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Who bears the indirect costs of flood risk? An economy-wide assessment of different insurance systems in Europe under climate change

Nina Knittel [a], Max Tesselaar[b], W. J. Wouter Botzen[b,c,d], Gabriel Bachner[a] and Timothy Tiggeloven[b]

[a]Wegener Center for Climate and Global Change, University of Graz, Graz, Austria; [b]Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, Amsterdam, The Netherlands; [c]Utrecht University School of Economics (U.S.E.), Utrecht University, Utrecht, The Netherlands; [d]Risk Management and Decision Processes Center, The Wharton School, University of Pennsylvania, Philadelphia, PA, USA

ABSTRACT
Anticipated increase in future river flood risk highlights the need for effective flood insurance, as it enables hedging against this risk. However, its design varies significantly across countries. This study contributes to the debate on designing flood insurance mechanisms from an economy-wide perspective, considering both socioeconomic and climate changes. We apply a multi-regional computable general equilibrium (CGE) model for 2050 and find that, under current insurance market systems, flood risk causes regional GDP losses of up to −0.5%, societal welfare losses of up to −1%, and private and public consumption losses of up to −0.5% and −2.4%, respectively. These estimates are all relative to a scenario without flood risk. Our results indicate that flood risk intensifies pressure on public budgets. We find that insurance market reforms, including a higher degree of risk-sharing, mandatory purchase requirements, and public reinsurance, can alleviate adverse welfare effects and the burden on public budgets.

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Flood insurance; Flood risk; Public-private partnership; Public budget; Computable general equilibrium model

1. Introduction

Extreme flood events in July 2021 in Germany, Belgium, the Netherlands, and Austria showed that flood risk is already materializing as high monetary costs in many parts of Europe. In the future, the river flood risk is expected to further increase in the EU and the UK due to several drivers, such as land subsidence and climate and socioeconomic change (Alfieri et al., 2015; Dottori et al., 2018; Winsemius et al., 2016). In particular, climate change can intensify extreme dry or wet hydrological conditions, which affects the flood risk (Seneviratne et al., 2021; Tabari, 2020). Among all natural hazards, flooding may have the largest impact on society (CRED and UNISDR, 2015; IPCC,

CONTACT Nina Knittel nina.knittel@uni-graz.at Brandhofgasse 5, 8010 Graz, Austria

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2022). Specifically, river flooding is among the most critical climate impacts in the European regions today and will be so in the future (Ciscar et al., 2014; Feyen et al., 2020; IPCC, 2022).

The expected changes in flood risk clearly point to the increasing need to implement adaptation measures (Willner et al., 2018a). One response is to improve flood protection standards. However, reducing flood risk to zero is often infeasible or inefficient, meaning a residual flood risk remains (Ward et al., 2017). For individuals who face such residual risks, flood insurance provides financial protection by spreading the risk over time and space. If designed effectively, insurance may also stimulate household-level adaptation by policyholders against flood risks (Botzen, 2021; Kousky, 2019; Schwarze & Wagner, 2007). Currently, the design of insurance mechanisms varies significantly across Europe (Hudson et al., 2020). Depending on which insurance system is in place, a flood event has varying implications for the policyholders, the insurance provider, and the public sector. In some systems, increasing flood risk can cause insurance premiums to rise and become unaffordable for low-income households. It may, therefore, also involve a significant insurance coverage gap, which causes uncertainty as to who will ultimately pay for flood damages (Cremades et al., 2018; Hudson et al., 2019; Mechler et al., 2014). Hence, to comprehensively enhance resilience to flood risk, the reforms of flood insurance arrangements must be considered.

We contribute to the emerging literature on the macroeconomic effects of natural hazards by linking a partial equilibrium model of flood insurance markets based on a catastrophe flood risk model with a computable general equilibrium (CGE) model. Our novel approach allows us to make projections of expected annual flood damage under various socioeconomic and climate change scenarios to calculate premiums for various current stylized insurance market systems. The partial-equilibrium model simulates the future demand for flood insurance coverage and the implementation of specific flood risk reduction measures. These parameters feed into the CGE model to assess the economy-wide impacts of flood risk, mediated by flood insurance markets, on macroeconomic indicators such as GDP, private and public consumption, and ultimately societal welfare.

The remainder of the paper is structured as follows: Section 2 reviews existing insurance market systems in Europe, the literature associated with its debate, and different modeling approaches in the context of climate risk assessments. Section 3 introduces the applied methodology, including a description of the partial equilibrium and CGE models. Section 4 presents the results. First, we analyze the implications of projected flood damages to the economy in 2050 under current insurance market systems. Second, we simulate and analyze how insurance market reforms can improve these implications, while recognizing the role of different actors (public and private agents). Section 5 discusses the findings and limitations, and section 6 concludes this article.

2. Background and literature review

2.1. Flood insurance arrangements in Europe

Focusing on common market features of insurance market systems, three main arrangements can be identified within Europe: a *voluntary or semi-voluntary system*, a *solidarity market structure*, and a *public-private partnership* (PPP; Hudson et al., 2019). These systems differ in terms of premium-setting rules, reinsurance arrangements, and insurance purchase requirements. In Europe, most flood insurance markets are characterized by *voluntary* insurance uptake and premiums that fully reflect individual flood risk. Optional insurance poses the threat that only households at substantial risk of flooding choose to insure, an effect known as adverse selection. In theory, a feedback effect of continuously rising premiums may occur due to an increasing concentration of high-risk policyholders for insurers as lower-risk households opt out of insurance coverage. Insurance purchase requirements and accurate, risk-reflective premiums can prevent this market failure in practice (Hudson et al., 2017). An additional advantage of risk-based premiums is that they may enhance risk awareness and risk-reducing behavior (Botzen & Van Den Bergh, 2008; Kunreuther, 2021). However, demand for flood insurance coverage when it is optional is often sparse (Maccaferri et al., 2012). One reason for this is that many European countries provide ad hoc compensation payments to private households in case of a flood event; these are funded by disaster funds or other public budget items (e.g. the *Katastrophenfonds* in Austria). While the resources of these funds usually suffice in average years, they are quickly depleted when a severe disaster occurs and requires additional monetary sources. This causes pressure on public budgets, particularly when other expenditures cannot be cut for refinancing or when no additional public debt is incurred. Uncertainty regarding the required level of damage compensation also implies that public budgets may incur fiscal stress in the long term when they do not prepare for higher costs.

A system characterized by *solidarity*, where premiums are insensitive to risk, stands in contrast to risk-based premiums. This system is effective at limiting the costs for those in high-risk areas, but it comes at the expense of those living in low-risk areas, and it does not provide any incentive to reduce the individual's risk, a process known as a moral hazard (Poussin et al., 2013). Although moral hazard is a well-known theory in insurance economics, its presence in natural hazard insurance markets is not unanimously confirmed (Hudson et al., 2017; Michel-Kerjan, 2010).

Several studies have advocated for a PPP system, which combines the advantages of various insurance strategies (Botzen et al., 2010; Hudson et al., 2019; Husby et al., 2016; Paleari, 2019; Surminski et al., 2015; Tesselaar et al., 2020b). In this approach, private insurers provide coverage at limited risk-based prices, while the government enforces mandatory insurance purchase requirements and provides reinsurance at low cost (Hudson et al., 2019; Kunreuther, 2015; Paudel, 2012). Recent modeling studies conclude that this risk-sharing approach is the most beneficial and resilient to climate change based on indicators such as affordability, insurance uptake, and coverage (Hudson et al., 2019; Tesselaar et al., 2020b; 2020a).

A shortcoming of the existing literature on the insurance design debate is that the above conclusions are based on partial equilibrium or optimization models that neglect the economy-wide perspective; in particular, they do not account for the government sector or indirect feedback effects, which have implications for societal welfare. In order to support decision-making, quantitative modeling and analysis of flood risk and flood insurance design is important. Decision-makers are typically interested in the effects on economic indicators, such as monetary flood damages, and on economy-wide and indirect effects of floods and responses to them (e.g. Reiter et al., 2022). To overcome these shortcomings and to address the question of who bears the indirect costs of flood risk under different insurance market systems, we assess the macroeconomic impacts of flood risks in a comprehensive manner, accounting for various flood loss compensation schemes. In the next section, we discuss relevant modeling approaches and the associated literature and motivate the choice of applying a CGE model in this study.

2.2. Modeling approaches

A growing body of literature employs macroeconomic modeling approaches to assess catastrophic disaster impacts on the economy (e.g. Okuyama, 2007; Okuyama & Santos, 2014; for an overview, see Zhou & Chen, 2021). The majority of these studies use integrated assessment models (IAM; for an overview, see Diaz & Moore, 2017); structural models such as CGE models, (multi-regional) input–output (IO) and network-based models; and econometrics (Piontek et al., 2021).

While IAMs are comprehensive in their spatial coverage, they are very coarse in sectoral detail and work with reduced-form impact functions, which limits their potential to implement climate-related damages (Pindyck, 2013). As climate change impacts vary significantly in their appearance and effect, a genuine attempt to thoroughly link catastrophe models with the model parameters affected is vital for understanding the economy-wide implications of climate change. IO and network models have a higher sectoral resolution, but conventional models usually assume production technologies to be rigid (i.e. fixed expenditure shares). Hence, these models have instead been used to assess the short-term effects of mostly single sudden-onset events rather than long-term averages (Koks et al., 2019; Otto et al., 2017; Willner et al., 2018b). Econometric assessments are usually also very detailed in the effects of, for example, extreme weather events (Osberghaus, 2019), but they fail to consider macroeconomic feedback effects.

CGE models feature relatively high sectoral resolution (higher than IAMs, but lower than IO), which enables capturing (inter-)sectoral effects and allows economic shocks to be implemented accurately, rather than applying coarse damage functions to the entire economy. Several exemplary studies have followed such an integrated approach (Bosello et al., 2012; Carrera et al., 2015; Pauw et al., 2011). In contrast to IO models, a crucial feature of CGE models allows the accommodation of a long-term perspective, which is the possibility of substitution in intermediate as well as final demand as a reaction to price changes. Another key characteristic that distinguishes CGE models from demand-driven IO models is that factor endowments are scarce, and thus factor supply constrains overall economic income and activity. In the context of this paper, this is relevant because the flood shock further constrains the capital availability of producers in the economy. Hence, CGE models are particularly useful for analyzing how the direct effects of a localized economic shock – such as flood damages – propagate into indirect effects on macroeconomic indicators and public budgets. Knowing the size of the exogenous shock parameters further allows to identify the difference between direct and indirect effects and determine the amplification of direct impacts through economy-wide feedback effects. Hallegatte et al. (2007) and Mandel et al. (2021) have demonstrated the importance of this amplification ratio for macroeconomic damages due to extreme events in the context of global financial interlinkages.

Despite the ample advantages of CGE analyses, there are also several drawbacks. CGE models are often criticized for lacking transparency and requiring many crucial assumptions (Sue Wing, 2004). In particular, the parameter specification and choice of functional forms significantly drive results (Zhou & Chen, 2021). While, for example, the assumed values for elasticities of substitution typically rely on econometric estimations, sensitivity analyses can further improve the robustness of the results. Moreover, modelers must carefully decide on the three macroeconomic balances (government, external, and savings-investment balance) given the present research scope (Lofgren et al., 2002).

Regarding the topical coverage of the existing literature, different insurance market systems and, accordingly, the differentiated effects across actors are typically not accounted for. For example, focusing on the post-disaster recovery phase, Gertz et al. (2019) have investigated the macroeconomic effects of recovery funds; however, they do not differentiate between insurance payouts and publicly funded compensation payments. Other studies have specifically examined the role of insurance in mitigating economic damages in general (e.g. Crichton, 2008; EIOPA, 2021) or the role of government support in reducing the indirect losses of floods (Oosterhaven & Többen, 2017). The role of the government in the context of disasters has been discussed comprehensively (e.g. Bouwer et al., 2007; Gamper et al., 2017), but few studies have assessed the budgetary effects of disaster risk management quantitatively (Bachner et al., 2019; Bachner & Bednar-Friedl, 2018; Hoffmann & Stephan, 2018; Parrado et al., 2020; Unterberger et al., 2019).

To overcome the above-described limitations and address the research gap, we integrate flood risk data and insurance parameters into a CGE model. The flood risk data based on a global flood risk model is used to estimate flood insurance outcomes in a partial equilibrium setting. Although CGE frameworks have been used to examine how several resiliency measures limit the impacts of disasters (Hu et al., 2014; Prager et al., 2018; Rose et al., 2016; Rose & Liao, 2005; Xie et al., 2014a; 2014b), to our knowledge, this is the first study that explicitly considers the influence of insurance arrangements and links a partial-equilibrium model to a CGE model for natural hazard impact analysis. The regions analyzed here are in the EU and the UK.

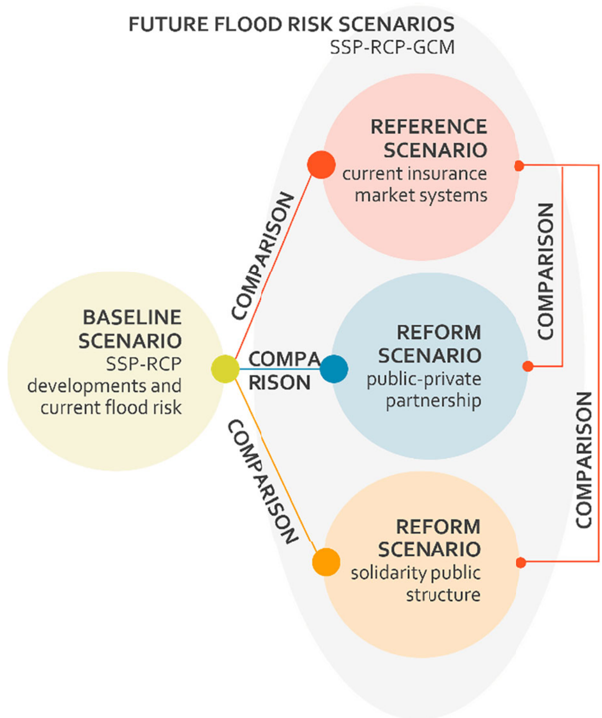
3. Methodology

3.1. Scenario comparison framework

Our scenarios are implemented within the SSP-RCP scenario framework, the state-of-the-art framework in current climate change research. Shared socioeconomic pathways (SSPs; O'Neill et al., 2017) describe generic narratives of how the socioeconomic system will develop, while representative concentration pathways (RCPs; Moss et al., 2010) depict greenhouse-gas emission trajectories until 2100. SSPs and RCPs are combined to represent different plausible future 'worlds' in which climate change impacts materialize, and the effects of climate policy can be studied (for details on the scenario combinations chosen for the present analysis, see Table A4 in the Appendix).

In our analysis, we compare a *flood risk scenario* to a *baseline scenario* in 2050 to identify relative differences between two potential states in the future, thereby isolating the effect of flood risk and changes in insurance systems (see Figure 1). The *baseline scenarios* are calibrated according to the quantitative parameters of the SSP storylines, combined with different RCPs, and entail current flood risk, assuming that this remains constant over time. The *flood risk scenarios* are based on the same assumptions as the *baseline scenarios*, but

Figure 1. Scenario comparison framework.

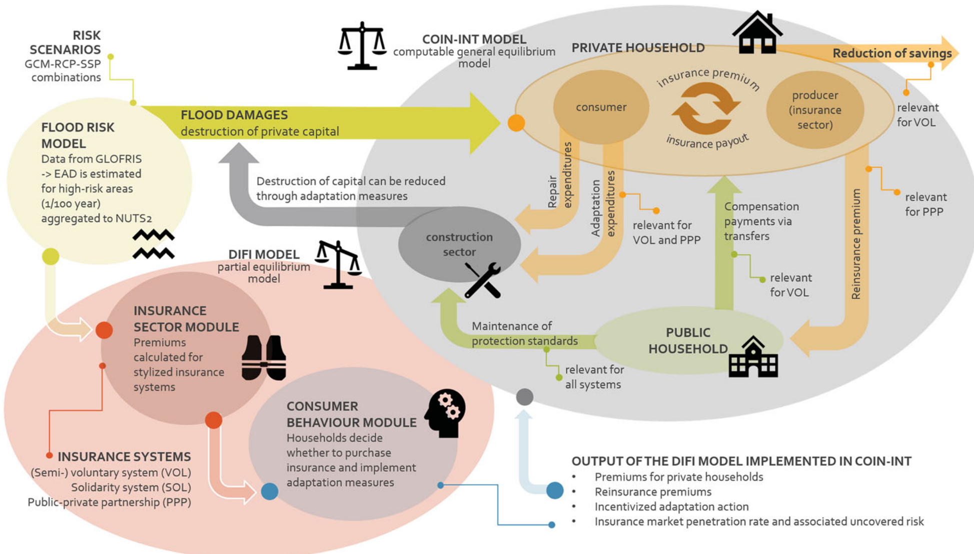


they further involve future flood risk (impact data). The flood risk data is based on the same SSP-RCP combinations as the respective *baselines*. The *flood risk scenarios* also represent the current insurance market systems and the two reform scenarios. Therefore, there are three potential states for the insurance market system. The first is the current arrangement in each country (see Figure 3 [D]). Hence, this provides results for a climate change impact assessment without a reform of the current insurance market systems; we also refer to this scenario as the *reference scenario*. The second state is the *reform scenario*, where each country has a PPP, and the third state is the *reform scenario,* where each region's insurance market is based on a solidarity public structure (SOL).

In our explorative scenario analysis, we first examine how river flooding will affect the economy in 2050 with current insurance market systems (compared to the *baseline scenario* without flood risk). In the second step, we analyze the economy-wide effects of flood impacts under the two alternative systems (*reform scenarios*) compared to the *baseline scenario* without flood risk and the *reference scenario* to identify the influence of the hypothetical insurance market reforms.

In the following, we describe the models applied in this analysis as well as the sequence of how the output of one model is used as an input for another model. Figure 2 conceptually depicts the interactions of the models. First, we present the Dynamic Integrated Flood and Insurance (DIFI) model, which is a partial equilibrium model of the flood insurance sector, and the underlying data stemming from the hydrological impact model GLOFRIS. Second, we introduce the CGE model (COIN-INT) for the macroeconomic evaluation of

Figure 2. Model interface and data flows across models. The flood risk model (light green bubble) provides data on future flood risk, which is used in the DIFI model (light red bubble). First, it is applied in the insurance sector module (red bubble) to calculate insurance premiums for three stylized insurance market systems. Based on these premiums and the underlying insurance market system, in the consumer behavior module (blue bubble), households decide whether to purchase insurance and to implement adaptation measures. The resulting parameters are implemented in the COIN-INT model (gray bubble), differentiated for the private (orange) and the public (green) household.



the different insurance market systems. Third, we detail the implementation of relevant parameters from the DIFI model into the COIN-INT model.

3.2. The DIFI model

For the flood and insurance data, we use the DIFI model described in Hudson et al. (2019) and Tesselaar et al. (2020a). The DIFI model simulates the impacts of climate change and socioeconomic scenarios on flood insurance premiums, insurance penetration rates, and incentivized risk reduction efforts by households under stylized versions of existing European flood insurance arrangements. A detailed description of the DIFI model and the data sources used is provided in Appendix (A1); here, the most important processes to obtain the parameters used in the CGE model are described. These parameters include the expected annual flood damages (EAD), flood insurance and reinsurance premiums, the insurance penetration rate, and the amount of risk reduction generated by insurance incentives.

First, river flood risk for 2010 and projections for 2050 are used to estimate flood insurance premiums on the NUTS2-level.[1] Flood risk projections are estimated using the global flood risk simulator GLOFRIS (Ward et al., 2017; Winsemius et al., 2016), which applies observed water levels in a hydrological model in order to calculate EAD for 2010,

[1] The nomenclature of territorial units for statistics (NUTS) classification is a hierarchical system for dividing the economic territory of the EU and the UK. The NUTS2-classification consists of 242 regions.

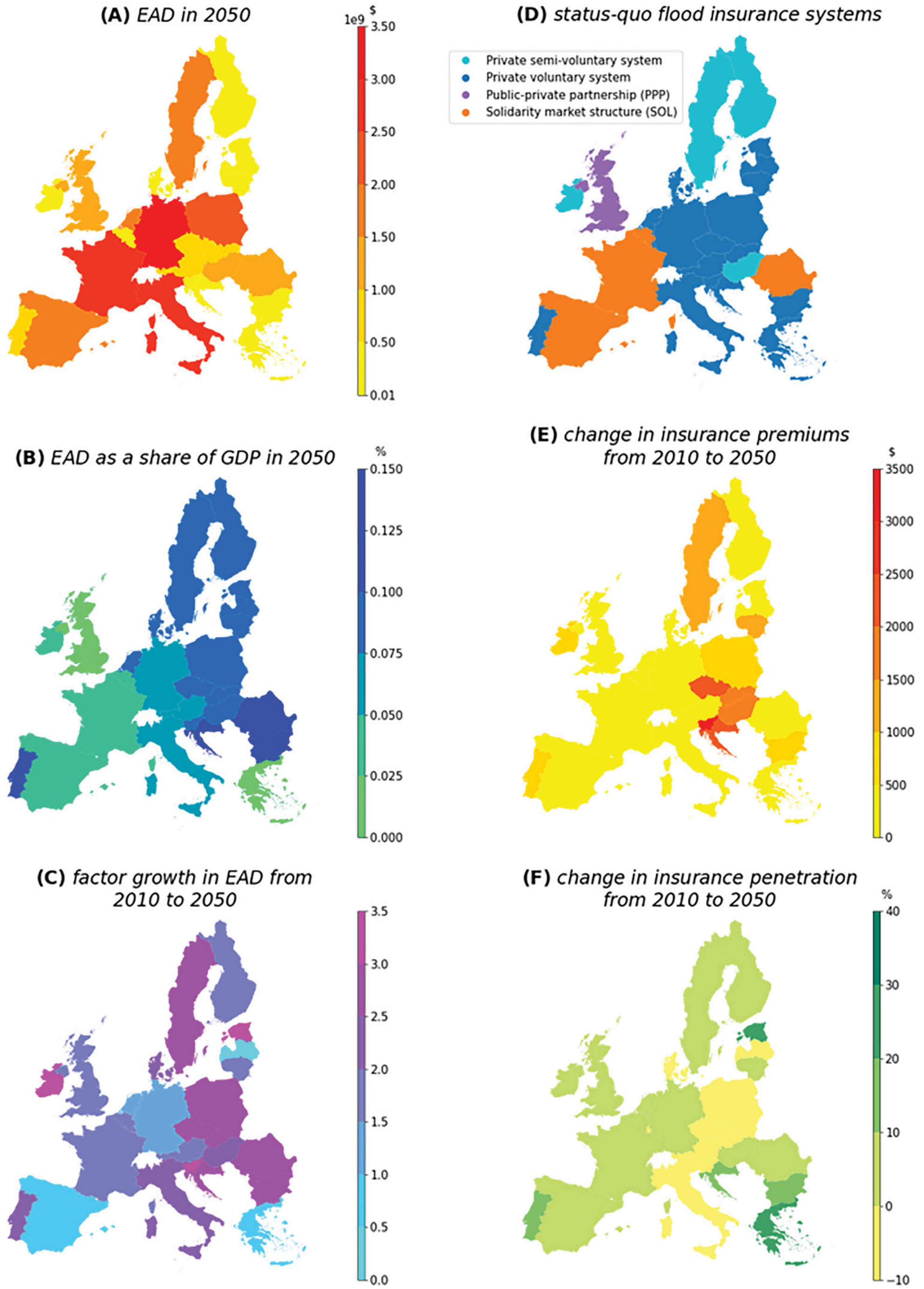
and it applies expected water levels under future climatic and socioeconomic scenarios to simulate EAD in 2050.

As the policy debate around flood insurance performance and potential reforms largely addresses areas at high risk of flooding (Dixon et al., 2006; Surminski & Eldridge, 2017), the flood risk estimates are further calculated specifically for these high-risk areas. In particular, these floodplains are defined as areas where a flood is expected to occur at least once every 100 years (1/100 yr). The EAD estimates and the projected exposed population in high-risk areas are used to simulate flood insurance premiums for three stylized insurance systems within the EU and the UK (see Figure 3 [D] for regional allocation to insurance systems). Each system is characterized by different premium-setting rules, reinsurance arrangements, and purchase requirements. Regarding premium-setting rules, we first identify a system where premiums fully reflect individuals' flood risk, meaning that premiums in high-risk areas are significantly higher than in areas with lower risk. This system is, for example, applied in Germany and the Netherlands, where insurance uptake is entirely voluntary, and reinsurance coverage is obtained from the private market. In our categorization, we refer to this system as the 'voluntary' insurance system. A variation is the 'semi-voluntary' system, which differs from the former only by having insurance purchase requirements to some extent, for example, by including flood coverage in general homeowner insurance policies (e.g. Finland) or by making flood coverage obligatory for a mortgage (e.g. Sweden). Second, we identify a 'solidarity' flood insurance system, in which flood risk is fully shared among the country's population. This publicly organized system, as applied in, for example, France and Spain, maintains equal insurance premiums and mandatory coverage for all. Third, the flood insurance system in the UK is characterized as a collaboration between private insurers and the government; hence, it presents a PPP. Flood insurance coverage is mandatory, and premiums in the UK are risk-based up to a certain threshold, after which the excess risk is shared among households in low-risk areas. The government is involved in a reinsurance pool that facilitates this limited cross-subsidization of risk and guarantees solvency in the case of a very large disaster.

An important assumption to note here, and one that applies to all stylized insurance systems, is that in the long run and on the aggregate level, insurance companies' expenditures are entirely covered by what they collect through premiums, as they would otherwise go out of business. As insurance is meant to spread risk over time and space, damages in a certain year or location may exceed the premiums collected; however, the insurer can recover from this loss through surpluses in other regions or the past and future.

The estimated insurance premiums and flood risk are then used in a household behavior module to simulate demand for coverage and the uptake of flood risk reduction measures. These decision processes are simulated for each household residing in a high-risk area and for each NUTS2 region separately. For each simulated household, we transform the 'objective' flood risk estimates into 'subjective' flood risk in order to capture the misperception of flood risk, which is found to be especially significant for disasters that occur with low probability but have high consequences (Kunreuther & Pauly, 2004). The decision to purchase flood insurance is then simulated in an expected utility framework (Savage, 1954) that considers subjective flood risk, the insurance premium, and household income to assess whether coverage is affordable (we refer to Hudson et al. (2019) for a detailed description). An important assumption here is that insurance coverage is optional for all, while

Figure 3. Expected annual flood damages (EAD) in 2050 in USD (A), as a share of GDP in 2050 (B), and their expected growth from 2010 to 2050 (C) under the RCP8.5-SSP5 scenario combination. The attribution of stylized flood insurance systems (D), the change in insurance premiums from 2010 to 2050 (E), and insurance penetration (F) are based on current insurance systems.



in reality, insurers may refuse coverage for those facing very high flood risk. The simulated households are additionally given a choice to implement wet or dry floodproofing measures (Hudson et al., 2016), which are structural adaptations that either prevent water from entering the building (dry floodproofing) or limit the damage done to the building when it is flooded (wet floodproofing). The household decision process modeled to implement these adaptation measures consists of a subjective cost–benefit analysis, where costs and effectiveness to reduce flood risk for both measures are taken from Aerts (2018). In all insurance systems that maintain risk-based premiums, the application of these measures leads to a premium discount equal to the reduced risk. Therefore, these insurance systems have the added benefit of actually reducing physical damages.

The parameters described in this section are estimated on the NUTS2 level but, for application purposes, are aggregated to the regions in the COIN-INT model, which is introduced in the next section.

3.3. The COIN-INT model

The macroeconomic model COIN-INT is a global, multi-regional, multi-sectoral CGE model. In CGE models, the general key mechanisms are as follows. The economic system is initially assumed to be in a state of flow equilibrium, where all markets are simultaneously cleared, representing an optimal state of the economy. This state is referred to as general equilibrium. This equilibrium is then disturbed exogenously by a system intervention, such as flood damages, leading to endogenous responses in the system. CGE models assume that agents – producers and consumers – behave optimally; that is, they minimize production costs and maximize utility from consumption under technological and budgetary constraints. Specifically, agents react to relative price changes – triggered by an exogenous shock – altering the quantities they demand certain goods. These demand changes again trigger relative price changes and second round-effects until a new equilibrium emerges. The resulting new equilibrium is a set of new prices and allocated quantities of goods and factors, which can be compared to the original equilibrium (or a reference case) to identify the effects of the shock. Hence, the difference between the two equilibria captures the indirect effect of the shock (Sue Wing, 2004).

The core algebraic fundamentals of COIN-INT are described in Bednar-Friedl et al. (2012). The model has been updated to the GTAP9 database (Global Trade Analysis Project, the base year 2011; Aguiar et al., 2016). The underlying input–output tables set the initial conditions for expenditure shares of producers and consumers, international trade flows, and endowments of the production factors of labor, capital, land, and natural resources, which in total reflect economy-wide income. Here, COIN-INT is used in its comparative-static variant and calibrated to depict possible future scenarios in terms of future points in time. This means that we do not model pathways over time; instead, we compare future snapshots of the economy (e.g. in the year 2050) under different future circumstances.

Regarding the regional aggregation of the model, we focus on EU regions and the UK, as the DIFI model provides data on the NUTS2 level for European countries. However, within Europe, some regions lack a modeled insurance market, such as Malta, Albania, Switzerland, and Norway. We aggregate regions according to similarities in economic structure and current insurance market systems. Thus, European countries constitute 21 regions, while the rest of the world is aggregated into five regions. Regarding the sectoral resolution, the model depicts 20 sector aggregates. For details on regional and sectoral aggregation, see the Appendix.

To allow for the analysis of different agents in the flood insurance context, we follow Bachner et al. (2019) and refine the existing model by separating final demand and income. Thus, instead of a single representative regional household, each region has a private household and a government agent. The private household is endowed with production factors. These factors are supplied to the market and generate the household's income, which is either spent for private consumption (according to a constant elasticity of substitution [CES] consumption function) or allocated to savings. The savings-investment closure is set by a fixed savings rate, determining investments. Investment is solely conducted by the private household. The public government agent receives its income from the following taxes: sales taxes on output, tax on capital gains, labor tax, value added tax, and export tax. Concerning the government closure, we fix all tax rates, thereby determining flexible public revenue, which provides the total amount of the available public budget to be spent. Total public revenue is spent for public consumption, which mirrors the provision of public services to society and its contribution to economy-wide welfare, as well as direct transfers to the private household. Regarding the development of the budget deficit, we assume a constant deficit-to-GDP ratio, which is an empirically well-supported assumption for the structural deficit and is also in accordance with the criteria of the EU Stability and Growth Pact (Bachner et al., 2019).

On the supply side, we model 20 production sectors, each of which combines factors and intermediate inputs (i.e. outputs from other sectors) according to nested CES production functions. The expenditure shares of the production functions are calibrated subject to the GTAP9 database. Each sector belongs to one of the following six groups, with different types of nested production functions: Resource-using sectors, agricultural sectors, primary energy sectors, and refined oil products, process-emission generating sectors, and non-resource using sectors (see the Appendix for details).

International trade is implemented via the Armington (1969) assumption, where imports and domestically produced goods are imperfect substitutes. Imports and domestically produced goods can thus be substituted subject to elasticities of substitution (based on Aguiar et al. (2016)). Foreign trade is closed by a constant/fixed trade balance and grows with GDP.

The calibration of the baseline of 2050 involves two steps. In step one, we use data on (i) population growth, driving labor force growth, (ii) cropland cover, driving the availability of land resources, (iii) autonomous energy efficiency improvements, as well as (iv) GDP growth rates (based on SSPs, see O'Neill et al. (2017)), which together drive the economic system towards 2050. Given these exogenous parameters, we calibrate regional multi-factor productivity improvements as a slack endogenous variable to meet exogenous SSP-specific GDP growth rates. The model parameters are calibrated such that global CO2 emissions match with the SSP marker scenarios (Fricko et al., 2017). In step two, we also implement an SSP-RCP-specific CO_2 tax, which is set such that global CO_2 emission trajectories deviate from step one to meet RCP emission trajectories. For a detailed description of this process, we refer to Bachner et al. (2022).

3.4. Model linking

Costs related to flood risk enter COIN-INT in three ways (see Figure 2). First, for every SSP-RCP combination, flood damages reduce the effectively usable capital stock by reducing the productive capital endowment of the economy (and, therefore, the capital income of the private household), representing the destruction of assets. The amount of damage is based on data from the GLOFRIS model and reflects average effects (EAD in 2050). Second, the costs of dikes and other flood protection structures are implemented as additional public investments to maintain the current level of protection. Third, ongoing maintenance costs to prevent the decay of protective structures are assumed to amount to 1% of annual investment costs. The increased public expenditures for protection infrastructure and its maintenance are modeled as increased demand for construction services that crowd out other generic public consumption. These interventions are the same across all insurance market systems.

The different insurance market systems are implemented in the CGE model in terms of varying demand for insurance premiums and adaptation expenditures, public investments for flood protection, and transfers between the public and the private household. The transfers obtained from the public sector range from zero – for example, in the southern EU and Greece – to the total uncovered risk – for instance, in Ireland, depending on how the regions' government typically handles disaster losses. The applied rate of compensation for each country is stated in the last column of Table A1 in the Appendix. With a high rate of compensation, high uncovered risk in the voluntary systems leads to an increased burden on the public budget and reduced public spending. We hereby assume that non-climate-related transfers are held constant and that additional transfers induce a decrease in public consumption. Over time, a low rate of compensation implies that the reconstruction of damaged assets must be financed out of private savings. Thus, investment in new productive capital is reduced, leading to weakened capital accumulation. However, these effects are not implemented in the model, as we pursue a static approach, and they are instead reported exogenously. For a detailed list and description of the impact data and insurance parameters implemented and their differentiation across insurance market systems, see the Appendix.

4. Results

We first present results for the flood risk assessment with current insurance market systems in each model region (section 4.1), followed by the results with a reform of insurance market systems towards a PPP or a SOL in all model regions (section 4.2). Each subsection first describes the direct impacts of climate and socioeconomic change on each region's flood risk and insurance parameters and then addresses the comprehensive macroeconomic implications, including indirect damages. For illustration purposes, we describe the results and the underlying mechanisms in this section for one scenario combination, namely, SSP5-RCP8.5 driven by the general circulation model (GCM) GFDL-ESM2M. This combination represents an intermediate climate model signal within a high-end emission scenario (SSP5-RCP8.5). To put these results into perspective, we show the effects of other scenario combinations in section 4.3 for the EU and the UK.

4.1. Future flood risk under current insurance systems

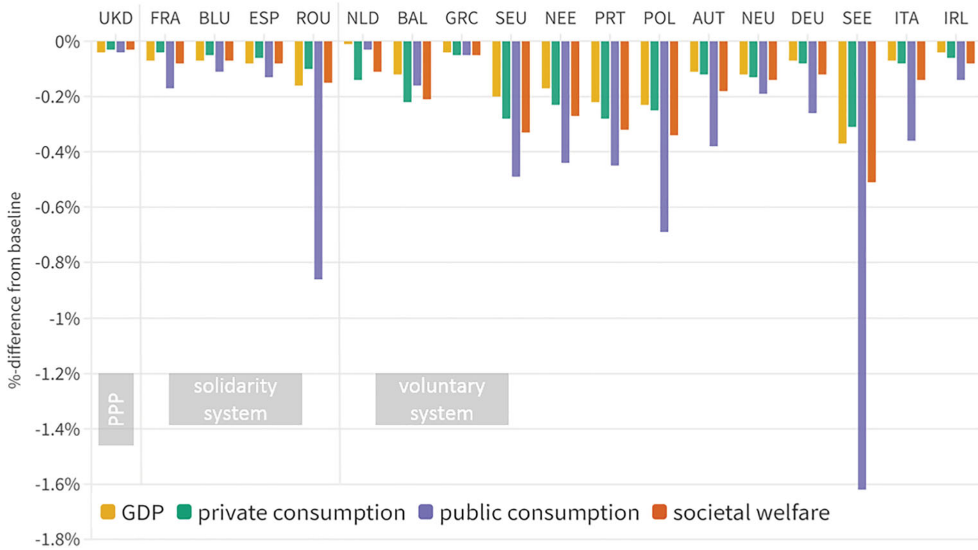
4.1.1. Direct effects

Direct costs associated with flood damages essentially drive the macroeconomic and indirect effects (e.g. GDP and societal welfare). Figure 3 summarizes the most important components. On the left-hand side in Figure 3, we depict the flood damage estimates (EAD) for the EU and the UK under RCP8.5-SSP5 in absolute terms for 2050 (A), as a share of GDP in 2050 (B), and the growth factor between 2010 and 2050 (C). In absolute terms, the direct flood damages in 2050 range from USD 155 million in Greece to over USD 3 billion in Germany. In relation to regional GDP, flood damages range between a minimum of 0.02% in the UK and a maximum of 0.15% in the southeastern EU (Hungary and Bulgaria). We see that in relative terms, low-income regions tend to be on the more vulnerable end of the distribution, with the most vulnerable regions being the southeastern EU, Romania, the southern EU (Croatia and Slovenia), Poland, Portugal, and the northeastern EU (Czech Republic and Slovakia). This indicates lower flood protection standards in low-income regions. Despite serious absolute damages, high-income countries, such as the UK, Belgium and Luxembourg, France, and Ireland, rank among the least vulnerable regions, with higher protection standards. However, some lower-income regions, such as Greece, show low damages due to drier conditions with climate change.[2]

On the right-hand side of Figure 3, we show the attribution of regions to stylized insurance systems, which are based on each region's current insurance arrangement (D), how increasing flood risk translates into rising insurance premiums under currently existing insurance systems (E), and projected change of insurance uptake until 2050, which also considers mandatory purchase requirements in several countries (F). Our results indicate that premiums would rise significantly until 2050 under current insurance systems. In regions such as Germany, Italy, and Poland, risk-based premiums directly translate increasing flood risk into higher premiums for residents in high-risk areas. However, while the increase in flood risk in these regions is substantial, the population exposed to floods there is also large, which makes the rise in risk-based premiums per household less severe. Thus, the highest increases in flood risk in Figure 3 do not necessarily correspond to the most significant increase in premiums. The largest increase in premiums can be seen in Slovenia, Croatia, and the Czech Republic, where a relatively small population resides in floodplains. In countries such as France and Spain, the significant increase in flood risk is spread out equally among the population due to the solidarity system, causing only a slight increase in premiums per household. Finally, higher insurance premiums and a lack of willingness to pay for coverage lead to a decline in flood insurance uptake in regions where it is optional. When insurance penetration rates decrease, fewer households are incentivized to apply risk reduction measures through a premium discount, resulting in lower levels of dry and wet floodproofing measures. Detailed results on the NUTS2 level can be found in Figures A2-A4 in the Appendix.

[2] Whether or by how much a region becomes drier varies across different climate models (GCMs) and with increasing geographical resolution. This implies that flooding can still occur and cause high damages, yet not on the aggregate annual but on a local and sub-annual level.

Figure 4. Macroeconomic implications of flood risk with current insurance market systems relative to a baseline scenario with current flood risk in 2050 for EU regions and the UK; RCP8.5-SSP5 scenario combination. Region acronyms: UKD = United Kingdom; FRA = France; BLU = Belgium, Luxembourg; ESP = Spain; ROU = Romania; NLD = Netherlands; BAL = Baltic States (Estonia, Latvia, Lithuania); GRC = Greece; SEU = southern EU (Croatia, Slovenia); NEE = northeastern EU (Czech Republic, Slovakia); PRT = Portugal; POL = Poland; AUT = Austria; NEU = Northern EU (Denmark, Finland, Sweden); DEU = Germany; SEE = southeastern EU (Hungary, Bulgaria); ITA = Italy; IRL = Ireland.



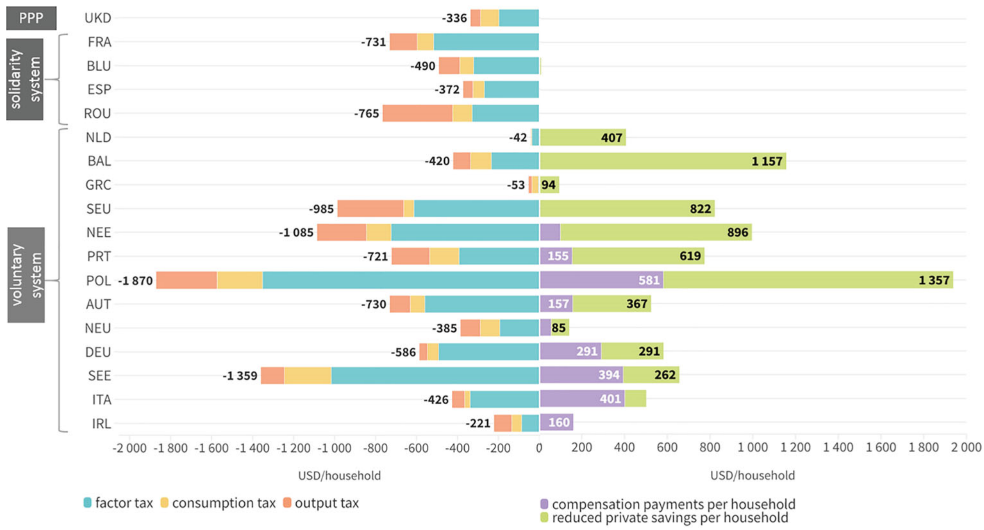
4.1.2. *Economy-wide effects*

Figure 4 presents the macroeconomic effects on GDP, private and public consumption possibilities (quantities), and societal welfare, measured as changes in economy-wide consumption possibilities (quantities). European regions are clustered according to their current insurance market system; within the voluntary system, they are clustered based on the public compensation rates they maintain from low (left) to high (right). A low (high) compensation rate implies that the public sector compensates for a small (large) fraction of uninsured damages. The results are given as a relative deviation to the baseline in 2050.

Flood risk negatively affects all macroeconomic indicators in 2050. Generally, the effects are more significant for consumption quantities and societal welfare than for GDP and are even more pronounced for the public than for private consumption. GDP is less severely affected because the shift from consumption expenditure towards investment for reconstruction is rather GDP neutral. In contrast, welfare focuses on consumption possibilities, which declines due to forced additional investment. While this can restore the previous state, increased investment is balanced by reduced consumption.

In general, the macroeconomic outcomes strongly reflect the patterns of the direct damages as a share of GDP (Figure 3 [C]), with the largest effects observed for the southeastern EU, Poland, Romania, the southern EU, and Portugal. As insurance systems primarily determine how flood risk is shared among public and private actors, our results reflect the fact that the existing insurance market systems do not determine overall cost patterns in terms of relative GDP loss; therefore, differences in insurance market systems

Figure 5. Change in tax income for consumption, factor, output, and trade tax (left) and burden-sharing of uncovered risk (right) expressed in USD per household; reduced private savings borne by the private household and compensation payments borne by the public sector; RCP8.5-SSP5 scenario combination.



do not explain initial differences in economy-wide costs. Hence, in a cross-regional comparison setting, a country's vulnerability and exposure are primarily decisive for relative flood costs. For example, although Romania has a solidarity system, it is nevertheless among the most strongly affected regions. However, for all regions with a solidarity system (France, Belgium and Luxembourg, Spain, and Romania), the impact on private consumption is less pronounced than on GDP. The reason is that risk is spread equally across all households at lower premiums in the solidarity system than in the voluntary system or the PPP.

In contrast to the PPP and the solidarity system, the voluntary system results in substantial uncovered risk. This implies that private households either rely on public compensation payments to cover reconstruction payments or need to finance reconstruction out of their own means by reducing their savings to finance additional expenditures. The extent to which the public sector compensates for uncovered risk differs across regions. According to these compensation shares, Figure 5 (right) shows how the burden is shared between each region's private and public sectors. The additional public compensation payments entail increased pressure on the public budget, especially when other transfers or public expenditures are not cut and no additional public debt is incurred to refinance these compensation payments. Our results show that public consumption is particularly affected in regions with a voluntary system and a high rate of compensation, such as Germany, Italy, Poland, Ireland, and the southeastern EU. The impact on private consumption is larger in regions where no public compensation payments are issued, as is the case in the Netherlands and the Baltic States.

The increasing pressure on public budgets is further intensified by a reduction of public revenue from various sources as a result of indirect feedback effects. This additional pressure is presented in Figure 5 (left) and puts the direct public burden (Figure 5, right) into perspective. The indirect effects of lost tax revenue exceed direct compensation payments in several regions. Net tax revenue decreases in all regions, with a particularly strong effect on the factor tax (e.g. capital and labor). The destruction of capital leads to lower capital availability for production, which results in two effects: first, less capital can be employed in production, implying a smaller tax base (quantity effect); second, capital becomes scarcer and therefore more expensive (price effect). In total, tax revenue from capital decreases, and thus the first effect dominates. As capital and labor are only partially substitutable, labor becomes relatively abundant and its demand decreases, leading to lower wages and hence lower tax revenue from labor. The overall output of the economy declines with the destruction of capital as a production factor. This reduces the tax base for the output tax and thus tax revenue imposed on output. Lower economic activity implies a lower use of intermediate input goods and lower income for the private household. In turn, this reduces consumption and, thereby, the consumption tax revenue for the public budget. When contrasting the decline in public revenue with necessary additional spending for compensation payments in voluntary systems, some regions seem particularly at risk in 2050. These regions include Poland, which incurs a reduction of USD 1,900 in public tax revenue per private household and additional expenditures for compensation payments of USD 600 per private household, as well as the southeastern EU (SEE), where tax revenue declines by USD 1,400 per private household, and compensation payments amount to USD 400 per household. In conclusion, in our modeling framework, lower revenue for the public sector implies that the public agent's expenditures must also decrease, leading to a reduction of public good provision and thus societal welfare.[3]

4.2. Future flood risk after insurance market reforms

4.2.1. Implications for insurance parameters

We assess how a change in insurance systems towards a PPP or a SOL system can enhance the capacity of insurance to cope with climate change. While both systems maintain mandatory insurance purchase requirements to enhance the risk-pooling capacity, such a change induces premiums to rise or fall depending on the initial system.

The PPP system maintains a limited degree of risk cross-subsidization, in which premiums can rise until a certain benchmark is reached. As soon as the benchmark is reached, the excess risk is transferred to low-risk households. For regions that initially have a SOL system, such as France, Romania, Spain, and Belgium (in BLU with Luxembourg), premiums for high-risk areas increase after changing to a PPP. For regions with voluntary insurance coverage with risk-based premiums in their initial system, such as Austria, Germany, Italy, and the Netherlands, premiums decline when changing to a PPP system. As a result of mandatory insurance uptake, the insurance penetration rate rises significantly for these latter regions. Following the higher insurance uptake in the PPP system, more households are subject to the incentive to apply risk-reduction measures, which results in higher household-level risk-reduction.

The SOL system maintains full cross-subsidization of risk, meaning that the premium a household pays is completely independent of the individual flood risk it faces. In contrast to the PPP system, the risk-independent premiums in a SOL system give no signal

[3] Note that this is only true given the modeling choice of not allowing to incur public debts. Parrado et al. (2020) investigate the effects on public budgets allowing for additional debt.

of individual flood risk to households; therefore, they do not provide an incentive for risk reduction. For this reason, a change to a SOL system may reduce premiums and increase coverage, while it may also lead to less household-level risk reduction effort compared to a voluntary or PPP system.

4.2.2. Indirect effects after insurance market reforms

Figure 6 displays the percentage point difference for impacts on GDP, private and public consumption possibilities, and societal welfare between the current insurance arrangements (*reference scenario*) and each of the two *reform scenarios*, a PPP or a SOL system. A positive value represents an improvement over the effect of the current insurance market system, that is, lower flood damages, while a negative value represents a worse outcome compared to the initial situation.

It immediately becomes apparent that there are only marginal differences in GDP outcomes between the three insurance market systems, as they determine the burden for public and private consumption rather than overall GDP effects. The change towards a PPP in regions that maintain either a voluntary or a SOL system in the reference scenario implies weaker impacts on public consumption in all of these regions, as the public sector receives a reinsurance premium from the private household to cover the most extreme portion of the risk. For the same reason, the UK, the only country with a PPP in the reference scenario, is worse off after introducing a SOL system, with a slight decrease in public consumption triggered by the absence of public revenue from the reinsurance premium. The effect is relatively small, however.

For regions that maintain a voluntary system in the initial state, either reform scenario constitutes an improvement for private and public consumption and overall societal welfare. This is largely due to the introduction of mandatory insurance purchase requirements under the proposed insurance market reforms. As a consequence, insurance coverage

Figure 6. Differences in macroeconomic outcomes when changing from the current system to a publicprivate partnership (PPP) or a solidarity market system (SOL), expressed as a percentage point difference from effects with current insurance market systems for EU regions and the UK; RCP8.5-SSP5 scenario combination.

increases, and potential compensation payments to uninsured households by the public agent decrease. This reduces the burden on the public budget. The private household mainly benefits from lower insurance premiums, which reduce the distortion of private consumption. Another relevant factor is expenditures for adaptation measures; in contrast to the SOL system, the PPP reform scenario incentivizes adaptation measures; hence, private consumption is less affected in the SOL system compared to current systems and the PPP. However, while the improvement of private consumption tends to be higher in the SOL system, public consumption is least affected in the PPP. For example, Poland's private and public consumption are less affected by alternative insurance systems than the current one. The strongly affected SEE region also experiences an improvement in private and public consumption by switching to a PPP or a SOL system. We also find that the improvement for private or public consumption varies significantly across regions. In regions with a high compensation rate in the initial state, such as Italy and Germany, but also Poland and the southeastern EU (SEE), an insurance market reform reduces the amount of uncovered risk. This translates into a more potent relief for the public sector than for the private household. In contrast, the alleviating effect of an insurance market reform is more substantial for the private household in regions with low public compensation rates, such as the Netherlands and the Baltic States.

4.2.2.1. Amplification rate. Figure 7 depicts the amplification rate, which indicates the extent to which direct impacts translate into indirect impacts on GDP and societal welfare across all regions and the three insurance market systems. An amplification rate of 1 indicates that the indirect damage, measured as the percentage change of the macroeconomic indicators, equals the direct damage measured as a share of GDP. A rate larger than one means that indirect effects are more significant than direct impacts. For example, a rate of 2 implies that the macroeconomic feedback effects double the direct damages.

We find significant differences across regions. For GDP, the majority of regions lie between an amplification rate of 1 and 2.5. At the upper end are regions with serious direct damages as a share of GDP, such as the southeastern EU (SEE), or regions with extensive direct damages in absolute terms, such as the northeastern EU (NEE). The amplification rates for societal welfare show greater disparities across regions and among insurance market systems. In the reference scenario, regions with serious direct damages (as a share of GDP) tend to have an especially high amplification rate. Poland, for example, can benefit from an insurance market reform by reducing the rate from 4 to around 2.5. Despite not ranking among the most vulnerable regions, Austria and Italy also show high amplification rates of around 3 under voluntary insurance markets, which can be reduced to below 2 with an insurance market reform. In contrast, direct flood damages in the SEU region are amplified by a factor of 2.8, which is in the middle of the field despite its high vulnerability, as demonstrated in Figure 3.

4.3. Economy-wide effects under different climate and socioeconomic scenarios

Finally, we analyze the costs of the different insurance market systems for the EU and the UK in total (regional results are shown in Figure A9 in the Appendix). While adopting the same system in the whole EU is not a realistic scenario, this analysis illustrates the

Figure 7. Amplification rate of direct damages to indirect damages (GDP and societal welfare) with current insurance market systems in the reference scenario (REF), a public-private partnership (PPP), and a solidarity market structure (SOL) for all EU regions and the UK; RCP8.5-SSP5 scenario combination.

relative macroeconomic advantages and disadvantages between systems. In addition, we present the effects on macroeconomic indicators for the chosen combinations of climate and socioeconomic scenarios to discuss modeling uncertainties.[4]

The insurance market reforms have little effect on the GDP impact induced by the flood risk scenario; only a slight advantage is observable for the PPP, when insurance policies incentivize damage prevention through adaptation action (Figure 8). At the private household level, both reform scenarios are superior to current insurance market systems. The main driver of this advantage is that there is no uncovered risk in the two alternative systems (PPP or SOL). In the PPP, however, as a part of the private household, the insurance sector transfers a reinsurance premium to the public sector, reducing its consumption possibilities. In addition, premiums and adaptation expenditures are significantly higher in the PPP than in the SOL. Therefore, in the aggregate, the solidarity structure seems to perform slightly better than the PPP for the private household.

For the public sector, the currently prevailing insurance market systems also induce the highest overall consumption losses, as it is assumed that the compensation payments issued do not cut other transfers but do affect public consumption. However, while both alternative systems have no uncovered risk, public consumption is affected differently. The PPP induces lower costs than the SOL system for two reasons. First, as stated above, private insurers pay a reinsurance premium to the public sector to cover potential excessive damages. This increases disposable income and thus counteracts the effect of direct

[4] Scenarios were combined as follows: SSP1-RCP2.6, SSP1-RCP4.5, SSP2-RCP2.6, SSP2-RCP4.5, SSP2-RCP6.0, SSP3-RCP4.5, SSP5-RCP4.5 and SSP5-RCP8.5. See Table A4 in the Appendix for details on GCM choices for each scenario combination.

Figure 8. Uncertainty ranges (boxplots) across scenario combinations (GCM-RCP-SSP)5 for flood riskinduced damages in 2050 on GDP, private and public consumption, and societal welfare with current insurance market systems in the reference scenario (REF), a public-private partnership (PPP), and a solidarity market structure (SOL) for all EU regions and the UK in total.

flood damages. Second, private households' risk reduction measures reduce flood damages, resulting in lower damages to the economy (which is also mirrored as the smallest GDP loss under PPP).

When considering societal welfare as the combination of public and private performances, the relative advantages of the PPP system over the SOL prevail, with each reform scenario resulting in lower damages than the reference scenario with current insurance market systems. The results in Figure 8 also support the conclusion that, while a variation of emission and socioeconomic scenarios implies that absolute values are (quite) different, the relative effects across insurance systems and indicators remain unaffected: (i) GDP effects remain largely unaffected by the underlying insurance system; (ii) private consumption losses are lower with any insurance market reform compared to the reference scenario, with the SOL scenario being marginally superior to the PPP scenario; (iii) public consumption yields the lowest losses in the PPP system; and (iv) for societal welfare, which reflects the aggregate effect of private and public consumption, the PPP system is slightly advantageous.

5. Discussion

5.1. Discussion of main findings

When assuming that current insurance schemes prevail until 2050, across all socioeconomic and climate scenario combinations, GDP changes by a minimum of 0% for Belgium and Luxembourg and a maximum of −0.5% for the southeastern EU, with private consumption effects ranging from 0% (UK) to −0.5% (southeastern EU) and public consumption from 0% (Spain) to −2.4% (southeastern EU). Societal welfare ranges from 0% (Belgium and Luxembourg) to −1% (southeastern EU). With a change in insurance systems, private consumption losses can be reduced by up to 0.2 percentage points (pp) in the southern EU. Public consumption in the strongly affected SEE region is reduced by up to 0.6 and 0.8 pp for a change towards a solidarity system and a public-private partnership, respectively. Societal welfare losses can be reduced by up to 0.2 pp in several regions, such as the southern and southeastern EU, the Netherlands, the Baltic States, and Portugal.

Although our results point towards desirable features of reforms to cope with climate change, several studies have rightly argued that there is no one-size-fits-all solution for insurance markets (Hochrainer-Stigler & Lorant, 2018; Schwarze et al., 2011; Surminski et al., 2015). While limiting costs for policyholders and maximizing societal coverage against flood risk poses significant challenges (Tesselaar et al., 2020b), these actions may be necessary to reduce potential problems for the public budget and allow for more productive use of financial means. High premiums can discourage households from obtaining insurance coverage when doing so is optional (Roder et al., 2019), partly because individuals often undervalue the actual risk of flooding to their homes (Botzen et al., 2015; Kunreuther & Pauly, 2004). Therefore, insurance uptake can be improved by reducing or limiting the rise in premiums, making coverage mandatory, or including it in general homeowner insurance policies. Moreover, formalized insurance arrangements improve public ex-post compensation arrangements, which many citizens in certain EU countries currently rely on. This is because ex-post disaster relief may depend on political and economic circumstances (Garrett & Sobel, 2003; Pielke & Downton, 2000), creating uncertainty regarding compensation for affected households and complicating budget planning for the government. In line with this reasoning, our findings indicate that a higher degree of risk-sharing and mandatory insurance purchase requirements are beneficial for EU countries compared to a voluntary system. These recommendations are also aligned with suggestions in the literature to move towards a higher degree of risk-sharing among different actors (Hudson et al., 2019; Tesselaar et al., 2020b; Unterberger et al., 2019).

Given the role of public actors in providing disaster aid for uninsured households, the implications of flood risk for public budgets have been a key focus of this study. The private voluntary system poses significant challenges for relatively low-income countries and regions, such as Poland and the southeastern EU. The combination of reduced fiscal space for public finances due to lower tax bases and the increased expenditure for relief payments with higher flood risk intensifies the pressure on public budgets. Gurenko and Zakout (2008) also showed that substantial additional stress may be placed on the fiscal position during extreme events when natural hazards are not accounted for in budget-planning processes and are coupled with weak fiscal conditions. Thus, in line with Hochrainer-Stigler and Lorant (2018), we suggest that risk due to natural disasters should be explicitly incorporated into public budgets and planning processes, and potential partnerships with private actors should be established. Further, an insurance system that entails mandatory purchase requirements decreases the uncovered risk and can therefore alleviate the burden on the public budget and reduce fiscal vulnerability. Further, ex-ante risk management and financing measures can be taken, such as implementing risk prevention, offering state-sponsored insurance to households, or engaging in sovereign risk-financing measures (Cummins & Mahul, 2008).

5.2. Discussion of limitations and suggestions for future research

We now discuss some limitations of the present study and suggest directions for future research. To begin, the insurance systems included in this study are stylized in order to assess the impact of certain significant insurance system differences on macroeconomic indicators. Although the allocation of countries to stylized insurance systems roughly resembles reality, the details of national insurance systems, including the insurance premiums actually charged, may differ from those presented here. For example, we assume fully risk-based premiums in countries with a voluntary insurance system, while in reality, there are obstacles to implementing such a system. These include legislation that prevents insurers from rejecting coverage to households, the application of insufficiently detailed flood risk maps, or the bundling of flood risk with other types of risk, which causes the final premium to diverge from the calculated flood premium (Seifert-Dähnn, 2018). Thus, instead of giving the most accurate representation of the flood insurance market in 2050, we focus on substantiating specific insurance market reforms that may contribute to societal adaptation to increasing flood risk. Furthermore, we do not account for the transaction costs of the insurance market reforms. Thus, we assume a smooth transition from one system to another without incurring any difficulties or friction.

Regarding the order of magnitude of the results, we note that the flood risk and insurance parameters focus on households located in the 1/100-year flood plains in each region, as these are most relevant to the discussion of flood insurance market reforms. However, a large event, such as a 1/500-year flood that also affects areas outside the 1/100-year flood plains, might lead to substantially larger losses than our model results suggest (Aerts et al., 2013; Ward et al., 2017; Winsemius et al., 2016). Although a single large event may cause large, sudden welfare losses due to high compensation payments, there is no reason to believe that extending our scope to include 1/500-year flood plains will significantly alter the conclusions of this study, as flood risk is considered in the expected annual values. However, river systems are geographically or climatically connected natural systems, and a warming climate worsens the preconditions for triggering compound flood events (Bevacqua et al., 2019; Ganguli et al., 2020; Jongman et al., 2014). When multiple events occur simultaneously in several EU regions, these regions also face the damages at the same time. As a consequence, when national funds are insufficient to finance the uncovered risk and countries apply for support from the EU solidarity fund, the pressure on EU funds increases. Hence, the insurance market reforms assessed may also limit future macroeconomic impacts on the EU level, such as the EU solidarity fund.

When mandatory purchase requirements are in place, the affordability of premiums is an important issue in the policy debate on insurance, especially for low-income households. While this is accounted for in the partial equilibrium model, we do not differentiate between different income groups in the general equilibrium model. As lower-income households tend to spend a proportionally larger share of their income on exposed assets such as housing, distributional implications and aspects of social inequality should be explicitly addressed in future research on assessing the macroeconomic effects of flood risk (see, for example, Pauw et al. (2011)).

A final limitation of the present study is that we do not account for the effect insurance and compensation payments have on the speed of recovery. This and further dynamic effects can be better studied in a dynamic setting, such as the impact on capital accumulation through reduced savings in each period. For example, several authors have applied simple growth models (Otto et al., 2023) or dynamic CGE models (e.g. Gertz et al. (2019), Hoffmann and Stephan (2018), and Husby et al. (2016)). In brief, these studies find that better insurance coverage can help speed up recovery in the aftermath of an event and thereby mitigate climate change-induced growth losses. In our context, the macroeconomic impacts in regions with a voluntary system and very low rates of public compensation, such as Greece, the Baltic States, the Netherlands, or the southern EU, are likely underestimated due to the unembodied effect of reduced private savings. However, dynamic modeling requires additional assumptions regarding the development of pathways. Still, future research can examine how such effects influence and potentially reduce overall costs.

6. Conclusion

This study addressed how river flood risk affects a country's or region's economy under different flood insurance systems for the EU countries and the UK. Our novel approach allowed us to make projections of expected annual flood damage under various socioeconomic and climate change scenarios and to incorporate the calculated premiums for different current stylized insurance market systems in a macroeconomic setting. Thus, we examined how flood insurance reforms can limit the impact of flood risk on the overall economy, which, to our knowledge, has not yet been studied. By providing quantitative indicators for the effects of different insurance arrangements on various economic agents, this study contributes to and informs the debate on how to design insurance mechanisms against weather hazards, specifically focusing on riverine flood risk. Therefore, this study offers valuable information for government decision-makers and public and private insurance providers in their planning processes.

The results show that increasing flood risk represents a challenge for the European economies in 2050, and the degree of economy-wide impacts varies according to the underlying insurance market system. While we find that GDP losses are relatively insensitive to the design of insurance arrangements, they do affect consumption and welfare indicators. This is because the negative impacts of flooding on GDP are largely offset by increasing consumption from, for example, the construction sector due to reconstruction activities. Only insurance systems with risk-based premiums can reduce overall flood damages (i.e. via incentivized adaptation measures) and slightly lessen the negative GDP effect. However, we find that an insurance market reform of mainly voluntary systems can reduce the negative impacts on private and public consumption and societal welfare.

In particular, achieving high societal flood insurance coverage through mandatory insurance purchase requirements increases public and private consumption due to reduced ad hoc financing of losses after a flood by both private households and governments. Mandatory flood insurance purchases may be problematic in combination with fully risk-based premiums due to unaffordability issues, which suggests that either a degree of risk-sharing or additional measures, such as subsidies or vouchers for low-income households, may be needed (Kousky & Kunreuther, 2014). Limited risk-based premiums, as proposed in our defined PPP market structure, most effectively combine the stimulation of insurance coverage and risk reduction efforts by households while preserving a degree of solidarity and limiting the unaffordability of insurance. In most regions assessed, changing to a PPP market structure before 2050 is the optimal strategy to limit the decline of private and public consumption and societal welfare due to increased flood risk.

Concerning the pressure on public budgets, we find that future indirect effects from lost tax revenue exceed future expected compensation payments in many regions. Budgetary planning in the context of flood risks should thus take a comprehensive and economy-wide view instead of focusing only on the direct expected annual damages. In conclusion, while no engagement in insurance activities may seem the least expensive option for policymakers, additional expenditures arise when households are not sufficiently insured against damages, and governments are willing to compensate uninsured households to prevent households from moving into poverty. Implementing reforms of flood insurance arrangements, such as a higher degree of risk-sharing, mandatory purchase requirements, and a public reinsurer, can reduce overall macroeconomic costs and the burden on the public budget.

As discussed in the previous section, the present study is subject to limitations, and there is a potential for future research to address these issues. We considered stylized insurance systems to assess the impact of insurance system differences on macroeconomic indicators; however, future research may attempt to represent better real-world insurance systems and account for transaction costs during insurance market reforms. While we focus on flood insurance reforms for 1/100-year flood plains, the study does not consider larger flood events or compound flood events that may affect multiple regions simultaneously. The potential consequences for EU funds, such as the EU solidarity fund, should be further investigated. Another research avenue concerns the distributional implications of flood risk across different insurance market systems. While the affordability of premiums for low-income households has been studied in a partial equilibrium setting with the DIFI model (see Tesselaar et al. (2020b)), this is not explicitly addressed with the general equilibrium model, which in the current setting does not distinguish between different household groups. Finally, the study does not analyze the effect of insurance and compensation payments on the speed of recovery and dynamic effects, which could be studied in a dynamic setting.

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ORCID

Nina Knittel http://orcid.org/0000-0002-0694-3419

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