No over-production	
α_0	1
$\alpha_{\max}$	1
Rebuilding	
τ_{rebuild}	1 year

Capital shock

As explained above (1. Floods database), each flood consists in (i) the country affected, (ii) the size of the capital shock, in relative terms ($\Delta K/K$), due to this specific flood. This relative shock is applied to future tables uniformly across sectors.

Conclusion

1 Key findings

Climate change is already having visible impacts on individual well-being and ecosystem health, and these effects are expected to worsen in the medium term, largely due to past emissions. In this context, it is essential for each country to have a clear understanding of the impacts of climate change to which it is exposed—whether directly on its own territory or indirectly through its connections with other countries—in order to design effective climate adaptation policies and build consensus around them. In particular, this thesis explores whether current quantitative knowledge of climate change impacts in France is sufficiently comprehensive to effectively inform adaptation strategies.

To address this question, **Chapter 1** reviews assessments of climate change impacts referenced in France's adaptation planning and evaluation documents. We find that, despite a rich body of literature, many categories of impacts are not comprehensively quantified, and even fewer are comprehensively monetized. When aggregating the available monetized costs, we obtain an order of magnitude consistent with values reported for France in the macroeconomic literature, but significantly lower than the most recent estimates. This difference may be explained, among other factors, by the lack of monetization of certain impact channels, by methodological lag, or by the absence of cross-border risk considerations in the French institutional literature, which are supposed to be at least partly present in the recent macroeconomic estimates.

Given this last point, we then turned to the question: what quantitative tools can support the planning of adaptation to cross-border climate risks arising from trade? In **Chapter 2**, we propose a simple and flexible framework to systematically assess the trade-related climate cross-border risks by combining input-output tables and country-scale climate risk indices. We find that this indirect exposure is highly heterogeneous between countries. While its geographical pattern generally differs from those of direct climate change impacts, several countries suffer a double exposure and are exposed to both risks, as a result of regional trade integration and geographic concentration of climate risks. Moreover, almost every country faces high exposure for at least one broad category of products. In **Chapter 3**, we propose a framework to assess quantitatively the effect of both trade openness and trade bloc formation to the resilience to extreme weather events, by combining an event-based extreme weather event database, an input-output impact propagation model and an input-output tables projection algorithm. We show that trade

openness can help the most flood-affected countries smooth consumption by decoupling it from local production, but increases other countries' exposure to foreign shocks. Overall, while integration creates both winners and losers, global welfare improves, and isolating highly exposed economies would significantly worsen their situation. In a sense, trade retrenchment can thus be viewed as a form of maladaptation at the global level.

2 Policy recommandations

These results may lead to the following policy recommendations.

Chapter 1 shows that there is still significant scope to achieve a comprehensive quantification of impacts in France, as the magnitude of several major categories of impact remains unknown. Clarifying the effects of climate change would help in designing effective adaptation strategies and in communicating the necessity of such policies. Beyond quantification, the issue of monetization also arises, and we show that there is considerable uncertainty regarding the costs of climate change in France. This means that the scale of the challenge remains unclear compared with other economic policy priorities, although the more recent a study is, the higher the costs it tends to project, which is a cause for concern. However, these studies often operate as black boxes, with limited transparency about their underlying data and methods. It is therefore crucial to further develop bottom-up studies, always considering monetisation whenever possible, to provide greater substance to econometric assessments. Besides, these assessments should be regularly updated to keep up with the progress of climate impact assessment. Finally, cross-border risks should be more systematically documented in national risk assessments, as is already the case in some countries, such as the United States and the United Kingdom.

Given its scope, **Chapter 2** naturally points towards policy recommendations at the international level. First, several developing or least developed countries appear to be doubly disadvantaged: both by direct climate impacts and by trade-related cross-border risks. This result reinforces the notion of global inequalities between the countries responsible for the bulk of greenhouse gas emissions and those that suffer the most from the effects of climate change. Developed countries therefore have two reasons to finance adaptation in the Global South: both because of this inequality, and from a national resilience perspective, as all of them face high exposure for at least one broad category of products. Second, an adaptation option for countries particularly exposed to cross-border risks through trade is to further diversify their trading partners. We show that this would be costly, as the reasons for these countries' double exposure stem from their tendency to trade primarily with neighbouring countries. However, this may prove beneficial in the long term as the effects of climate change intensify.

Chapter 3 compares the policy levers available to address the increase in cross-border risks through trade due to extreme events. Mitigation is likely to be the most effective tool to reduce consumption losses for a vast majority of countries, and should therefore be prioritised. However, since it is possible that not all countries will take action to reduce their emissions, alternative strategies must also be considered. Moreover, changes in trade—whether through

greater openness or restriction, applied uniformly or selectively—can also serve as an adaptation mechanism to climate change, but two key issues arise. First, the cost–benefit analysis of reducing or closing trade links is not straightforward: if a country is severely affected, it may be preferable to increase openness, whereas less-affected countries might not have the same incentive. Before considering such solutions, a country should assess its relative position in terms of local climate risks, which may depend on the type of extreme event considered. Second, equity concerns emerge: do we really want countries spared from severe impacts to protect themselves while allowing the most affected to face the consequences alone? The tools we have developed provide quantitative insights into these two issues.

3 Limitations and avenues for further research

At the conclusion of this thesis, three main avenues are identified for further development of the work undertaken.

Application of the tools developed to assess trade-related cross-border risks for a given country

Chapters 2 and **3** develop new tools, which are then used to derive stylized facts at the global level, regarding inequalities in exposure and the consequences of different trade evolution scenarios. A natural extension of this work would be to propose a systematic methodology for applying these tools from a country-level perspective, and to identify which tools are most relevant for answering specific questions from the standpoint of policymakers seeking to quantify a country's exposure to cross-border risk. As explained in the introduction, we essentially have two types of trade data—customs data and input–output (IO) data. In this thesis, we have mainly relied on the latter, as it makes it possible to account for the share of goods and services originating from abroad within the totality of what is consumed or produced domestically: such data allow us to measure the extent of dependence in relation to the national economy. While this approach makes it possible to measure the share of consumption or production linked to a country facing higher geopolitical or climate risks, supply chain risk is even greater when a product is sourced from only a single location.

We addressed this aspect in **Chapter 2** by using a concentration index by sector. However, the available multi-regional input–output tables do not represent sectors at a very disaggregated level (26 and 45 sectors in the two datasets used), which masks the concentration of sourcing that may exist at the product level. Product-level data (covering several thousand categories) are collected for different countries by customs authorities and are standardised at the global level in databases such as UN Comtrade or the BACI database. The limitation of this approach is that, for a given product, it is possible to determine whether the majority of imports (or exports) come from a specific country, but without any indication of the share of imports (or exports) in national consumption (or production). Building on several country case studies, this work would aim to demonstrate how IO data, combined with national risk indices, can be used, first, to compare a given country's exposure to the most climate-vulnerable countries, and second, to leverage customs data to identify the goods most affected by concentration in

climate-risk areas. It would also be possible to draw on the trade evolution scenarios developed in **Chapter 3** to examine how exposure changes over time and across different scenarios.

Extending the framework of Chapter 3 to different types of extreme events

One limitation of **Chapter 3** is that it examines changes in the propagation of costs under different scenarios of international trade evolution from only one type of extreme event—floods. Given that databases on extreme events—and their projected evolution under climate change—exist for different types of hazards, it would be interesting to apply the framework developed in this work to them. In particular, this would make it possible to assess whether the conclusions reached in the case of floods hold for other events, and how this might alter the optimal scenarios for different countries.

Another limitation of **Chapter 3** is that it is difficult to accurately capture the forward propagation of shortages along supply chains when extreme events are small relative to the scale of the modelled geographical units. Spatial disaggregation algorithms for input–output tables do exist and could be used to move from 188 countries to several thousand regions. Given that extreme-event databases have high spatial resolution (for example, the flood database operates at a one-degree scale), they would not be a limiting factor in downscaling. The main challenge would be computational: it would require careful optimisation given the large number of simulations to be performed, should the representative-event methodology used in Chapter 3 be followed. This downscaling is essential, as it allows for better modelling of the forward consequences along supply chains and of the non-linear amplification associated with lower reconstruction capacity in the event of large shocks.

Framing the cost–benefit analysis of trade openness in the face of climate change impacts within a broader perspective

Finally, **Chapter 3** examines the policy levers available to address the increase in cross-border risks through trade in the context of climate change, using a simple cost–benefit analysis. In the short term, the benefits arise from smoothing local shocks through imports, while the costs relate to the propagation of foreign shocks. However, a country's trade policy is not determined solely on the basis of the short term supply chain consequences of extreme events. In particular, in the long term, if we only consider climate change related issues, the costs of trade closure must take into account not only the reduction in gains from trade, but also the loss of benefits associated with predictable long-term impacts of climate change. For the latter, this includes, for example, the potential shift in comparative advantage resulting from relative improvements in agricultural productivity in Northern countries, even though agricultural productivity is projected to decline in all regions as a result of climate change. Developing a theoretical model that incorporates both the impacts of extreme events—unpredictable—and slow-onset changes—predictable by firms—as well as comparative advantages and gains from trade, would provide a broader perspective on how states choose to respond to the supply-chain consequences of climate change.