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Climate-driven flooding widens economic inequalities across EU regions

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With growing consensus on the scale of climate change and its direct impacts on societies and economies, the debate on how direct climate damages cascade through interconnected economic systems eventually leading to profound indirect effects remains open amid limited quantitative evidence. The localised nature of climate risk means that regional economies may face stark differences in how they are impacted by the direct and indirect physical risks. In Europe, the world's fastest warming continent, concentrated local damages spill over asymmetrically into tightly-interconnected regional markets, potentially leading to increased inter-regional inequalities despite the continent's prioritisation of economic unity through its regional cohesion policy. Solid regionalized economy-wide analysis could identify if physical climate risks serve as structural drivers of future regional inequality, offering timely insights for policy interventions to curb exacerbating socio-economic adversities. Here, using an empirical dynamic computable general equilibrium model disaggregated to NUTS2 European regions, we explore a range of regional economic projections from two particularly costly climate-driven hazards: river flooding and sea-level rise. Our methodology captures complex economic feedbacks across granular regions and sectors to estimate both direct and indirect economic repercussions of combined sea-level rise and river flood events by 2100. We find that these climate-induced hazards represent an economically divergent force for the European regions. In contrast to aggregated studies, the resulting regional economic projections reveal wide heterogeneity in combined (direct and indirect) physical risks, with the most affected regions experiencing devastating declines in GDP up to 51% by 2100. Our disaggregated projections capture the effects of two climate-induced hazards with distinct geographical hotspots - coastal and inland - which occur simultaneously though unfold at different rates, enabling a detailed assessment of regional economic inequalities. Low income regions experience by far the highest proportional losses, leading to increases in both between and within-country regional inequality.

In the coming decades, natural disasters are expected to increase in frequency and severity as a result of climate change, posing human, ecological and economic risk[1]. The direct consequences of natural hazards including lives lost, damages to infrastructure, homes and businesses, are localised to exposed regions. Indirect effects emerging via complex economic feedbacks can exacerbate damages in directly affected regions and also spill over to other regions via interconnected markets. Low income regional economies may be particularly exposed to these direct and indirect effects if they have underinvested in protective climate adaptation capital, or exhibit a weakened capacity to absorb climate shocks by reconstructing destroyed capital or reallocate economic activity to unaffected sectors[2]. The economy-wide impacts of climate hazards may therefore amplify physical climate risks and become a driver of regional economic disparities over the remainder of this century.

Researchers and policymakers alike are increasingly interested in understanding the causes and consequences of increasing disparities in the economic development of regions[3]. In the past decades, despite some convergence between high and low income countries, a rise in inter-regional economic inequality has been observed in many parts of the world[4]. The EU treats the reduction of inter-regional disparities as a key priority, spending substantial budget on cohesion funding aimed at reducing spatial inequalities on the continent. Despite significant cohesion funding efforts, findings on their efficacy are mixed[5]. Inter-regional inequality is on the rise in Europe, threatening economic progress, social cohesion, and political stability for the continent[6]. A growing body of global evidence suggests that climate change may compound these trends, thus widening disparities between countries[7,8] and among sub-national regions[9,10]. Yet these reduced-form approaches capture only direct

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physical impacts and cannot trace the indirect economic channels - capital reallocation, trade spillovers, terms-of-trade adjustments - through which damages translate into divergent regional outcomes.

Capturing these indirect economy-wide effects requires advanced computational macroeconomic modelling[11]. Several model types including Integrated Assessment Models[12] and Input-Output models[13] have been extensively applied to evaluating the macroeconomic consequences of climate risk. However, computable general equilibrium (CGE) models stand out among the advanced modelling approaches for climate impact assessment due to features such as price flexibility, input substitution, and non-linearities, thus allowing for assessment of multi-regional system-wide feedbacks and cascading indirect effects of shocks such as climate-driven natural disasters[14]. In CGE assessments of climate hazard impacts, spatially granular monetary estimates of direct damages based on hydrological modelling[15], land cover maps and region-specific depth-damage curves[16] typically enter the model in a bottom-up manner as exogenous shocks. Climate-induced losses exogenously shock the model through several possible channels, including the destruction of capital stock[17–20], productivity declines[21], lost labour productivity[19,20], and forced household expenditures on repairing their homes[17].

Among the various climate-induced hazards, flooding stands out as the most costly, also in Europe. Driven by both sea-level rise (referred to interchangeably as SLR and coastal flooding) and intensified river discharge (river flooding or fluvial flooding), European flooding concerns are particularly acute given that it is the fastest-warming continent and is already experiencing a rapid increase in climate extremes such as heatwaves, droughts and heavy precipitation events[22]. Furthermore, from 1980 to 2024, the EU has already seen around €822 billion in economic losses due to weather and climate-related extremes, with flooding accounting for 47% of damages[23]. Unlike slow-onset climate impacts like SLR, river flooding generates large, sudden and recurring economic shocks that can produce long-lasting structural effects. As shown by[17], even with its slow onset, SLR is projected to induce significant damages and changes in European local economies between now and 2100. Moreover, projected flooding risks are not uniformly distributed: a significant share of Europe's economic activity and population is concentrated in river basins and coastal zones, meaning that disruption in a few vulnerable regions can have outsized direct consequences. Flooding also interacts with existing spatial patterns of economic specialisation, with regions dependent on flood-sensitive sectors such as manufacturing, transport, and tourism facing greater risks of persistent productivity losses and other indirect damages through trade networks. As climate change is expected to increase the frequency and intensity of flood events, these dynamics raise concerns that recurrent shocks may amplify rather than dampen existing regional inequalities.

The economy-wide impacts of several types of climate hazards have been assessed using CGE modelling techniques including SLR[17,19,24,25], river floods[18,20,26,27], and storms[21]. These studies typically model single hazards, with few exceptions including[28] who evaluate multiple climate impacts on public debt in Austria and[29] who jointly evaluate the impacts of SLR and temperature-induced changes in tourism flows on global macro-regions. A second dimension along which the CGE literature varies is spatial granularity: while some studies operate at the national level[28] or across a small number of countries[30], recent contributions have begun to model climate impacts at sub-national resolution for individual countries[20] and for Europe[17,18], demonstrating that coarser aggregations can mask substantial heterogeneity in regional exposure and indirect spillovers. A third dimension - the distributional consequences of climate hazards across regions - remains comparatively underexplored in the CGE literature. Beyond the reduced-form evidence on regional climate inequality noted above[7,9,10], distributional analyses have been extended to within-country inter-household inequality[31–34] and to poverty[35–37]. A complementary strand of structural work - spatial integrated assessment models - has begun to quantify climate-induced spatial inequalities at global scale[38], but these models operate at grid-cell resolution rather than policy-relevant administrative units and do not specifically model flood hazards in a European context. These studies collectively demonstrate the value of CGE and structural methods for climate impact assessment, yet the intersection of multi-hazard modelling, sub-national regional granularity, and explicit regional inequality decomposition remains unaddressed.

The intersection of three features distinguishes our contribution from the prior literature. First, we evaluate two climate-induced hazards, sea-level rise and river flooding, jointly within a single coherent macroeconomic framework, which allows us to identify regions whose exposure is amplified by the simultaneous incidence of both. Existing multi-hazard CGE applications either focus on small numbers of countries[28,30] or use coarser macro-regional aggregations[29]. Second, we operate at the spatial granularity of 234 NUTS2 European regions, which is fine enough to expose the heterogeneity in direct exposure, sectoral composition, and trade linkages that drives indirect economic spillovers across the continent. Multi-region CGE applications do reach sub-national European scale[17,18], but consider only one hazard. Third, we provide an explicit decomposition of the resulting regional inequality into between- and within-country components using a Theil index, allowing us to assess whether climate damages widen gaps between countries or within them. Existing climate-inequality work at regional scale[9,10] relies on reduced-form empirical methods and cannot trace the indirect economic channels - capital reallocation, trade spillovers, terms-of-trade adjustments - through which physical damages translate into divergent regional outcomes. To our knowledge no prior study combines all three. The contribution of our paper is therefore the integration of these elements within a flood-specific, Europe-calibrated framework, allowing us to address a question existing tools were not designed for: whether climate-induced flooding acts as a structural driver of European regional economic divergence.

To analyse the impacts of climate-driven SLR and river flooding on European inter-regional inequality, we use a bottom-up multi-regional CGE model. Specifically, we utilize the EU-EMS CGE model, consisting of 8 sectors and 234 regions in the EU27. EU-EMS has been used for several empirical policy analyses at the European NUTS2 level[17,39]. In our application, the model is shocked by regional direct damage projections generated by different hydro-morphological models of SLR[40] and river flooding[41]. Over the course of our analysis, we assume that levels of protective adaptation capital remain constant. Rather than evaluating the efficacy of any particular adaptation strategy, our approach serves as an evaluation of the potential costs of inaction on climate change[42].

The aim of our research is to evaluate the economy-wide economic losses resulting from SLR and river flood projections for the remainder of this century and their implications for between- and within-country inter-regional inequality in the European Union. To address this goal, we estimate regional changes in GDP per capita resulting from projected climate-driven flooding under 2 °C (SSP2 RCP4.5) and 3 °C (SSP5 RCP8.5) warming scenarios compared to a baseline “business as usual” scenario simulation without warming-induced damages. The use of regional GDP per capita is a conventional metric for assessing inter-regional inequalities due to its high correlation with many relevant societal and economic wellbeing indicators[3].

In the following section, we first report the aggregate, economy-wide impacts of climate-driven SLR and river flooding on the EU, before examining the regional distribution of these economic effects and their implications for EU inter-regional inequality. We then discuss these findings in the context of broader economic challenges facing Europe and current cohesion policy, before offering concluding remarks.

Results

Economy-wide impacts of climate-driven SLR and river flooding

Without further public or private adaptation, economic damages from climate-driven SLR and river flooding are projected to range from €826bn (2°C scenario) to €1.41tn (3°C scenario) by 2100 in the EU. The scale of these losses to the EU economy is in the order of magnitude of losing the economic output of the current Dutch economy (in the low warming scenario) or the current Spanish economy (in a high warming scenario). As shown in the Supplementary Figure S1, both coastal and fluvial flooding drive these losses. Fluvial flooding contributes a larger share earlier in the century with slow-onset SLR increasing its share of damages towards the end of the century.

Since climate-induced damages include both river flooding and SLR losses, the NUTS2 regional economies most negatively affected include both coastal and inland regions. Figure 1 shows the geographic distribution of the total economic damages from both hazards across EU regions. A breakdown of the distribution of economy-wide damages from separately evaluated SLR and river flooding is available in the Supplementary Figure S2.

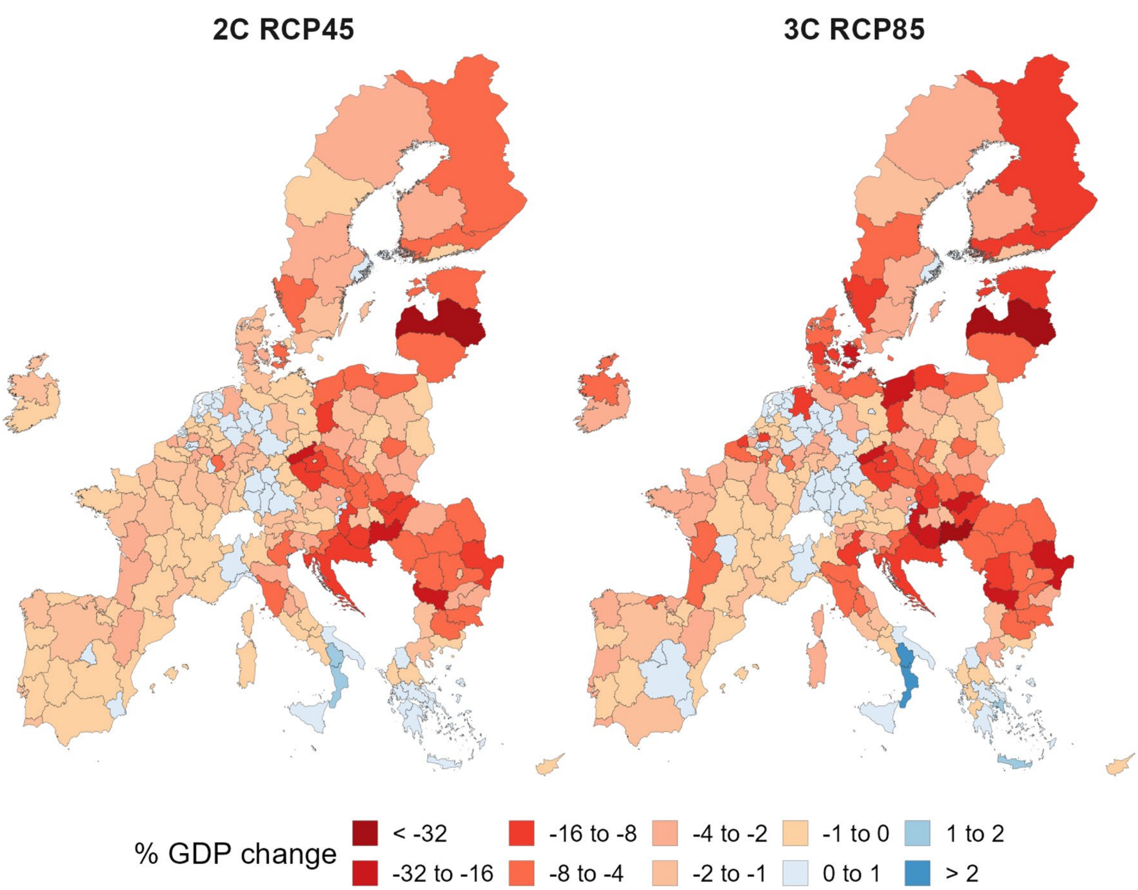

Fig. 1. Distribution of total economic losses (direct and indirect) from the joint consideration of SLR and river flooding and SLR across EU27 NUTS2 regions in 2100 under 2 °C RCP 4.5 (left panel) and 3 °C RCP 8.5 (right panel) warming scenarios. Changes in GDP are the results of empirically-calibrated CGE simulations with a recursive-dynamic setup running at a 5-year time step. SLR and river-flood induced GDP effects are calculated against a no-damage baseline with effects ranging from −51% for LV00 (Latvia) to +3% for ITF5 (Basilicata). Maps produced in R v4.5.1 using packages ggplot2 v4.0.0 (https://ggplot2.tidyverse.org/), sf v1.0.21 (https://r-spatial.github.io/sf/), and eurostat v4.0.0 (https://ropengov.github.io/eurostat/).

Regional GDP losses simulated in the EU-EMS CGE model reflect total economic damages from climate-driven coastal and fluvial flooding, including readjustments made by economic actors in response to the direct effects of flood damages. The damages are calculated against a "business as usual" baseline scenario, where we assume an economic trajectory in which regional GDP grows by 2% per annum and there are no climate-induced damages.

The economic burden of climate-driven flooding is distributed unequally among European regions. Regarding direct flood damage risk, regions differ in terms of hazard severity (that unfolds differently over time for SLR vs river floods), exposure (with different hotspots in coastal vs inland regions), and vulnerability (also affected by the sectoral composition and current wealth of each regional economy). Furthermore, although some regions are not directly affected, they experience positive and negative indirect cascading effects of either of the hazards that hurt other regions. Existing levels of flood adaptation, which are assumed constant over the course of the analysis, play a key role in regional exposure to damages. Regarding indirect impacts calculated within the CGE framework, regions also vary in terms of their economic strength, which contributes to their ability to recover from flood damages, and connectedness via trade networks with other regions/countries, which defines exposure to indirect effects and economic spillovers.

Regional distribution of economic effects

Positive spillovers

While many of Europe's regions are projected to see devastating economic losses as a result of climate-induced damages, Figure 1 also shows several regions where the model produces positive GDP spillovers under the modelled climate scenarios. The three regions with the largest positive spillovers under the 3 °C RCP85 scenario are Basilicata (ITF5, +3.1%), Calabria (ITF6, +2.1%), and Attica (EL30, +1.2%). A sectoral breakdown of gross output for these regions is presented in Figure 2, panel a, with both sea-level rise and river flooding contributing to their economic gains via the regional trade matrix - consistent with their geographical position adjacent to regions experiencing losses from both hazards (Supplementary Materials Figure S2).

Two mechanisms jointly drive these spillovers. The first operates through the model's investment bank, which pools European and rest-of-world savings and allocates them across regions in proportion to relative capital returns. Flood-damaged regions experience large reductions in income and household savings, which reduces their demand for investment goods and lowers the EU-wide price of investment goods. Undamaged regions, whose nominal savings are largely unchanged, can therefore acquire more real capital per euro of savings. The result is a broad-based investment surge: investment grows by 32% in EL30 and by over 100% in ITF5 and ITF6 by 2100 (Supplementary Figure S3), with gains distributed across sectors rather than concentrated in any single industry. The second mechanism explains why construction is the largest gainer in Figure 2, panel a, over and above what the broad investment surge alone would predict: undamaged regions supply reconstruction goods to flood-affected neighbours via interregional trade, generating an additional output boost specific to that sector. Detailed breakdowns of contributions to GDP, consumption, government spending, investment, imports, exports, capital, and labour for the three most positively affected regions are provided in Supplementary Figures S4–S6

Negatively affected regions

At the tail end of the damage distribution are regions experiencing severe levels of economic losses from climate-induced flooding assuming current adaptation levels are maintained. The twenty most negatively affected regions are displayed in Supplementary Table 3. The six worst-affected regions are shown in Figure 2, panel b. Zealand in Denmark (DK02) is projected to lose 23% of its GDP in 2100 under 3 °C RCP85, driven almost entirely by SLR, with private services, transport and logistics, and utilities seeing the most severe losses. The fifth to second most impacted regions are landlocked regions exposed to severe river flooding: West Transdanubia (HU22, −23%), Northwest Bulgaria (BG31, −24%), Northwest Czechia (CZ04, −28%), and Southern Great Plain (HU33, −35%). Output losses are pervasive across sectors in these regions, with only other public services showing modest losses. In HU33 specifically, losses in the construction sector are nullified by forced reconstruction demand on infrastructure and residential capital, which sustains construction output despite the broader decline in regional activity. Post-disaster reconstruction therefore acts as a partial stabiliser for the construction industry, but in the most severely affected regions the stimulus is overwhelmed by economy-wide reductions in income, consumption, and investment that drive output losses across all other sectors.

Beyond the direct destruction of capital, an indirect channel further amplifies these losses. Since capital and labour are complementary in production, capital destruction depresses wages and reduces household income. Repair costs to residential and infrastructure assets drain household savings further, causing investment goods demand to collapse. This contraction in investment goods demand from the most damaged regions is the same mechanism underlying the positive spillovers described in the previous section, operating in reverse: as damaged regions buy fewer investment goods, the global price of investment goods falls, allowing undamaged neighbours to acquire more real capital per euro of their unchanged savings. Detailed breakdowns of contributions to GDP, consumption, government spending, investment, imports, exports, capital, and labour for the six most negatively affected regions are provided in Supplementary Figures S7–S12.

Economically compounding effects

Latvia (LV00) is the most severely impacted region, with exposure to both river flooding and SLR producing a 51% drop in GDP under the 3 °C RCP8.5 scenario. For Latvia we see evidence of economically compounding damages, in which the total damages from the combined hazard scenario exceed the sum of the damages from each hazard simulated separately. These economically compounding effects arise from the interaction of multi-hazard damages with several non-linear features and boundary conditions of the model. We see evidence of both positive and negative compounding in the sectors displayed in Figure 2, panel b. Negative compounding in

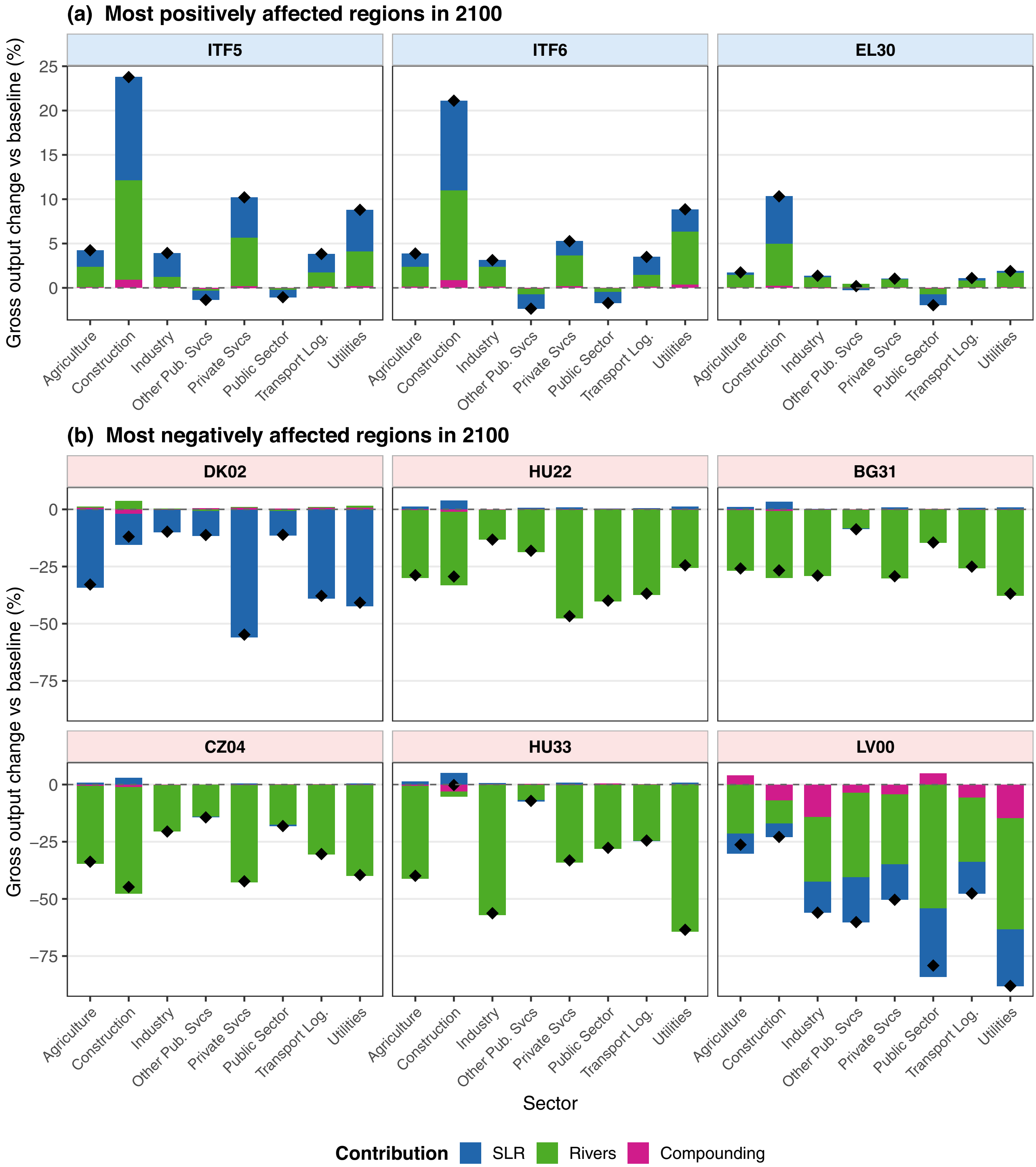

Fig. 2. The figure shows the 3 most positively affected regions according to GDP under the 3 °C RCP85 scenario in panel a and the 6 most negatively impacted regions in panel b. The black diamonds indicate the percentage change in gross output in 2100 versus a business as usual baseline for each economic sector. The stacked bars represent contributions from sea-level rise (blue bars), river flooding (green bars) and compound effects (pink bars). The compound term is calculated as the residual change in gross output in a scenario with both SLR and river flooding compared to the addition of the separately simulated damages from the two hazards.

the gross output of particular sectors can be explained by the removed absorptive capacity of unaffected sectors when multiple hazards occur. In the case of single hazards, economy-wide losses are buffered by the ability of regional economies to shift activity to unaffected sectors. When regions are hit by significant damages from multiple hazards, this ability is lost. Positive compounding effects as seen in agriculture and the public sector for

Latvia (LV00) are a likely artefact of minimum consumption floors imposed by our choice of linear expenditure system that includes subsistence quantities for goods. When damages from the hazards are calculated separately, the sum of sectoral output losses may imply that consumption levels of certain important goods associated with the respective sectors fall below the pre-defined minimum subsistence levels. In the multi-hazard scenario, the minimum consumption levels preserve a certain level of output for the sectors. This mechanically increases the sectoral output to a level above the sum of the separately calculated levels, thus leading to positive compound effects.

Beyond the domestic output side of the economy, Supplementary Figure S12 shows other channels through which compounding effects emerge for Latvia. We see a negative compounding in the terms of trade, as the Latvian economy experiences outsized increases in imports and decreases in exports when both hazards are accounted for simultaneously. These effects emerge as the domestic economy's ability to supply goods and services reaches such a low point that export levels cannot be maintained and imports must be made to meet demand for goods, services, and reconstruction of damages infrastructure. Turning our attention to capital stock and investments, we see some positive compounding, likely driven in the case of capital by a non-negativity boundary condition. In the latter years, Latvia's capital stock becomes almost completely depleted - in fact, towards the end of the century, the sum of the individually calculated shocks implies an impossible negative stock of capital, which is rectified through what appears as positive compounding. Likewise, we see positive compounding in investments. This emerges due to increasing returns to capital investment (i.e. marginal product of capital) as the capital stock gets depleted. As the capital stock gets to very low levels under multi-hazard damages, the benefits to investors of investing in affected sectors now facing large unmet demand begin to increase exponentially, therefore increasing investments relative to what would be implied under the sum of the separate scenarios.

The accumulation of all of the aforementioned economic effects leads to negative compounding effects of SLR and river flooding on the Latvian economy. Aside from Latvia, most regions do not see very large compound effects as demonstrated in Supplementary Figure S13. Latvia appears to be the only region experiencing large compound effects because it is an outlier in terms of the uniquely large levels of projected damages from both SLR and river flooding. This implies that there is a critical level of damages from a region's secondary hazard that leads to significant levels of economically compounding damages.

Impacts of climate-driven flooding on EU inter-regional inequality

Low income regions disproportionately impacted

Our analysis of the extreme ends of the distribution in the previous section illustrates that European regions are unequally impacted by climate-driven flooding on a number of levels. Firstly, regions are differentially exposed to physical damages and have vastly different baseline levels of adaptation. Secondly, negative economic effects for the most vulnerable regions like Latvia are amplified by compound effects that emerge through the interaction of multiple hazards and propagation of economically compounding losses over time. Thirdly, regional inequalities are further widened by capital spillovers benefiting unaffected regions and further harming those exposed to the worst effects of climate change.

The final layer of our analysis requires relating the projected spatial inequalities induced by climate-driven SLR and river flooding on the current distribution of economic development across the continent's regions. From the perspective of regional convergence as a policy goal, it is important to know if the regions facing positive or negative economic effects from climate-driven flooding tend to be poor or rich regions. In principle, depending on the direction of this relationship, climate-driven flooding could be an equalising or divergent force. To answer this question, we group the regions according to their level of economic development and calculate the average economic impact within each group of regions. The results of our analysis are demonstrated in the top panel of Figure 3. We see a stark regressive pattern in how regional economies are impacted by the joint impact of SLR and river flood damages.

Low income regions (those with less than 75% of the EU average GDP per capita) experience by far the most significant losses, reaching 4.5% (3.4%) of GDP in 2100 under the 3 °C (2°C) scenario. Medium income regions (75% to 119% of average) have the next largest damages, averaging 1.8% (1.4%) in the 3 °C (2°C) warming scenario, followed by high income regions (120% to 149% of average) with 1.5% (1%) average losses under the 3 °C (2°C) warming scenario. Very high income regions (more than 150% of EU average GDP per capita) see the lowest relative GDP losses of 0.8% (0.5%) of GDP in the 3 °C (2°C) scenario. Overall, these findings suggest that climate-driven river flooding and SLR together form an economically diverging force for European regions. The economies of lower income regions are disproportionately impacted by the direct and indirect economic impacts of projected flooding between 2025 and 2100.

In the middle and bottom panels of Figure 3 we show how individual hazards - river flooding and SLR - drive disproportional impacts on less developed regional economies. The clearest pattern we see is that river flooding drives the majority of the uneven impacts on low income regions, with low income regions seeing an average cumulative loss in GDP of 4% in 2100 from river flooding alone. This is consistent with our finding that the majority of the top 20 worst affected regions are low income and landlocked (Supplementary Table 3). For river flooding, there is little difference in the losses experienced by economies in the middle of the income distribution, with the medium and high income groups seeing similar impacts. In fact, in the 3 °C scenario the high income group experiences marginally worse GDP losses than the medium income group. Climate-induced river floods create a growing economic rift among European regions, with most of the divergence concentrated in the extremes of the income distribution. In other words, very high income regions are mildly impacted by river flooding, and very low income regions witness large losses to their economic output, leaving them consigned to a trajectory of relative economic decline.

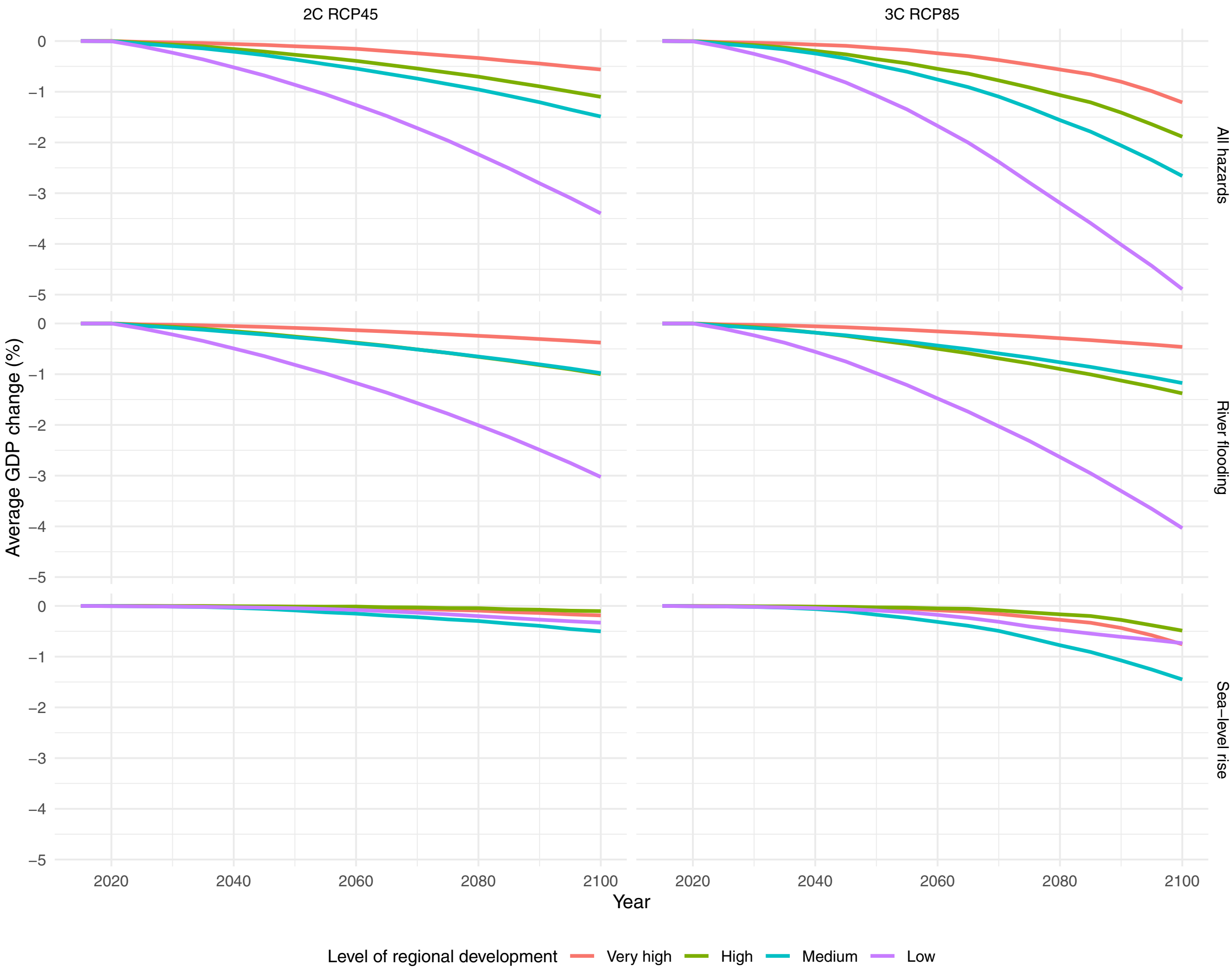

Fig. 3. 234 EU NUTS2 Regions are grouped into the following four levels of regional development based on GDP per capita at current prices in 2023. Very high regions have >150% of EU average GDP per capita, high regions are 120% to 149% of the average, medium regions are 75% to 119% of average, and low regions are below 75% of the average. Within each group, we display the combined effects of river flooding and SLR on GDP per capita compared to the baseline without damages. We compute a simple average of the GDP per capita growth rate for each region rather than an income-weighted average to avoid under-representing small or low income regions.

The economic effects of slow-moving SLR are relatively more evenly distributed among higher and lower income regions, but a regressive pattern remains. Unlike river floods, SLR increases inequality among regions in the middle-upper part of the income distribution. Medium income regions see the highest losses, while high income regions see the lowest losses. There is little effect of SLR on divergence between very high and low income regions.

Evaluating either hazard in isolation would paint a misleading picture of how climate-driven flooding threatens worsening inter-regional economic inequalities in Europe. Considering river flooding alone infers that climate-driven inequalities will only emerge at the top and bottom of the income distribution and that the middle of the distribution is unaffected. Taking SLR in isolation would imply the opposite, that climate-driven inequalities only grow among middle-income regions. However, when we evaluate both hazards simultaneously, a much clearer pattern emerges (Figure 3, top panel). Climate-driven SLR and river flooding together form a growing economic rift that divides European regions, with low income regions most adversely and disproportionally affected by direct and indirect climate-induced damages, followed in order by medium income, high income, and very high income regions.

Between and within country regional inequality increases

To further explore how the economic impacts of climate-driven SLR and river flooding impact inter-regional inequality we calculate a decomposed Theil index as shown in Figure 4. The Theil index of total inequality (shown in green in the figure) measures the spread of regional GDP per capita compared to the average of all regions. As a result of the economy-wide impacts of coastal and fluvial flooding under a 3 °C scenario, total

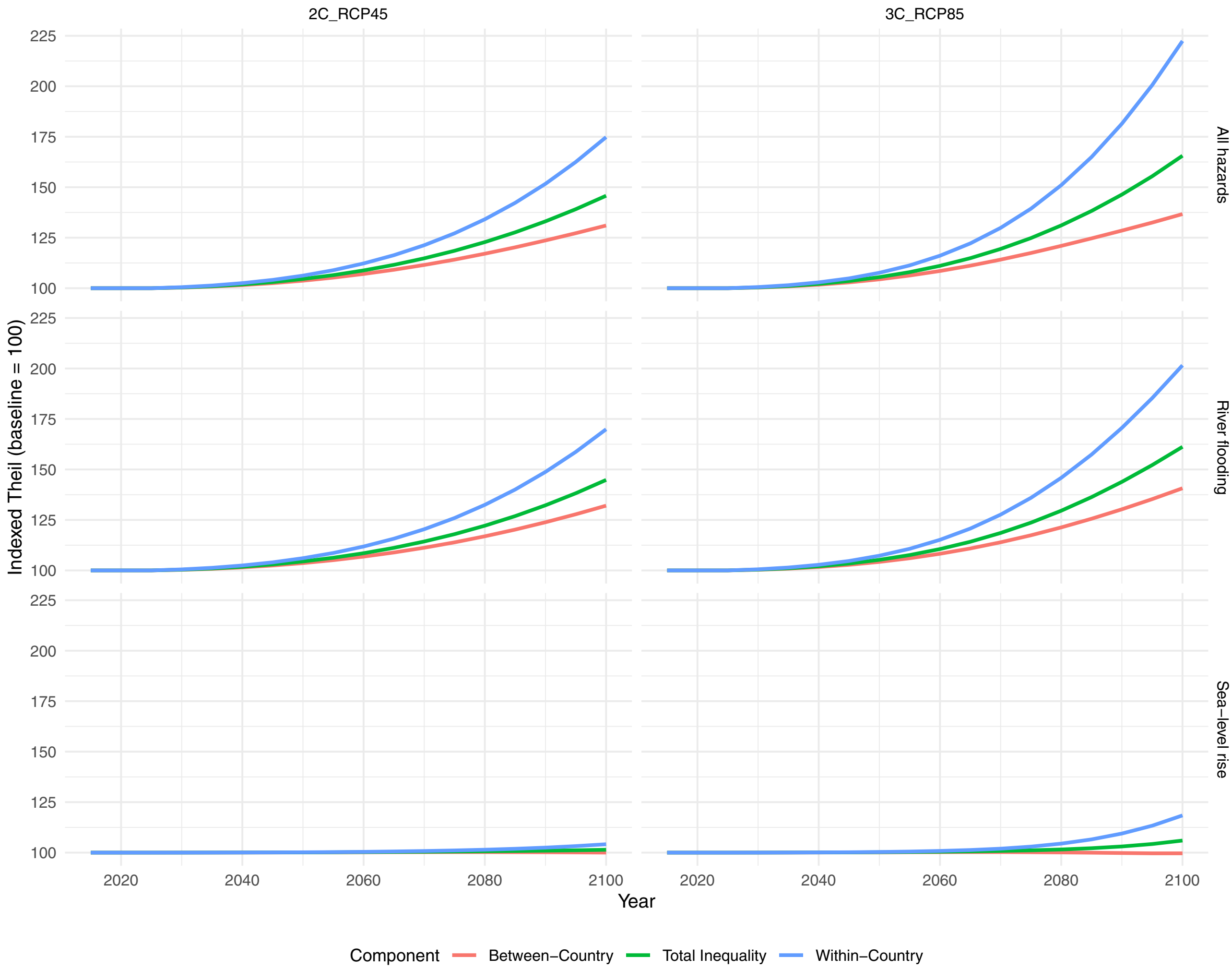

Fig. 4. Indexed Theil decomposition of regional inequality in GDP per capita into between-country, within-country, and total regional inequality components. GDP per capita data at current prices for 2023 (the latest available year) are obtained from Eurostat as a baseline for regional economic inequality. We assume that the 2023 data is broadly representative of regional inequality in 2025. Projected regional changes in GDP per capita from the EU-EMS CGE simulations are applied to the baseline GDP per capita data for each 5-year time step beginning in 2025. The green line shows total inter-regional inequality across 234 EU NUTS2 regions. The red and blue lines respectively show an additive decomposition of total inter-regional inequality into a between-country and within-country component.

Theil inequality between EU regions increases by 65% compared to a no-damages business as usual baseline by end-century. The increase in total regional inequality is primarily driven by river flooding which most severely impacts less developed regions of central and eastern Europe. SLR results in a more modest increase in inter-regional inequality which only emerges by the end of the century. The smaller contribution from SLR suggests a more balanced regional distribution of economic damages from coastal flooding and is also indicative of the more slow-moving nature of SLR.

The Theil index can be additively decomposed into a between-country and within-country component, shown respectively in red and blue in Figure 4. The increase in total regional inequality is primarily driven by the within-country component, i.e. by divergence in GDP per capita of NUTS2 regions within countries. Under the 3 °C scenario, within-country regional inequality increases by more than 120%. Between-country inequality is also projected to increase although to a lesser extent compared to the within-country component of regional inequality. The finding that increased regional inequalities are primarily driven by divergence within countries demonstrates the importance of sub-national assessments in assessing the economic impacts of climate change damages.

Discussion

Our analysis shows that climate-induced flooding acts as a structural driver of European regional economic divergence. Without further adaptation, projected SLR and river flooding together impose economy-wide losses of up to €1.4 trillion on the EU by 2100, but these aggregate figures mark profound regional heterogeneity. The most exposed regions face GDP losses up to 51% while a small number of indirectly benefiting regions see modest gains. The distributional pattern is consistently regressive with low income regions bearing disproportionately large losses relative to their economic base, driven primarily by river flooding concentrated in central and eastern Europe. The Theil decomposition reveals that this translates into a 65% increase in total inter-regional inequality by end-century under the high warming scenario, with within-country divergence growing more than twice as fast as between-country divergence. This last finding is particularly significant: it means that climate-driven flooding is not primarily a story of poor countries diverging from rich ones, but of regional economies within the same country being pulled apart, with implications that national-level analyses and aggregate country-level cohesion metrics would systematically miss.

To examine this, we compute bottom-up estimates of direct and indirect economic losses from both coastal and fluvial flooding using a regionally calibrated CGE model and analysing the distribution of the effects across 234 NUTS2 regions of the EU. This framework allows us to move beyond the aggregate picture in two respects. Firstly, by jointly modelling the hazards at sub-national resolution, we can identify regional hotspots whose exposure is amplified by the simultaneous incidence of both, as well as the positive spillovers that accrue to unaffected neighbouring countries. Secondly, by bringing the resulting regional GDP projections to a decomposed Theil index, we can separate the divergent force of flooding into its within-country and between-country components.

These findings have direct policy relevance to decision-makers at sub-national, national, and European levels. Our estimates of the regional distribution of climate-induced damages provide new insights on the economy-wide implications of multiple hazards, in the absence of further climate adaptation. The worst affected NUTS2 regions face losing up to half of their GDP by the end of the century without further action. The European economy as a whole faces €1.4 trillion in losses by 2100 under a 3 °C warming scenario which becomes an increasingly probable reality as our climate continues to change. Addressing the consequences of climate-driven hazards becomes an increasingly daunting task for European policymakers over the rest of this century. Already facing several other structural economic challenges including ageing population, low competitiveness and innovation[43], the additional economic challenge of climate-driven flooding may threaten the ability of Europe to sustain its strong social welfare systems and high quality of life if appropriate adaptive planning and action against climate disasters is not taken soon.

Our novel findings on the implications of climate-driven SLR and river flooding for European regional divergence should also be of interest to EU policymakers from the perspective of cohesion. Our analysis suggests that climate-driven flooding will be an economically divergent force for the EU, mainly driven by river flooding. Given current adaptation levels, less economically developed regions are significantly more exposed to economic losses from flooding, which places them on a path of relative economic decline. These trends are likely to worsen over the coming decades if more advanced economies are able to invest more in protective capital, leaving less developed economies even further behind in terms of flood exposure. Without ambitious targeting of adaptation investments and recovery funding to low income regions, flooding is projected to lead to an increase in inter-regional inequality in the EU, both between and within countries. This will prove challenging both for EU regional cohesion objectives and for balanced regional development goals of individual member states.

The current 2021-2027 Cohesion Policy offers support for climate disaster resilience by funding climate adaptation projects[44] and for disaster recovery through the RESTORE mechanism. Separately, the EU Solidarity fund has provided post-disaster relief since its incorporation in 2002[45]. However, the amounts dedicated to climate adaptation are thus far relatively small, forming just 3% of the Cohesion Policy budget. Furthermore, EU Solidarity fund payments only cover around 5% of damages. While the RESTORE mechanism is a positive development allowing regions to reallocate Cohesion Policy funds for post-disaster recovery, the latest MFF proposals for the 2028-2034 period signal a reduction in funding for Cohesion Policy in favour of other strategic goals of the EU. With this in mind, it is unclear whether the current suite of EU fiscal policies is sufficient to address the climate-induced increases in inter-regional inequality projected in our analysis. Future research should quantitatively evaluate the efficacy of current policies in light of projected hazards and explore the design of alternative policy designs aimed at ensuring that the EU's least wealthy regions are not trapped in a cycle of climate-induced economic stagnation. Possible avenues for future policy design could include increased emphasis on preventative adaptation investments in regions that are both low income and exposed to high levels of climate-induced damages.

Our analysis identifies economically meaningful compounding damages in the case of Latvia, the single region uniquely exposed to severe direct losses from both sea-level rise and river flooding. This finding is conditional on the structure of the EU-EMS model: the recursive-dynamic closure with five-year market clearing and a single investment bank tends to dissipate compounding effects across regions through capital reallocation. Other macroeconomic modelling traditions are likely to generate stronger compounding dynamics. In particular, stock-flow consistent models with explicit financial sector balance sheets and endogenous credit constraints have been shown to amplify climate shocks through balance-sheet propagation channels that our framework does not capture[46,47]. A useful direction for future work would be a comparative exercise that quantifies regional climate damages across CGE and stock-flow consistent modelling traditions, with a view to identifying the contribution of financial-sector channels to the prevalence and magnitude of multi-hazard compounding.

A set of methodological limitations relate to the underlying hazard inputs themselves: the COACCH coastal damage projections do not explicitly include wave-driven inundation processes (wave setup, runup, and overtopping) and therefore likely understate damages on wave-exposed coastlines such as the Atlantic. Incorporating state-of-the-art wave-resolving coastal hazard models into future versions of the analysis would refine the geographical distribution of SLR-driven economic damages. Furthermore, there are some unavoidable limitations in our approach to harmonisation of flood damage input data across the two hazards. These limitations relate to the absence of a unified depth-damage methodology across the two hazards and different assumptions about the climate trajectory in the second half of the century.

A further limitation of our analysis is that our scope is restricted to two flood hazards, and we do not model protective adaptation investments beyond the baseline level. Omitting hazards such as droughts and heatwaves means we likely understate both the number of regions experiencing compounding damages and the overall extent of climate-induced regional inequality. While the no-further-adaptation assumption provides insights on the costs of inaction[42] that can serve as a benchmark for policymakers, it does not capture how adaptation investment would alter the regional distribution of damages. Additionally, while the analysis contains rich regional and sectoral granularity, there is no heterogeneity in household attributes within regions - an increasingly important dimension for evaluating economic welfare[48]. Some inter-regional inequality studies move beyond GDP per capita by examining how income is distributed among households within regions[49,50], but this is beyond the scope of the current analysis.

Several directions for future work follow from these limitations. Expanding the hazard set to include droughts and heatwaves would be a natural extension: as heat-related hazards are likely concentrated in southern Europe, which is typically less economically developed, their inclusion may amplify the projected increase in inter-regional inequality. Future modelling work could also explore specific adaptation policies, evaluating their efficacy in reducing economy-wide impacts and their implications for the regional divergence demonstrated here. Finally, research unifying the economic dynamics of CGE modelling with granular inter-household data would provide valuable insights into how climate hazards may shape inequality within European regions over the remainder of this century.

Methods

Model: EU-EMS

In our analysis we use the EU-EMS modelling system developed by PBL Netherlands[39]. We choose a spatial computable general equilibrium specification, featuring a regional breakdown of the EU27 into 234 NUTS2 regions. Sectoral disaggregation is available for 63 NACE Rev.2 economic sectors, which we aggregate into 8 sectors for the purpose of our analysis. The sectoral and regional granularity of the model is based on regional trade flows and input-output data[51].

The model is recursive-dynamic, running at a 5-year time step from the calibration year 2015 to 2100. The representative household for each region earns wages in the labour market which they use for consumption and savings. Savings are reallocated as investments across all regions. Household consumption follows a linear expenditure system that specifies minimum consumption requirements of different goods and services depending on how important they are to the household.

Selected features of the model are illustrated in Figure 5. For illustrative purposes, some aspects of the model are not shown, notably the time and spatial dimensions of the model. Figure 5 can be therefore be considered as a basic description of how a single region's economy operates in one time period.

As with the majority of macroeconomic models used for climate impact assessment, EU-EMS does not explicitly model land-use change processes such as urbanisation or shrinking cities. These enter the model dynamics implicitly through household labour mobility, which allows workers to reallocate across regions in response to changing wage conditions. By contrast, structural economic changes such as sectoral transformation and inter-regional labour migration are captured endogenously, as they emerge from market adjustments in response to flood-induced shocks to capital and productivity. Other forms of population relocation - including climate-driven migration and demographic life-cycle relocation - fall outside the scope of CGE analysis and are not modelled. As a result, baseline regional vulnerability reflects the economic structure of the calibration year, and structural shifts that may independently alter exposure over the simulation period, such as long-run urbanisation trends, are not explicitly accounted for.

Data on climate-driven physical damages

Expected annual economic damages from river floods are obtained from[41]. The authors use hydrological modelling of river streamflows in combination with flood maps, population density maps, land cover maps, and country-specific depth damage curves to generate estimates of climate-driven direct economic damages from river flooding for European regions. Estimated damages are provided for a number of climate scenarios corresponding to average global warming levels. We use the 2 °C and 3 °C scenarios although a 1.5°C scenario is also available. The climate scenarios are obtained from the EURO-CORDEX ensemble of climate projections[52]. Crucially, it is assumed in[41] that the climate remains constant after the year in which the EURO-CORDEX ensemble indicates that the respective warming level will be reached. For the 2 °C (3°C) scenario, that global warming level is projected to be reached on average around the year 2042 (2058) and to stay at that level indefinitely.

The COACCH SLR damage estimates are produced by the DIVA modelling framework[53]. DIVA models coastal flood risk by combining sea-level rise scenarios with extreme water level return periods from a hydrodynamic tide-surge reanalysis, to estimate expected annual damages to assets in a stylized coastal floodplain. Tidal variability is implicitly embedded in the damage projections through the extreme-water-level inputs that drive coastal flooding. Wave-driven inundation - wave setup, runup, and overtopping - is not explicitly represented in DIVA's flood module, which is a known limitation of the underlying hazard model and is shared by most large-scale coastal flood damage assessments at continental scale. For wave-exposed coastlines this omission likely produces a downward bias in the coastal damage estimates we feed into EU-EMS.

The SLR estimates from the COACCH project are provided as a full set of SSP-RCP emissions combinations. To ensure consistency with the average warming scenarios provided in the river floods data, we select the RCP-SSP combinations that most closely match the respective warming scenario. Keeping in mind that the river flood

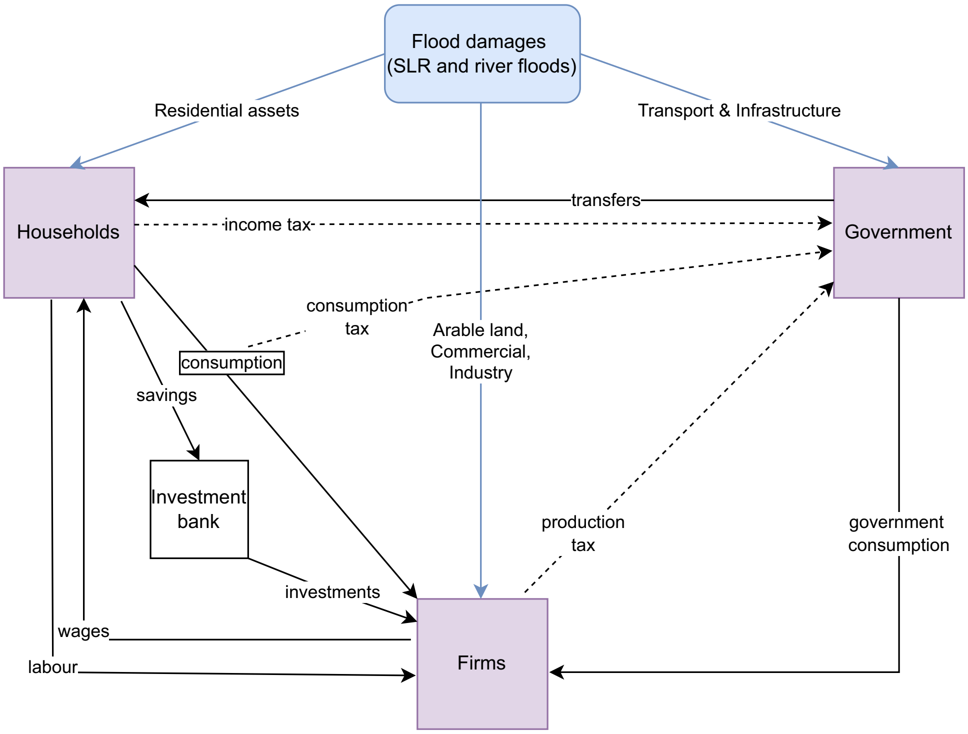

Fig. 5. Selected features of baseline EU-EMS CGE model. Model agents are shown in purple boxes, selected baseline model features shown by black arrows, direct climate damage channels shown by blue arrows.

Hazard	Data source	Medium warming scenario	High warming scenario
River floods	Dottori et al. (2023)	2 °C	3 °C
Sea-level rise	COACCH (Lincke et al. 2021)	SSP2–RCP4.5	SSP5–RCP8.5

Table 1. Overview of climate scenarios used for river flooding and sea-level rise.

projections hold the 2 °C and 3 °C warming levels constant once they have reached that level around mid-century and the SSP-RCP combinations are full climate projections until 2100, the scenario matches shown in Table 1 are imperfect but are the most compatible combinations.

Any assessment of the climate impacts, and especially a multi-step analysis of the economic costs of climate inaction[42] inevitably involves a fusion of data from different imperfectly aligned sources. In our case, the river-flood damages from[41] and the SLR damages from the COACCH project[53] originate from different modelling chains and use different depth-damage methodologies. Dottori et al. combine hydrological streamflow modelling, land-cover maps, and country-specific depth-damage functions from[16] to produce expected annual damages at NUTS2 level. COACCH uses the DIVA modelling framework, which represents extreme coastal water levels (mean sea-level rise combined with tides and storm surge return levels) and applies DIVA's internal depth-damage functions to coastal land-use exposure at the level of coastal segments. As described in further detail below, we harmonise the resulting damage estimates along two dimensions before passing them into EU-EMS to assess the corresponding indirect damages.

How climate damages enter the model

In order to understand how direct damages from climate-induced flooding cascade through interconnected regional economies, it is important to first understand some spatial characteristics of the affected regions. For instance, the economy-wide implications of a flooding event in a services-oriented region will be profoundly different to those of an agricultural or industrial dominated region. To capture this heterogeneity in sectoral impact channels, we disaggregate direct damages according to how historical flooding events have damaged different asset classes. We use data on direct losses to five asset types (residential, commercial, industrial, transport and infrastructure, arable land) due to floods (coastal, fluvial and pluvial) from the ESPON-TITAN project[54]. These estimated losses were obtained by overlaying European depth-damage functions for the five asset types[16]. From this, we extract a damage distribution matrix for each historical event describing how the damages were distributed across asset types. Where possible, we apply the historical asset-based distribution of damages in the same NUTS2 regions to transform the regional projected direct damages from flooding into asset-specific estimates. For specific regions without historical damages from any of the floods, we use national averages.

This approach was developed for the analysis of economy-wide impacts of SLR[17] and we now extend it to also apply to losses from fluvial flooding. We disaggregate the projected regional damages from both hazards into the same five asset classes, before being passed as exogenous shocks to the appropriate model sectors using the mapping shown in Table 2. This downstream harmonisation ensures that the two hazards enter EU-EMS through a common asset-class taxonomy regardless of differences in their upstream methodologies.

Direct economic damages from flooding consist of damages to business capital, residential housing and transport infrastructure. Damages to business capital are simulated in the model by reducing the capital stock of the respective sector. Since there is no stock of housing in the model, damages to housing are treated as forced consumption of housing construction which effectively forces households to repair damages to their homes. Similarly, damages to transport infrastructure are assumed to be immediately repaired by the government. For both households and government, the forced repairing of homes and infrastructure induces indirect economic effects due to the diversion of resources from other forms of consumption and government spending which would otherwise be optimal in the absence of flooding.

Flood damages induce several indirect effects which flow through the economy. The destruction of firm capital stock leads to many of these effects. For example, since capital and labour are complementary with respect to output, wages decline in sectors whose capital is affected by damages, thus reducing household income. Furthermore, capital reallocation effects occur between sectors and regions. Damages to households which are operationalised by forcing them to finance repairs to their homes by reducing savings and other forms of consumption also ripple through the demand side of the economy. For illustration, Figure 6 outlines selected indirect channels that are propagated by direct flood shocks to the economy.

Regional inequality analysis

NUTS2 regions are grouped into four levels of economic development based on GDP per capita in 2023. Very high development regions have GDP per capita greater than 150% of the EU average, high development regions have between 120% and 149% of the average, medium regions have GDP per capita between 75% and 119% of the average, and low development regions have GDP per capita below 75% of the average. These groupings follow the approach of[6] and the GDP per capita data is from EUROSTAT[55]. The EUROSTAT data are measured at current prices in Euro per inhabitant and are based on the 2023 NUTS2 classification. For consistency with the geographic unit of the EU-EMS model, the data are converted to the 2010 NUTS2 classification with the Joint Research Centre NUTS converter tool using covariate build up area[56].

To match the 2023 GDP per capita to the CGE model's 5 year time step, we assume that the distribution of GDP per capita across regions in 2023 is representative of the distribution in 2025. From 2025 onwards, we apply the GDP growth projections from the CGE simulations to the GDP per capita baseline. Since there are no differences in how demographics evolve between baseline and climate impact scenarios, gross GDP changes simulated in the model with respect to the baseline also implicitly represent GDP per capita changes.

Theil decomposition of regional GDP per capita

We use a Theil decomposition to evaluate the impacts of climate-driven coastal and fluvial flooding on regional inequality[57].

Let $i = 1, \ldots, N$ index regions and $c = 1, \ldots, C$ index countries. Let y_{ic} denote GDP per capita in region i belonging to country c.

Define the overall mean GDP per capita as

$$\mu = \frac{1}{N} \sum_{c=1}^{C} \sum_{i \in c} y_{ic}.$$

The Theil-T index of regional inequality is given by

Asset	Treatment	Sector	NACE codes
Arable land	Firm capital depleted	Agriculture	A01–03
Commercial	Firm capital depleted	Construction	F
		Private Services	I, J58–63, K64–66, L68B, M69–75, N77–82, S94–96
		Public Sector	O84
		Other Public Services	P85, Q86–88, R90–93
		Transport and Logistics	G45–46, H49–53
Industry	Firm capital depleted	Industry	B, C10–33
Transport and Infrastructure	Government financed repairs	Utilities	D35, D36–39
		–	–
Residential	Household financed repairs	–	–

Table 2. Asset classes to sectors mapping.

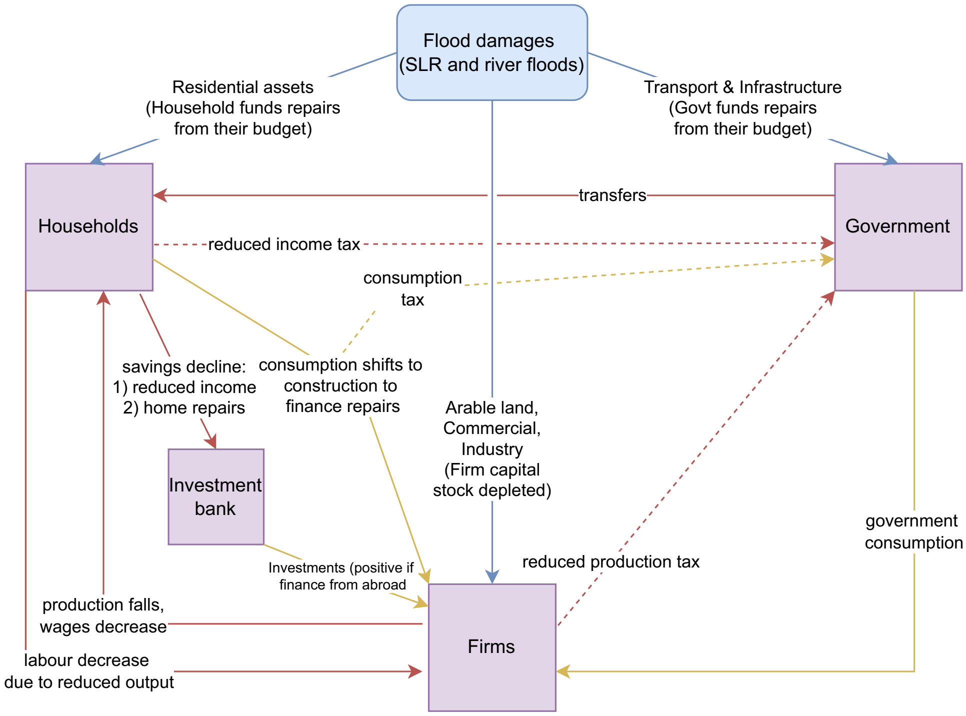

Fig. 6. Selected direct (blue arrows) and indirect (red/orange arrows) channels through which flooding flow through the economy in the EU-EMS CGE model.

$$T = \frac{1}{N} \sum_{c=1}^{C} \sum_{i \in c} \left(\frac{y_{ic}}{\mu} \right) \ln \left(\frac{y_{ic}}{\mu} \right).$$

This index admits an exact additive decomposition into a *between-country* and a *within-country* component.

Between-country inequality
Let

$$\mu_c = \frac{1}{n_c} \sum_{i \in c} y_{ic}$$

denote the mean GDP per capita of country *c*, where n_c is the number of regions in country *c* and $\sum_c n_c = N$.
The between-country component is defined as

$$T^{\text{between}} = \sum_{c=1}^{C} \frac{n_c}{N} \left(\frac{\mu_c}{\mu} \right) \ln \left(\frac{\mu_c}{\mu} \right).$$

This term measures the inequality that would prevail if all regions within a country earned exactly the country mean income.

Within-country inequality
The within-country component captures inequality arising from dispersion *within* countries. For each country *c*, define the country-specific Theil index as

$$T_c = \frac{1}{n_c} \sum_{i \in c} \left(\frac{y_{ic}}{\mu_c} \right) \ln \left(\frac{y_{ic}}{\mu_c} \right).$$

The aggregate within-country inequality is then given by

$$T^{\text{within}} = \sum_{c=1}^{C} \frac{n_c}{N} T_c.$$

Additive decomposition
The total Theil index can therefore be written as

$$T = T^{\text{between}} + T^{\text{within}}.$$

This additive property allows changes in regional inequality to be decomposed into contributions arising from cross-country divergence and from changes in within-country regional disparities.

Data availability
The datasets generated and/or analysed during the current study are available in the Zenodo repository, https://doi.org/10.5281/zenodo.18480626

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Author contributions
S.M.D performed the computational model runs, analysed the results, produced the visualisations and drafted the manuscript. T.C conceived the research design, revised the CGE model, devised the methodology for implementing damages from multiple climate hazards, contributed in analysing the results, and edited the manuscript. O.I developed the original regional CGE model, provided modelling support for the simulations, prepared the input data, and contributed in drafting the manuscript. T.F conceived the research design, helped contextualising the results and drafted the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
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