Grant agreement no. 776479

COACCH

CO-designing the Assessment of Climate CHange costs

H2020-SC5-2016-2017/H2020-SC5-2017-OneStageB

D4.3 Macroeconomic assessment of policy effectiveness

Work Package:	4
Due date of deliverable:	M 38 (APR/2021)
Actual submission date:	31/JUL/2021
Start date of project:	01/MAR/2018
Duration:	36 months
Lead beneficiary for this deliverable:	Netherlands Environmental Assessment Agency (PBL)
Contributors:	Kaj-Ivar van der Wijst (PBL), Francesco Bosello (CMCC), Shouro Dasgupta (CMCC), Ramiro Parrado (CMCC), Gabriele Standardi (CMCC), Laurent Drouet (CMCC), Johannes Emmerling (CMCC), Andries Hof (PBL), Marian Leimbach (PIK), Franziska Piontek (PIK), Detlef van Vuuren (PBL), Predrag Ignjacevic (VU), Onno Kuik (VU), Wouter Botzen (VU), Eva Preinfalk (Uni Graz), Nina Knittel (Uni Graz), Birgit Bednar-Friedl (Uni Graz), Elisa Sainz de Murieta (BC3), Max Tesselaar (VU), Gabriel Bachner (Uni Graz)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	
CI	Classified, as referred to in Commission Decision 2001/844/EC	

Disclaimer

The content of this deliverable does not reflect the official opinion of the European Union. Responsibility for the information and views expressed herein lies entirely with the author(s).

Suggested citation

Van der Wijst, K., Bosello, F., Ignjacevic, P., Preinfalk, E, et al. (2021). D4.3 Macroeconomic assessment of policy effectiveness. Deliverable of the H2020 COACCH project.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Table of contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Version log

Version	Date	Released by	Nature of Change
1.1	28/JUL/2021	PBL	First Draft
1.2	29/JUL/2021	VU	First review
1.3	30/JUL/2021	CMCC	Final version

Deliverable Summary

This deliverable is composed of four chapters: first, new damage functions are created using biophysical and economical impacts from previous COACCH work. Second, these functions are used in Integrated Assessment Models to evaluate the macro-economic impacts and provide cost-benefit optimal policy recommendations. Third, the damage functions are applied using a higher spatial detail to Europe to perform hotspot analysis on the NUTS2 and city-level. Finally, not only the climate damages are assessed: also the macro-economic impacts of national adaptation strategies are assessed.

Chapter 1: Creation of the new damage functions

This section translates the information from the COACCH WP2 (sectoral biophysical impacts) and WP3 (tipping points) into economic damage functions using a Computable General Equilibrium (CGE) model. This results in new reduced-form climate change damage functions and provides a significant improvement from current literature in data transparency, regional granularity and explicit uncertainty representation. In fact, we create harmonised damage functions for 14 macro-regions covering the globe and at the NUTS2-level for Europe. Given the fundamentally different timescale of sea-level rise damages from other climate change damages, we split the damages in two damage functions: one depending on sea-level rise, one depending on global mean temperature increase. Finally, we cover the full uncertainty range from the input data by providing the damage functions at different damage quantiles, from low to high estimates.

Chapter 2: Macroeconomic assessment and cost-benefit analysis

The new COACCH damage function estimates capture different kinds of uncertainties, both with regard to physical impacts and the effects of these on the economy. In this chapter, we apply these state-of-the-art damage functions in three Integrated Assessment Models, which differ in complexity. In a first experiment, we calculate the macro-economic effects of the damages given a fixed temperature path, using the full uncertainty range of the damage functions. We show how much of total GDP loss is due to sea-level rise, other direct damages, and indirect damages from accumulating GDP impacts. In the second experiment, we perform a full cost-benefit analysis using these models to calculate the optimal end-of-century temperature and associated

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

emission pathways, with their respective regional damage and policy costs. With medium damages, the optimal temperature is in line with the 2°C target from the Paris Agreement. When assuming the high end of the damage function, optimal temperatures are in line with a 1.5°C goal. Moreover, the uncertainty in the damage function is more important than the choice of discount rate. Finally, models of different complexities lead to similar results in optimal temperature outcome.

Chapter 3: Local-scale climate damage functions for Europe
In this section, we explore climate impact estimates in Europe using the recently developed NUTS-2-level damage functions. The EU-wide estimates are comparable in magnitude to the previously used set of damage functions (RICE model), but local differences emerge due to the higher spatial resolution of the functions and the possibility of accounting for the positive impacts of climate change in certain regions.

Absolute impacts are projected to be the highest in most developed countries in Europe, such as Germany, France, Italy and the UK. This storyline is matched by the high impacts expected to occur in most populated cities such as Paris, Cologne, London and Milan, all of which could experience total discounted impacts exceeding €1 trillion in the 21st century. All in all, the new damage estimates contribute to the increasing precision of the local scale results. The uncertainty range of the functions (low, median and high) contributes to an already existing set of uncertainties involving climate and socioeconomic developments.

Chapter 4: Macroeconomic assessment of national adaptation strategies
Adaptation is a well-established policy area in the three countries under investigation (Austria, Spain & the Netherlands). Nevertheless, there are distinct differences with respect to the institutionalisation of adaptation action and types of measures implemented across impact categories, demonstrating that adaptation does not follow a one-size-fits-all approach. While we find that there is a prevalence of structural measures in flood risk management in all three countries, there is a strong role for ecosystem-based measures in agriculture and forestry in the Austrian adaptation strategy. In contrast, adaptation in the Spanish agricultural and forestry sector is capital intensive, focusing on measures to face more frequent droughts and heat spells. With respect to the public funding of adaptation actions, the countries under investigation pursue different approaches. The implementation of the Austrian and Spanish adaptation strategy follows the concept of adaptation mainstreaming with measures funded out of the ministry's general budget and no dedicated budget foreseen. On the contrary, a dedicated annual budget is earmarked for the realisation of high flood protection levels pursued under the Dutch Delta programme.

The macroeconomic assessment of national adaptation strategies shows that adaptation is effective in reducing the negative sectoral and economy-wide effects of a range of climate impacts. The analysis of flood risk management and adaptation in the agricultural and forestry sectors shows that net-benefits of adaptation prevail, even for lower bound effectiveness assumptions of adaptation. These economy-wide benefits of

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

adaptation originate from an alleviation of climate impacts on directly affected sectors, such as the Austrian forestry or Spanish agricultural sector, as well as from the increased level of public demand for services and construction under the Dutch Delta programme.

With regard to the public budget, we find that adaptation reduces the negative effects of climate impacts on the revenue side of public budgets, due to a higher level of economic activity compared to a scenario without adaptation. However, adaptation actions are financed out of the public budget, such that financial resources have to be diverted away from other government expenditures. Yet, we find that the benefits of adaptation on the revenue side of the public budget more than offset the direct costs of adaptation in Austria and Spain, and for the case of a 100-year flood event in the Netherlands. Therefore, higher levels of government consumption and public transfers to private households can be attained when adaptation action is undertaken. Exemplified by a 100-year flood in the Netherlands, we see that large-scale projects such as the comprehensively planned Dutch Delta program are successful in reducing the economy-wide and budgetary impacts of extreme events. However, the uncertainty concerning the occurrence and magnitude of low-probability high-impact events and the considerable costs of effective adaptation might limit government action, especially when adaptive capacities are low and scarce public means are directed towards other topics on the political agenda.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

1. Revisiting the concept of damage functions

Authors:

Francesco Bosello*[3], Shouro Dasgupta[1], Ramiro Parrado[1], Gabriele Standardi[1], Kaj-Ivar van der Wijst[2,3]

[1] RFF-CMCC European Institute on Economics and the Environment (EIEE), Milan, Italy
[2] PBL Netherlands Environmental Assessment Agency, The Netherlands
[3] Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands
[*] Corresponding author

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

1.1. Introduction

The concept of reduced-form climate change damage function (CCDF), inextricably linked to the very nature of Integrated Assessment Models (IAMs), compacts and attracts all the challenges of and critiques to the process of social and economic assessment of climate change damages.

In a nutshell a CCDF translates a temperature increase into economic (GDP, income, welfare) losses for countries or regions. The relation between climate change and economic losses is summarized by a relatively simple exponential (usually quadratic) function and its few parameters.

The parameterization of these functions is derived from literature surveys, direct econometric estimations or semi quantitative approaches based on expert opinions. Often, economic losses are calculated for several different “impact areas” (e.g.: sea-level rise, other market sectors, health, non-market amenity of the environment, human settlements and ecosystem and catastrophic events) and then aggregated to determine a total loss as a percent of GDP for a given region. Temporal dynamics in damages are then originated by interpolating different temperature-GDP loss “couplets” along the CCDF chosen (Bosello 2014).

The Nordhaus’s DICE-RICE model family (Nordhaus, 1991; Nordhaus and Yang 1996; Nordhaus and Boyer 2000) opened the way to this approach that consolidated in the literature. The WITCH, REMIND, FAIR/IMAGE, CLIMRISK models used in the COACCH project, are also sharing this methodology for impact assessment.

The appeal of reduced-form CCDFs is immediate: their “simplicity” allows for a straightforward and full integration of the climatic and the economic systems at the basis of “hard linked” IAMs. It also enables the study of complex dynamic decision processes like, for instance, optimal mitigation policies, interaction across mitigation and adaptation, strategic behavior in international climate change agreements and their effects on mitigation effort, etc. (Bosello 2014).

They give rise to many criticisms as well. Some critiques are not specific to CCDFs, but relate to the underlying science. This anyway impacts the reliability of their results. According to Pindyk (2017, 2019) for instance, there is still a too weak empirical foundation to derive useful CCDFs and a better approach would be to use semi-quantitative techniques based on expert opinions. It has also been noted the difficulty to capture in a damage function many social facts like the role of institutions, conflicts, disruption of knowledge, learning and social capital potentially triggered by climate change (Anthoff and Tol, 2013; Stern, 2013). Some authors pointed to the complexity to include risk, irreversibility and catastrophic events (Weitzman, 2007, 2008, 2009, 2010; Ackerman and Stanton 2012).

A limitation that is peculiar of CCDFs is the “aggregated nature” where geographical and impact specificities, and endogenous market feedback are lost.

This section responds to COACCH objectives to translate the information from WP2 and WP3[1]: “into economic damage functions using the CGE model ICES to estimate the GDP losses associated with biophysical and physical impacts or using reduced-form functions from

[1] COACCH WP3 deals with tipping points. To account for extreme events and social economic tipping points we developed in this section an uncertainty analysis that considers the more extreme outcomes of the economic impact distribution. Catastrophic events are not considered, however very high losses that are potentially attributed for instance to extreme sea-level rise or other types of physical impacts are part of the CCDF estimation process.

*This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

econometric analysis .[2] The analysis will consider (1) sectoral impacts separately, (2) the uncertainty around the estimates, (3) different functional forms for the impact-temperature-response….".

1.2. The data base for the computation

COACCH D2.7 (Bosello et al. 2020) reports the economic impacts expressed as changes in GDP in the nine different combinations of selected social economic (SSPs) and representative concentration pathways (RCPs). To fully characterize the uncertainty space, macroeconomic costs are specified for a low, a medium and a high impact case. The range is obtained using as input to the macroeconomic model, for each impact, in each year, in each region, the highest and the lowest value produced by the sectoral impact assessment exercises. These, on their turn, depend mostly upon the different climate models used to perturb the sectoral impact model. Given its relevance in a regional (sub national) context as examined, also two alternative specifications of investment mobility across EU areas, "high" and "low" are considered. This is particularly important to test the robustness of results concerning impacts affecting capital stock and growth dynamics in the model, like sea-level rise.
Figure 1.1 offers a synthetic overview of the world results plotting GDP losses when the D2.7 impacts are implemented jointly, against the corresponding temperature increase characterizing the RCP considered, from 2020 to 2070. Positive values are damages while negative ones are benefits. The left panel reports all simulations including also an "indicative" comparison with the world damages extracted from Tol (2018) literature analysis. The right panel focuses on GDP damages in the two "extremes" of the RCP scenarios: RCP2.6 and RCP8.5 in a narrower range for temperature increase range.
At a first inspection it seems that the damages estimated in the COACCH project are higher than those available from the previous literature. This seems to confirm an ongoing trend of a progressive upward trend in damage estimates (Bosello and Parrado 2020). Although it is worth mentioning that this comparison is purely demonstrative as there are several elements that need to be accounted for to allow a fully consistent comparison. Firstly, it would be important to check which impact categories the different aggregate figures consider, secondly the assumption on behavioural parameters like equity weighting and discounting. The CGE outcomes from D2.7, in fact, do not discount and do not weight macro-regional utility. Finally, some check on inflation rates to compare results from studies using the same currency, but different reference year, would be needed (Tol, 2021).
All this said, for a 2.5°C warming COACCH macroeconomic estimates point to a loss between 2.7 and 12.4 of world GDP that resonates recent econometric estimates e.g., by Kahn et al (2019). It is also interesting to note, particularly evident in the right panel,

[2] The task also asked to derive input-specific physical and biophysical damage functions combining the direct impacts from sectoral models. We addressed this objective reporting direct damages and physical damages in the open access database results repository of the COACCH project. The information provided there will enable the estimation of damage functions. This deliverable addresses the building of economic CCDF needed for the subsequent analysis conducted in COACCH WP4.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

the persistence of the climate damages on the economy. In RCP2.6 even when temperature increase is stabilised, damages keep on increasing. This means that there are inertias in some damage originating processes (like for instance sea-level rise), but also in the economic system (the process of capital accumulation) that induce damages to persist (for more detail see Bosello et al. 2020).

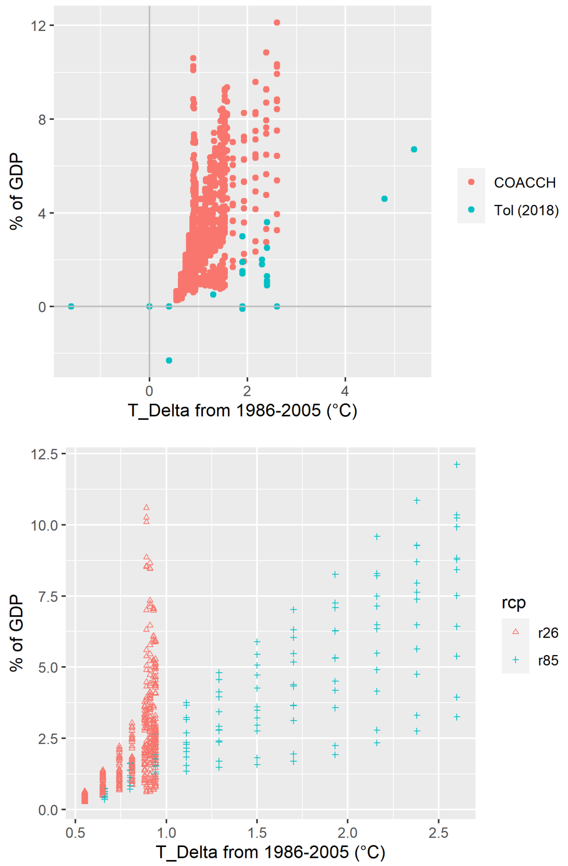


Figure 1.1: World GDP damages as a function of temperature change.

Similar plots (and data) are available for the 156 regions of the ICES model. The attributes of the macroeconomic damage data set originated by COACCH D2.7 are reported in **Table 1**.

Table 1: Overview of the COACCH macroeconomic damages dataset

Data	Description
Damages	Percentage change of GDP with respect to baseline
time frame	2020-2070 in 5-year time steps (11 observations per simulation)
Scenarios	9 SSP/RCP combinations
Uncertainty on impacts from climate change/impact models	"low, medium, high" impact levels as expressed by the impact models
Uncertainty on economic adjustments	"low" and "high" investment mobility in the EU
sources for impacts on agriculture	2 crop models combined with the rest of impacts (EPIC, LPjML)
Number of observations (per region)	1188[3]

[3] In estimating reduced form CCDFs the inertias depicted in Figure 1.1 may introduce biases. In other words, impacts can become larger only because time is passing and not because there are higher hazards impacting economic systems. This can imply a sort of "double counting" when CCDF are used in dynamic optimization models where growth effects are (again) considered. To avoid this potential

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

These are the basis for the estimation for COACCH reduced-form CCDFs.

1.3. CCDF estimation methodology

The first step for estimating a reduced-form CCDF is to shift from a reference system that reports damages along time, although in relation to different RCPS (as in Bosello et al. (2020)), towards one where damages are expressed as a function of "physical" variables.

Starting from the information originated in D2.7, we disentangled two datasets to estimate two different types of damage functions. The first specific to sea-level rise (SLR); the second to the remaining climate change damages.[4] In the first function, damages depend upon cm of sea-level increase, in the second upon temperature increase.

This choice proved to be the more appropriate to respond to the task goal to account for: "sectoral impacts separately". Indeed, Bosello et al. (2020) demonstrated that the sea-level rise component without incremental adaptation is the largest contributor to final macroeconomic losses, and to the evolution of damage trends, therefore the more relevant to "isolate". In addition, this is in line with what is done in other IAM's. For instance, Nordhaus (2010) divides damages into those depending on SLR and those on the remaining sources.

Sea-level rise damages have been "paired" to specific sea level rises associated to each RCP using data from IPCC (2013).

1.3.1. Sea-level rise CCDFs

Concerning damages from SLR two different reduced-form damage functions have been estimated: one assuming "current level adaptation" and one with incremental adaptation, when coastal protection upgrades following the prescription of "optimal" adaptation from the DIVA model (see Lincke et al. 2018). To account for the task goal: "consider different functional forms for the impact-temperature-response" three different functional forms have been also estimated: linear (1), quadratic (2) and logistic (3).

$$D = \beta_1 SLR \qquad (1)$$

$$D = \beta_1 SLR + \beta_2 SLR^2 \qquad (2)$$

$$D = a\left(\frac{\beta_1}{1+\beta_2 e^{-\beta_3 SLR}} - \frac{\beta_1}{1+\beta_2}\right) \qquad (3)$$

inconsistency, damage data were truncated when showing increases without corresponding increase in temperature. This left a total of 972 observations.

[4] The impacts are: agriculture, forestry, fishery, energy demand, energy supply, riverine floods, transportation, labour supply. With the addition of sea-level rise, they still give a partial representation of climate change impacts, missing important aspects like health impacts or biodiversity losses. This implies that the CCDF that can be extracted offers an underestimation of potential damages.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Although the quadratic specification is the most widely used in CCDF, the other solutions have been applied in the literature (see for instance Roson and Sartori (2016), Neuman et al. (2020)). Moreover, the specifications chosen were those that better fitted the data and that were also more consistent with a more theoretical reasoning.

1.3.2. Temperature related CCDFs

The macroeconomic damages associated to the remaining 8 climate change impacts are related to temperature increase. A linear function (4) and a quadratic function (5) are estimated.

$$D = \beta_1 T \qquad (4)$$

$$D = \beta_1 T + \beta_2 T^2 \qquad (5)$$

Different regression methods have been applied to estimate the β_i coefficients in (2), (3), (4) and (5): standard OLS, OLS robust to heteroscedasticity, and the quantile regression method.

The data have been produced to match the different regions of the IAMs applied in COACCH WP4: REMIND, WITCH, IMAGE, and CLIMRISK. In the latter case NUTS0-2 CCDF have been estimated for the EU.

The final choice, of the functional forms for the CCDFs has been:

- For the SLR with adaptation DFs (SLR-Ad): the linear specification, however, results are available for the logistic specification.
- For the SLR without adaptation DFs (SLR-NoAd): the quantile quadratic fits. For some regions a better fit was provided by the quantile linear specification. These are:

- INDIA, JAPAN, NAF, RSAS, SEAS, SSA, WEU (appearing in the FAIR (IMAGE) model)
- EUR, IND, JON, SSA (appearing in the REMIND model)
- Europe, India, jpn_kor, sasia, seasia, ssa (appearing in the WITCH model):
- ICES: All EU regions to be used for CLIMRISK

- For the temperature related DFs (NoSLR): the quantile quadratic fits.

1.3.3. Uncertainty

One of the purposes of the COACCH project is the transparent and as comprehensive as possible treatment of uncertainty. Bosello et al. (2020) describes how uncertainty has been included in the COACCH macroeconomic climate change impact assessment and the role of different uncertainty sources in driving results variability. To embed that uncertainty also in the calibration of CCDFs, and respond to the task aim to: “consider the uncertainty around the estimates”, we used two methods:

*This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

1. The first consisted in estimating CCDFs for the quantiles of the dataset. We did this by using a region-specific multiplication factor (a_r) that should be multiplied by each regression parameter. The values of a_r are calculated using again a quantile regression (independently of the regression method for the best fit), for the quantiles 0.025, 0.05, 0.16, 0.25, 0.33, 0.5, 0.67, 0.75, 0.84, 0.95, 0.975.
2. The second consisted in the "standard" reporting the confidence interval for each estimated parameter as emerging from the regressions. Accordingly, all estimated parameters from the linear and quadratic best-fits specifications are defined within a "low" and "high" range. Since the logistic fit is non-linear we do not provide confidence intervals.

Figure 1.2, Figure 1.3, and Figure 1.4 exemplify the fitted CCDF for the world, related to sea level rise, and related to the remaining impacts respectively, with uncertainty ranges. The supplementary material reports all the estimated functions (see next section).

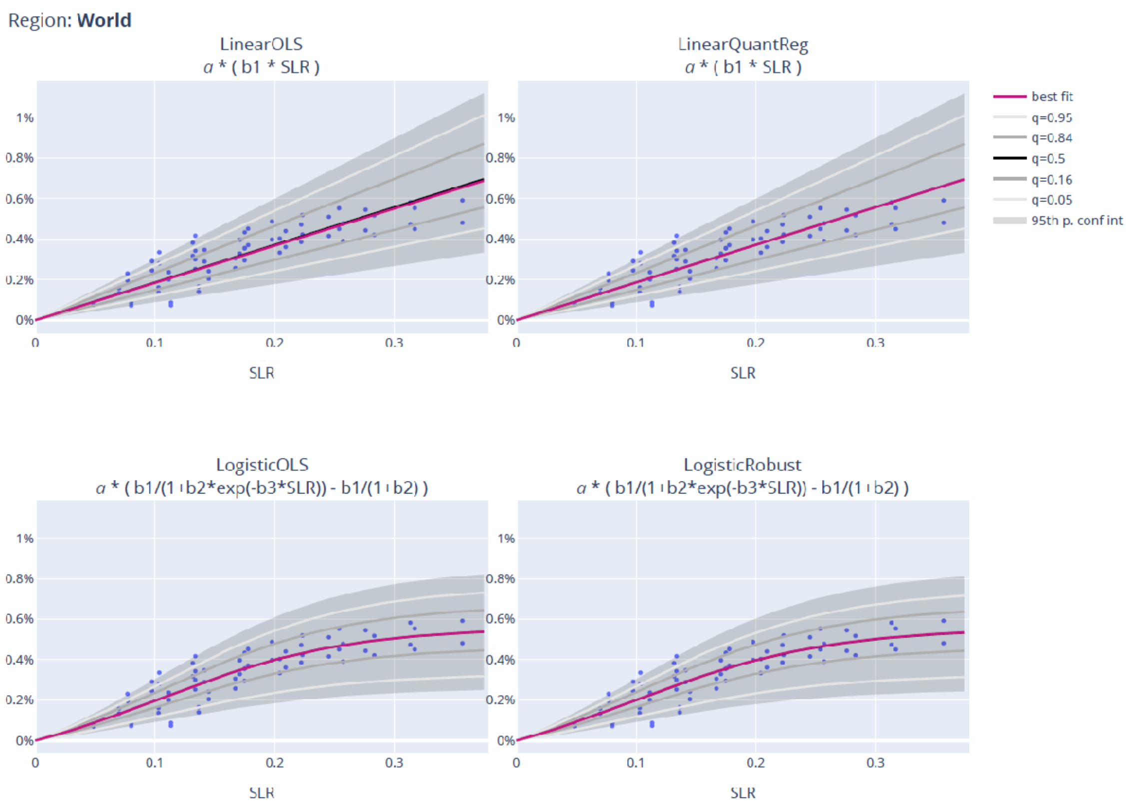


Figure 1.2: CCDF World SLR impact with incremental adaptation by functional form and regression method.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

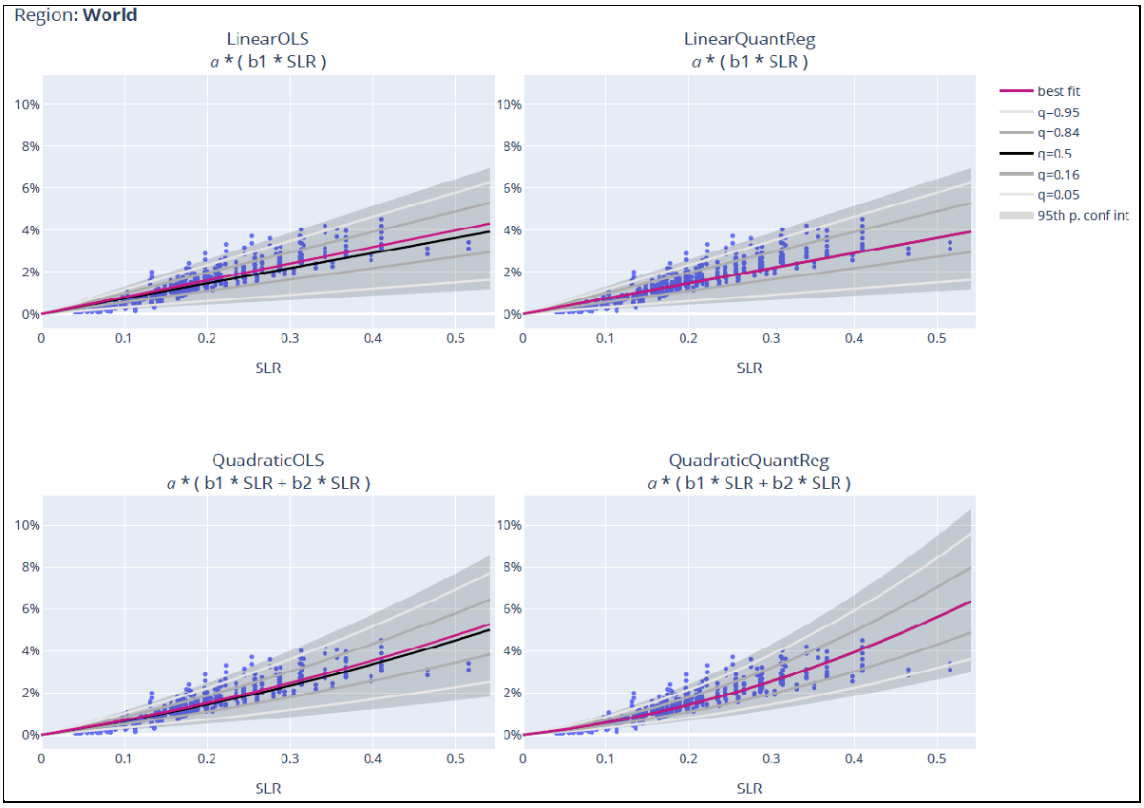


Figure 1.3: CCDF World SLR with constant adaptation impact by functional form and regression method.

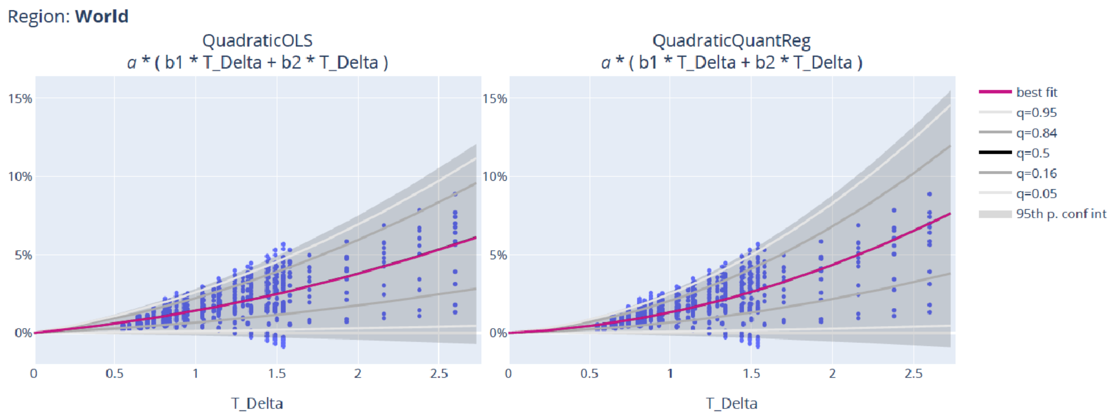


Figure 1.4: CCDF World all impacts except SLR (quadratic functional form by regression method)

1.4. CCDF parametrisation: results in the supplementary material

The parameters of the different CCDFs estimated for the regions of the different IAM used in WP4 are available in the supplementary material. The parameters for the

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

NUTS0/2 EU regions are not included in the annexes since the tables are too long, but are available on request.

The annexes are available in chapter 5, at the end of this deliverable.

Annex I: *CCDFs coefficients COACCH-WP4* contains the parameters for the following IAMs: FAIR (IMAGE), REMIND, and WITCH.

The file "*damage_coefficients-ICES-COACCH-WP4.xlsx*" contains the parameters for the ICES model regions to be used for the CLIMRISK model.

In each Annex, the regression method is reported in the table name. For example, the Quadratic Quantile Regression uses the 50th quantile regression of a quadratic function to fit to the data, giving the best fit values for the linear (b1) and the quadratic (b2) multipliers of the temperature.

The supplementary material also includes two additional annexes. These report the aggregated CCDFs estimated for all impacts including sea-level rise with increased and constant adaptation (coastal protection). These CCDFs can be used by the IAMs that cannot separate temperature and sea-level rise effects. To estimate these DFs, we used the global mean surface temperature change (°C) relative to 1986–2005 and the median SLR corresponding to RCP8.5 (IPCC, 2013: Annex II: Climate System Scenario Tables) and added-up both damages. Then, we fitted the aggregated damages as a function of temperature. Annex II: *CCDFs All impacts SLR Adaptation* and Annex III: *CCDFs All impacts SLR No Adaptation*, contain also the parameters for each quantile and for the regression confidence interval.

Figure 1.6 reports an example for the world aggregated CCDF with all impacts including SLR with constant and incremental adaptation and, for comparison, the case without SLR. Examples of the damage functions fitted at the world level with all impacts including SLR and uncertainty ranges are shown in Figure 1.7 (with SLR adaptation) and Figure 1.8 (without adaptation).

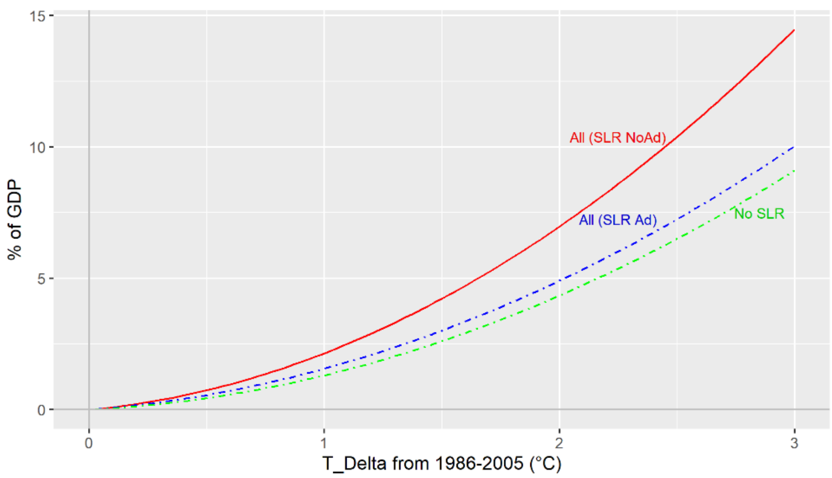


Figure 1.6: Aggregated CCDFs world: Including SLR without adaptation (red line), SLR with adaptation (blue dashed line) and all climate change impacts, but SLR (green dashed line)

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

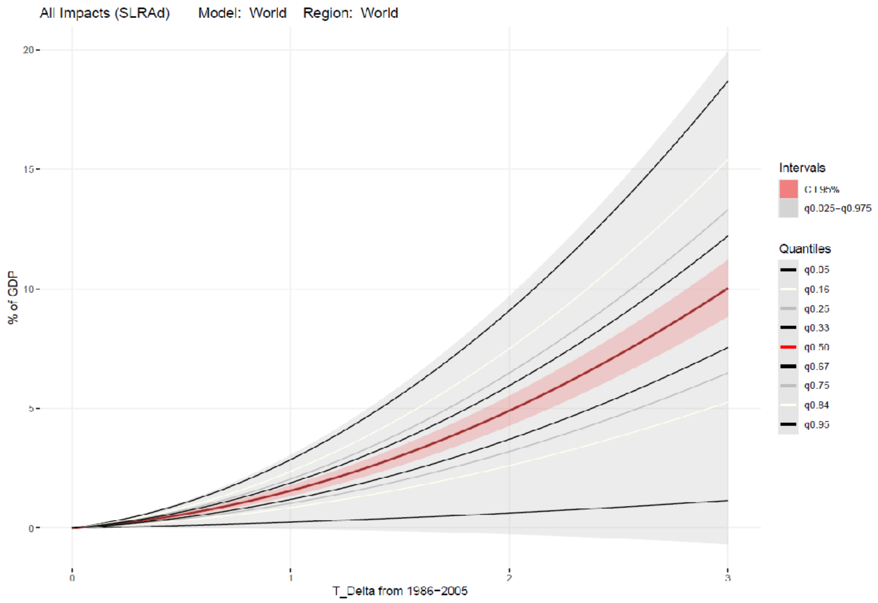


Figure 1.7: World aggregated CCDF embedding SLR incremental adaptation

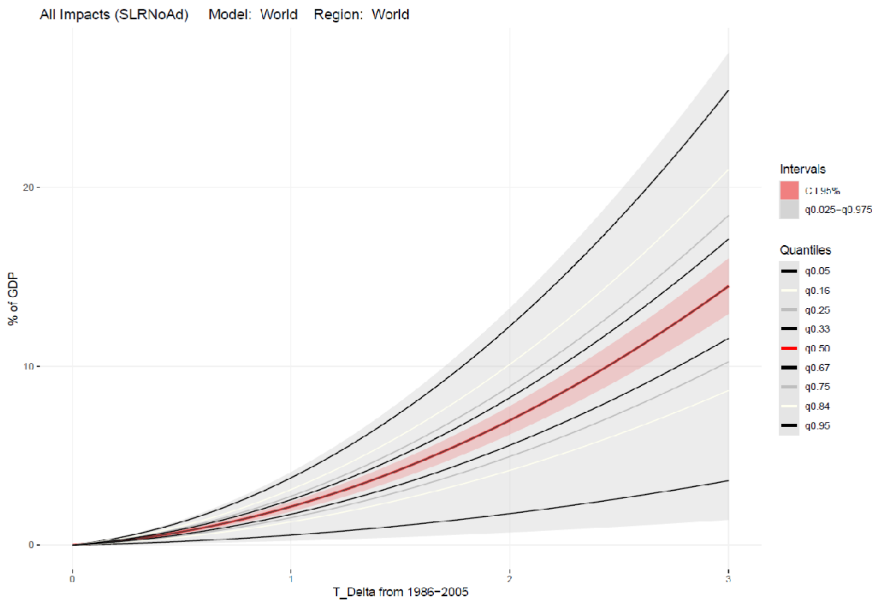


Figure 1.8: World aggregated CCDF embedding SLR constant adaptation

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

1.5. References

Ackerman F. and Stanton E.A, (2012), “Climate Risk and Carbon Prices: Revising the Social Cost of Carbon”, Economics: The Open-Access, Open-Assessment E-Journal, Vol. 6, 2012-10.

Anthoff, D. and R.S.J. Tol (2013), "The Uncertainty about the Social Cost of Carbon: A Decomposition Analysis Using FUND." Climatic Change, 117(3), 515-30.

Bosello, F. (2014), “The role of economic modelling for climate change mitigation and adaptation strategies”, in A. Markandya, I. Galarraga, E. Sainz de Murieta (eds.) “Routledge Handbook of the Economics of Climate Change Adaptation”, Routledge, Oxon and New York

Bosello F.; Parrado R. (2020), “Macro-economic assessment of climate change impacts: Methods and findings” EKONOMIAZ, vol. 97, pp. 45-61 (ISSN 0213-3865)

Bosello et al., (2020). D2.7. Macroeconomic, spatially-resolved impact assessment. Deliverable of the H2020 COACCH project

IPCC, (2013): Annex II: Climate System Scenario Tables [Prather, M., G. Flato, P. Friedlingstein, C. Jones, J.-F. Lamarque, H. Liao and P. Rasch (eds.)]. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1395-1445, published 31 January 2014.

Kahn, M.E., Mohaddes K., Ryan N. C. Ng., Pesaran M.H., Raissi, M., Yang J.C. (2019), ‘Long-term Macroeconomic Effects of Climate Change’, NBER working paper

Neumann, J. E., Willwerth, J., Martinich, J., McFarland, J., Sarofim, M. C., & Yohe, G. (2020). Climate damage functions for estimating the economic impacts of climate change in the United States. Review of environmental economics and policy, 14(1), 25–43. https://doi.org/10.1093/reep/rez021

Nordhaus, W.D., 2010. Economic aspects of global warming in a post-Copenhagen environment. Proceedings of the National Academy of Sciences, 107(26), pp.11721-11726.

*This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Nordhaus, W.D., (1991), To Slow or Not to Slow: The Economics of The Greenhouse Effect, The Economic Journal, Vol. 101, No. 407 (Jul., 1991), pp. 920-937.

Nordhaus, W.D. and J. Boyer (2000) Warming the World: Economic Models of Global Warming, MIT Press, Cambridge, MA.

Nordhaus, W.D. and Z. Yang. (1996), "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies." American Economic Review 86(4), pp 741–765.

Pindyck, R.S. (2017), "The Use and Misuse of Models for Climate Policy," Review of Environmental Economics and Policy, vol 11(1), pages 100-114

Pindyck, R.S. (2019), "The social cost of carbon revisited", Journal of Environmental Economics and Management, 94, 140-160.

Roson, R. and M. Sartori (2016), "Estimation of Climate Change Damage Functions for 140 Regions in the GTAP9 Database", Other Econometrics: Applied Econometric Modeling in Agriculture

Stern, N. (2013), "The Structure of Economic Modelling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models", Journal of Economic Literature 51(3), 838-859.

Tol, R. S. J. (2018), "The Economic Impacts of Climate Change. Review of Environmental Economics and Policy" 12, 4–25. https://doi.org/10.1093/ reep/rex027

Tol, R. S. J. (2021), "Estimates of the social cost of carbon have not changed over time," Working Paper Series 0821, Department of Economics, University of Sussex Business School.

Weitzman ML (2007) A review of the Stern review on the economics of climate change. J Econ Lit 45 (3):703–724

Weitzmann, M., (2009a), On modeling and interpreting the economics of catastrophic climate change, Review of Economics and Statistics, 2009, vol. 91 (pg. 1-19)

Weitzmann, M., (2009b), Additive damages, fat-tailed climate dynamics, and uncertain discounting, Economics — The Open-Access, Open-Assessment E-Journal, 2009, vol. 3 (pg. 1-29)

Weitzmann, M., (2010), Risk-Adjusted Gamma Discounting, Journal of Environmental Economics and Management, 2010, vol. 60 (pg. 1-13)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

2. Macro-economic assessment and cost-benefit analysis of updated damage functions

Authors:

Kaj-Ivar van der Wijst[*,1,2], Francesco Bosello[3], Laurent Drouet[3], Johannes Emmerling[3], Andries Hof[1,2], Marian Leimbach[4], Ramiro Parrado[3], Franziska Piontek[4], Detlef van Vuuren[1,2]

[1] PBL Netherlands Environmental Assessment Agency, The Netherlands
[2] Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands
[3] RFF-CMCC European Institute on Economics and the Environment (EIEE), Milan, Italy
[4] Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
[*] Corresponding author

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

2.1. Introduction

Cost-benefit analysis of climate change is used to provide insights into the advantages and disadvantages of different climate policy strategies. This method requires insights into a large set of unknown factors, including an assessment of damage for different levels of climate change. While in the past, most estimates of so-called damage functions were based on bottom-up sectorally modelled damages combined with monetarisation – recently also top-down empirical estimates (like Burke et al, 2015[1]) have become available. The 'bottom-up' damage function category consists of more coarse estimates (like the damages used in DICE[2], FUND[3] and PAGE[4]) and more elaborate estimates using physical impact models with subsequent monetisation (e.g. the PESETA[5] project for Europe). Most global "bottom-up" cost functions are relatively old. At the same time, considerable progress has been made in estimating physical impacts. Recently, the COACCH project has produced updated damage functions by monetising the physical impacts from various detailed impact models covering a wide range of sectors. These new damage functions have a high level of regional detail and provide large uncertainty ranges, accounting for the spread in physical impact model output.
The impact of new insights in damages not only depends on the direct damage formulation but also how they influence overall economic development. Here, we perform a model intercomparison of the implications of these new COACCH damage functions in three Integrated Assessment Models (IAMs): MIMOSA (which is based on FAIR), WITCH and REMIND in terms of macro-economic impacts. This is done using two main experiments. In the first experiment, we investigate how the damage functions translate to GDP losses and how the results from each model relate to each other. The second experiment provides optimal policy recommendations by analysing the combined effect of mitigation costs and damages in a cost-benefit analysis.

2.2. Methods

Damage functions

In general, damage functions provide insight into the loss of income or consumption due to global or local temperature increase. Here, we use the newly created COACCH damage functions (see Section 1 of this deliverable). In addition to taking up the latest information in physical impacts, these new curves offer several advantages over previous damage functions. First, the curves account for the large differences in time dynamics between sea-level rise and other impacts by creating two damage functions: 1) for sea-level rise only as function of sea level rise (in meters) and 2) for remaining impacts as direct function of temperature increase. Second, the COACCH damage functions provide a high degree of regional detail: the functions are calculated for almost each native region of the IAMs used in this deliverable (MIMOSA, WITCH and REMIND). Finally, an important new aspect of the COACCH damage functions is the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

explicit and consistent treatment of uncertainty. This is quantified through different *damage quantiles* (see Fig. SI.3.1). Unless otherwise stated, the medium damage estimate is the 50th quantile, with the low and high estimates respectively the 5th and 95th quantile.

Integrated Assessment Models

To assess the macro-economic implications of the new COACCH damage functions, we use three different IAMs of varying levels of complexity. IAMs are models designed to capture the interplay between, among others, the climate, the economy and the energy system.
MIMOSA[6] is a recent IAM based on FAIR[7] with 26 regions covering the whole world. It is a relatively simple Cost-Benefit IAM but still covers the relevant technological and socio-economic dynamics.[5] Temperature is a linear function of cumulative CO2 emissions. MIMOSA uses the DICE sea-level rise module.
WITCH[8] is a dynamic optimisation IAM of intermediate complexity, with 17 world regions.[6] The climate module is based on the DICE climate and sea-level rise module represented by a few simple equations.
REMIND[9] is a Computable General Equilibrium (CGE) model and has the highest level of detail in the representation of the economy of the three models. However, in contrast with MIMOSA and WITCH, REMIND does not model sea-level rise explicitly, and therefore uses a combined damage function that depends only on temperature.[7]
REMIND uses a stylised box model as climate module.
For further model detail refer to COACCH D2.1.

Harmonisation

To allow a comparison of the results between the models, we harmonise key assumptions. We use the SSP2[10] assumptions on baseline GDP and population growth, and baseline emissions. The discounting is also harmonised: by default, we use a Pure Rate of Time Preference (PRTP, also called utility discount factor) of 1.5%/year and an elasticity of marginal utility of 1.001, in line with a recent expert elicitation[11] on discount rates. Since temperature is an essential factor determining the climate damages, the climate models are calibrated such that the 2020 temperature is harmonised and equal to 1.16°C above pre-industrial levels[12]. Moreover, all damages are reported relative to 2020 damage levels. While the COACCH damage functions are calibrated for the 1986-2005 period and therefore report non-zero damages in 2020, we assume that the observed GDP of 2020 already incorporates these damages. Specifically, if the COACCH damage function relative to 1986-2005 temperature is noted by $D_{1986-2005}\left(T_t\right)$ for temperature level T_t, the damages as incorporated in the models are:

[5] See https://github.com/kvanderwijst/Project-MIMOSA/ for the model code and documentation.
[6] See https://www.witchmodel.org/ for the model code and documentation.
[7] See https://rse.pik-potsdam.de/doc/remind/2.1.0/ for the model documentation and https://github.com/remindmodel/remind for the model code.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

$$D_{rel.\,to\,2020\,level}\left(T_t\right) = D_{1986-2005}\left(T_t\right) - D_{1986-2005}\left(T_{2020}\right),$$

where T_{2020} is the temperature in 2020.

Finally, since each model uses different regional definitions, we aggregate all results to the five macroregions of the SSP database[10] (see https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about#regiondefs for the detailed country mapping of each region):

- ASIA: most Asian countries, except for the Middle East, Japan, the Russian Federation, Central Asia and the Caucasus region
- EENA: Eastern Europe and North Asia: Russian Federation, Belarus, Ukraine, the Caucasus region, Central and North Asia
- LAM: Latin America
- MAF: the Middle East and Africa
- OECD: includes all OECD and EU countries except Israel, Mexico and South Korea. Also includes Albania, Bosnia and Herzegovina, Bulgaria, Guam, Macedonia, Montenegro, Puerto Rico, and Serbia

While these key assumptions have been harmonised across the three IAMs, the models differ, among others, in their representation of the economy, their internal climate and sea-level rise module, and their representation of the energy sector.
The setup of each experiment will be discussed in the following sections.

2.3. Multi-model comparison of direct and indirect macro-economic effects

In the first experiment, we investigate the macro-economic effect of the COACCH damage functions in the three IAMs under RCP 6.0 (baseline emission trajectory) and RCP 2.6 (mitigation trajectory in line with Paris Agreement). By harmonising the temperature path and damage functions, we can analyse the extent to which the impact of direct damages on GDP differs between the models. The COACCH functions allow us to decompose impacts of sea level rise and other temperature-related impacts. Moreover, the models are used to also show indirect impacts from accumulated GDP effects[8]. The latter is calculated using the GDP difference with a corresponding run without damages. Unless stated otherwise, we assume that optimal adaptation has taken place against sea-level rise damages. The reported SLR damages are the sum of SLR adaptation costs and residual damages.

[8] The COACCH damage functions could also be regarded as including "indirect" damages, as they are created by a CGE which calculates damages as a result of market adjustments. This is however a methodological aspect of the damage functions themselves, which we ignore here. Instead, we call "indirect damages" the impact resulting from reduced GDP growth due to GDP losses in previous timesteps.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

We first focus on the regional differences. In Fig. 2.1, we show the damages in 2100 for the five macro-regions, for now, focused on the medium damage estimate (50^{th} damage quantile). In an RCP 6.0 scenario (Fig. 2.1a), the damages are the highest in the Middle East and Africa region, with total losses between 13% and 17% of GDP, followed by 12% to 14% for Asia. This figure does not show intra-regional differences; only the population-weighted average per macro-region is shown. For this reason, Egypt, part of the OECD region, looks so different from the surrounding countries, which are part of the Middle East and Africa region. The other three regions have lower total damages (6-8% for Latin America, 4-6% for OECD and 3-5% for Eastern Europe and Northern Asia).

Sea-level rise damages make up a significant part (12-16% of total direct damages) in Asia and the OECD region, compared to a much lower part for the other regions (as low as 2% of total direct damages for Africa). However, when using the scenario without sea-level rise adaptation (Fig. SI.1.1), total damages per region become substantially higher (from global average damages of 10-12% with SLR adaptation to global damages of 13-17% without SLR adaptation). This is especially pronounced in the OECD (4-6% total damages with SLR adaptation to 8-13% total damages without SLR adaptation).

Moving from RCP 6.0 to the Paris compliant RCP 2.6 reduces the total damages to a regional maximum of 4.5%, compared to the 15% for RCP 6.0 (Fig. 2.1b). The regional distribution of damages is similar to RCP 6.0, except that Asia has now slightly higher damages than Africa. Due to the slow processes of sea-level rise, the differences in sea-level rise damages between RCP 2.6 and RCP 6.0 are small. For this reason, the relative share of damages from sea-level rise becomes larger, especially in regions with relatively long coastlines, like Asia and the OECD. When we do not assume optimal SLR adaptation (see Fig. SI.1.1b), Asia and the OECD are the regions with the highest damages in RCP 2.6, as sea-level rise damages account for the majority of total damages.

Comparing the three models, the total direct damage costs (SLR plus non-SLR damages) are similar between the three models, with MIMOSA generally showing slightly higher damages than WITCH – which can be explained by the fact that WITCH uses a slightly lower temperature path than prescribed due to technical calibration difficulties (Fig. SI.1.5). REMIND also shows total damages similar to MIMOSA and WITCH, despite using the combined damage function instead of the two separate SLR and non-SLR damage functions. However, the differences are much larger in the RCP 2.6 scenarios without SLR adaptation (Fig. SI.1.1b), where the REMIND damages are between 20% and 75% lower than MIMOSA and WITCH. This effect is shown in more detail in Fig. SI.1.2, where MIMOSA is run with the separate damage functions and the combined damage function to isolate the effect of the different functions.

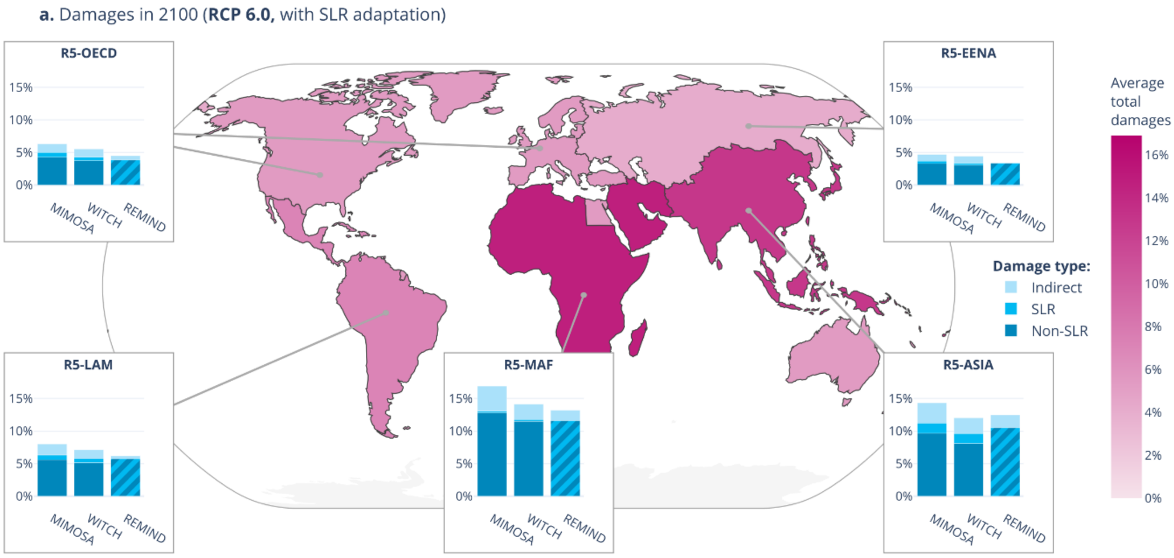
Sensitivity analysis

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Besides looking at 2100 and the 50th damage quantile only, this experiment allows assessing many key aspects simultaneously: different RCPs, regions, assumptions on sea-level rise adaptation, using IAMs with varying degree of economic detail. For this reason, in Fig. 2.2, we perform a sensitivity analysis using different damage quantiles and report the damage decomposition for different years.

As shown in Fig. 2.2, uncertainty in the damage function strongly affects the overall damages. As expected, the total damages are significantly higher with the high damage quantile (95th damage quantile): 18-22% as global average instead of 10-12% for the medium damage quantile. The global impacts can even be positive for lower damage quantiles up to 2050 due to significant gains in Latin America (see Fig. SI.1.4b). These gains are offset by sea-level rise damages towards the end of the century.

Until 2050, the differences between RCP 2.6 and 6.0 are relatively minor. They only strongly diverge towards 2100 (up to 50% higher damages in RCP 6.0 than RCP 2.6 in 2050, whereas the damages are 300% higher towards the end of the century). REMIND shows lower indirect effects than the other models. This is mainly due to adaptation mechanisms in the CGE optimisation. While in MIMOSA all economic assets are fixed, in REMIND, assets can be relocalised, facilitated by more advanced trade mechanisms.



*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

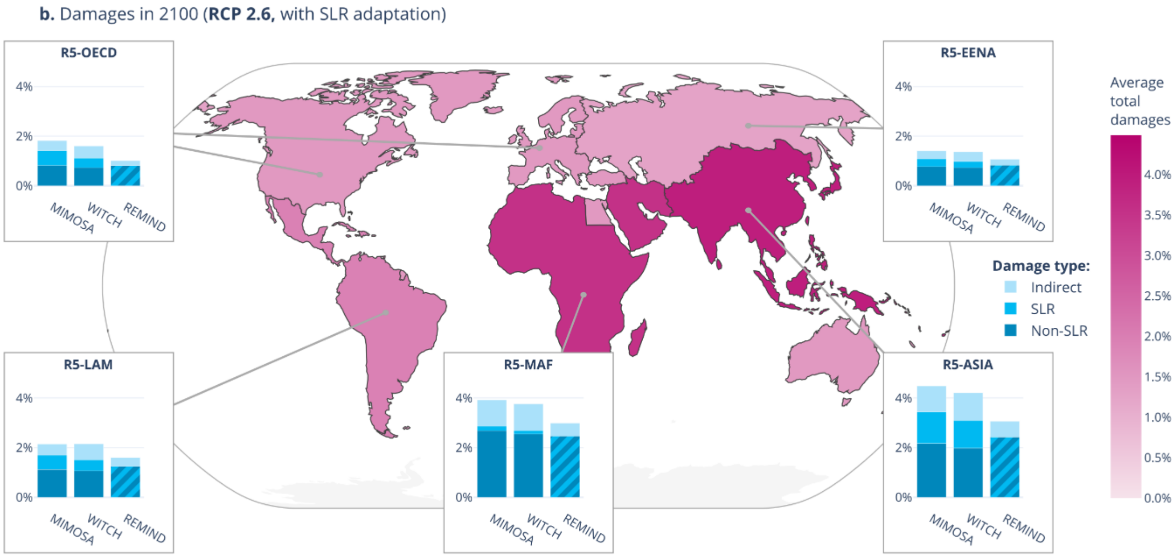


Figure 2.1. Damages in RCP6.0 in 2100 for the 5 SSP macroregions. The REMIND model does not model sea level rise explicitly.

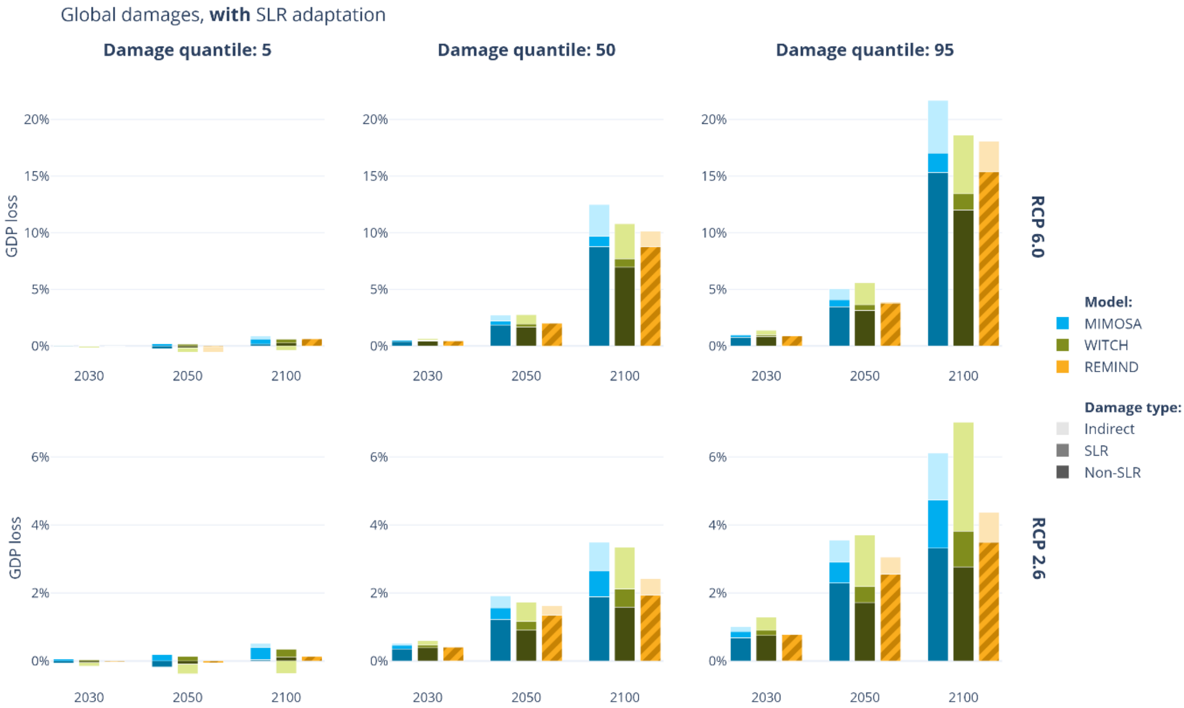


Figure 2.2. Damage cost decomposition of the GDP losses. Note that REMIND does not model sea level rise explicitly

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

2.4. Cost-benefit analysis

The first experiment ignored mitigation costs. This second experiment analyses the combined effect of the new damage functions and the model-specific mitigation cost specifications by performing cost-benefit analyses. In the main setting of this experiment, the only aspect we vary between runs is the damage function, since recent research has shown that damage uncertainty is the main contributor to cost-benefit result uncertainty[6]. Later in this section, we also compare the uncertainty from discounting parameters with the damage function uncertainty.

Damage uncertainty

The cost-benefit results are presented in Fig. 2.3. The cost-optimal end-of-century temperature for the medium estimates of damages is similar for REMIND and MIMOSA[9]: around 1.9°C above pre-industrial levels[10], which is basically in line with the Paris Agreement. As expected, the lower end of damages leads to higher optimal end-of-century temperature increases of 2.7-3.2°C and the higher end of the damages lead to optimal temperature increases which are very close to the 1.5 °C target of the Paris Agreement (1.4-1.7°C). Earlier[6], we showed that the optimal temperature depends on the damage curves using three sets of global independent damage functions covering the current literature range. Interestingly, the resulting optimal temperatures are similar to this study: 3.1°C for the DICE damage function[2], 2°C for Howard Total[13] and 1.5°C using the Burke et al[1] damage function. Using the COACCH damage functions, however, allows for a more internally consistent integration of uncertainty, instead of using three independent damage functions.

Model uncertainty

In general, the optimal emission pathways in MIMOSA and REMIND are similar, where MIMOSA is slightly more sensitive to a higher or lower damage function. This is due to a combination of low overall mitigation costs in REMIND (Fig. 2.3b) and more stringent constraints on mitigation potentials. In fact, the difference between the 50th and 95th damage quantile is low (only 0.2°C), since due to the low mitigation costs, the REMIND model already mitigates the largest share of the total mitigation potential in the 50th damage quantile run. With MIMOSA, the mitigation costs are higher (around 3% of GDP for the medium CBA scenario), but the model is more flexible in achieving higher

---

[9] At this point, we do not have results for this experiment for the WITCH model. However, we can compare the mitigation costs and carbon prices for the RCP 2.6 scenario from the previous experiment (Fig. SI.1.3). The carbon prices from WITCH and REMIND are very similar, but the corresponding mitigation costs are much larger in WITCH. The REMIND model is as a CGE more dynamic, with more possibilities to restructure the economy, which is hardly possible in WITCH and MIMOSA, leading to lower costs in REMIND.

[10] Note that these temperature estimates are median climate estimates and do not take into account uncertainty in the climate module.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

mitigation levels. It has less strict inertia constraints and allows for more net-negative emissions towards the end of the century than REMIND, explaining the lower optimal end-of-century temperature in the high damage quantile scenario. Finally, while the policy costs are higher in MIMOSA than in REMIND, the same optimal target is reached with the medium damage quantile since the total damages are also higher in a 2°C world in MIMOSA than in REMIND (as discussed in the previous experiment).

Impact of discounting

Another key component in long-term cost-benefit analysis is the discount rate. By default, we use a pure rate of time preference (PRTP) of 1.5%/year, combined with an elasticity of marginal utility of 1.001, in line with recent literature[6,14] and a recent expert elicitation[11]. To cover the full range of current discounting estimates, we perform a sensitivity analysis with a lower and higher discounting parameter. We use 0.1%/year as a low PRTP value, in line with the Stern[15] review, and 3%/year as a high PRTP value, as used in DICE-2016R model[16], while keeping the elasticity of marginal utility fixed.

As shown in Fig. 2.4, when considering the cost-optimal end-of-century temperature, the resulting uncertainty from damage function uncertainty is twice as large than resulting from discounting uncertainty. The damage function uncertainty leads to a spread of over 1.5°C in optimal temperatures, while the discounting uncertainty leads to a spread of around 0.7°C. Choosing a scenario without sea-level rise adaptation leads to an optimal temperature between 0.1°C and 0.2°C lower than with optimal sea-level rise adaptation. In fact, since sea-level rise damages can be hardly mitigated at this timescale, the models choose to reduce the other damages as much as possible by reducing the global mean temperature further.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Figure 2.3. (a) Cost-optimal emission trajectory and corresponding end-of-century temperature in cost-benefit runs for two models for the low, medium and high end of the damage function uncertainty range (damage quantiles). (b) GDP loss (compared to baseline GDP) decomposed in policy costs (mitigation costs), damage costs and indirect costs. Here, the indirect costs are the result of accumulated GDP impacts from both mitigation and damage costs.

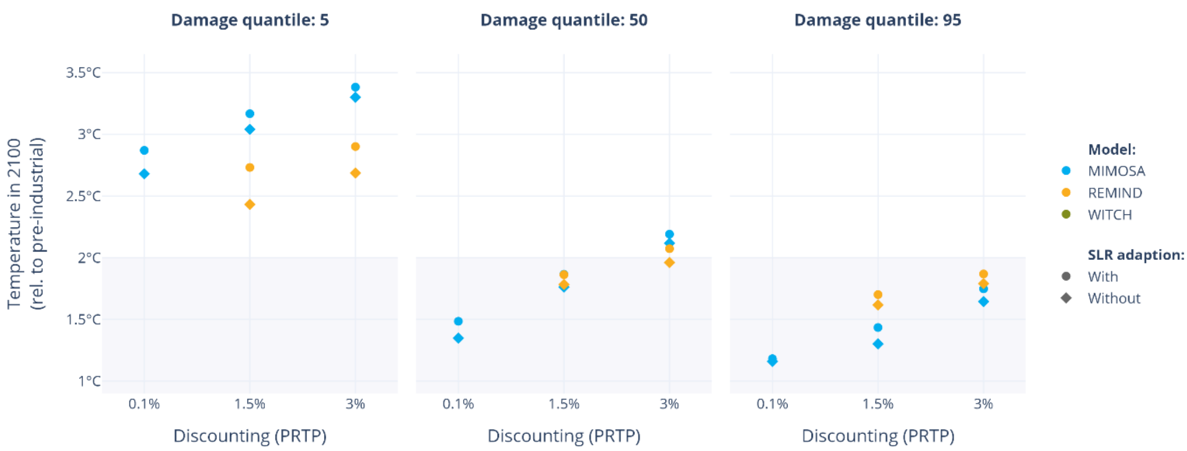


Figure 2.4. The optimal end-of-century temperature in CBA for different levels of discounting and SLR adaptation assumptions. The levels of discounting are quantified by three values of the Pure Rate of Time Preference (PRTP), also called yearly utility discounting.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

2.5. Conclusion

The macro-economic assessment of the new damage functions yields optimal policy recommendations in the form of cost-benefit analysis. With medium damages, the optimal temperature is in line with the 2°C target from the Paris Agreement. When assuming the high end of the damage function, optimal temperatures are in line with a 1.5°C goal. Moreover, the uncertainty in the damage function is more important than the choices of discounting. Finally, models of different complexities lead to similar results in optimal temperature outcome.

2.6. References

1. Burke, M., Hsiang, S. M. & Miguel, E. Global non-linear effect of temperature on economic production. *Nature* **527**, 235–239 (2015).
2. Nordhaus, W. Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *J. Assoc. Environ. Resour. Econ.* **1**, 273–312 (2014).
3. Anthoff, D. & Tol, R. S. J. The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) - Technical Description - Version 3.9. (2014).
4. Hope, C. Critical issues for the calculation of the social cost of CO2: Why the estimates from PAGE09 are higher than those from PAGE2002. *Climatic Change* vol. 117 531–543 (2013).
5. Ciscar;, J. C. *et al. Climate impacts in Europe: Final report of the JRC PESETA III project*. (Publications Office of the European Union, 2018). doi:10.2760/93257.
6. van der Wijst, K.-I., Hof, A. F. & van Vuuren, D. P. On the optimality of 2°C targets and a decomposition of uncertainty. *Nat. Commun.* 1–11 (2021) doi:10.1038/s41467-021-22826-5.
7. Den Elzen, M. G. J. & Lucas, P. L. The FAIR model: A tool to analyse environmental and costs implications of regimes of future commitments. *Environ. Model. Assess.* **10**, 115–134 (2005).
8. Emmerling, J. *et al.* The WITCH 2016 Model - Documentation and Implementation of the Shared Socioeconomic Pathways. *Work. Pap.* (2016).
9. Leimbach, M., Bauer, N., Baumstark, L. & Edenhofer, O. Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R. *Environ. Model. Assess. 2009 153* **15**, 155–173 (2009).
10. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **42**, 153–168 (2017).
11. Drupp, M. A., Freeman, M. C., Groom, B. & Nesje, F. Discounting disentangled. *Am. Econ. J. Econ. Policy* **10**, 109–134 (2018).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

12. Visser, H., Dangendorf, S., Van Vuuren, D. P., Bregman, B. & Petersen, A. C. Signal detection in global mean temperatures after ‘Paris’: An uncertainty and sensitivity analysis. *Clim. Past* **14**, 139–155 (2018).

13. Howard, P. H. & Sterner, T. Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates. *Environ. Resour. Econ.* **68**, 197–225 (2017).

14. Hänsel, M. C. *et al.* Climate economics support for the UN climate targets. *Nat. Clim. Chang.* **10**, 781–789 (2020).

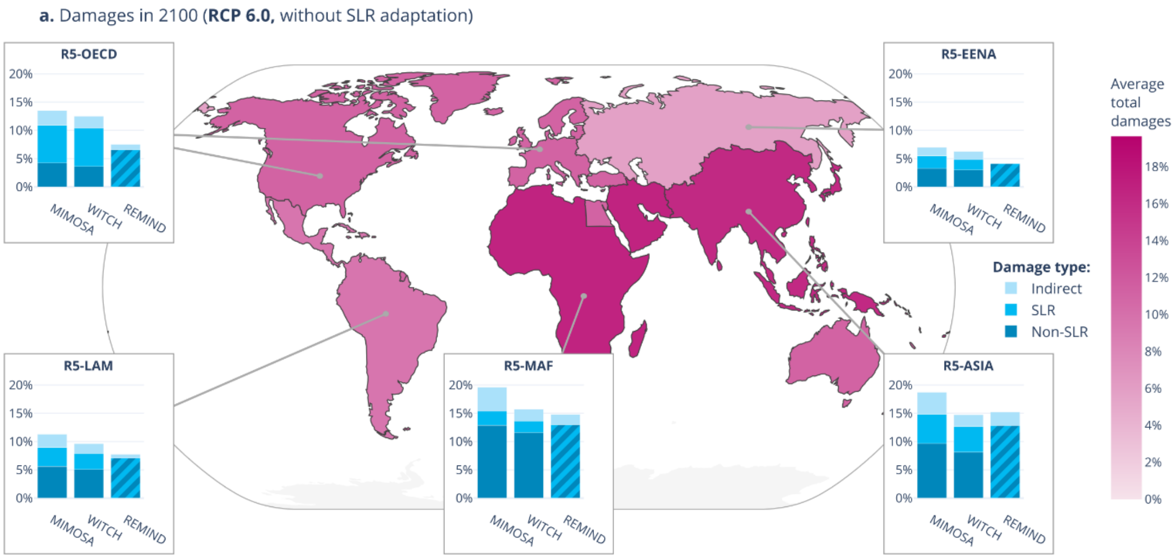
15. Stern, N. *The economics of climate change: The stern review*. *The Economics of Climate Change: The Stern Review* vol. 9780521877251 (Cambridge University Press, 2007).

16. Nordhaus, W. D. & Moffat, A. *A survey of global impacts of climate change: replication, survey methods and a statistical analysis*. http://www.nber.org/papers/w23646 (2017).

*This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

2.7. Supplementary Information

SI.1. Extra figures experiment 1: RCP comparisons



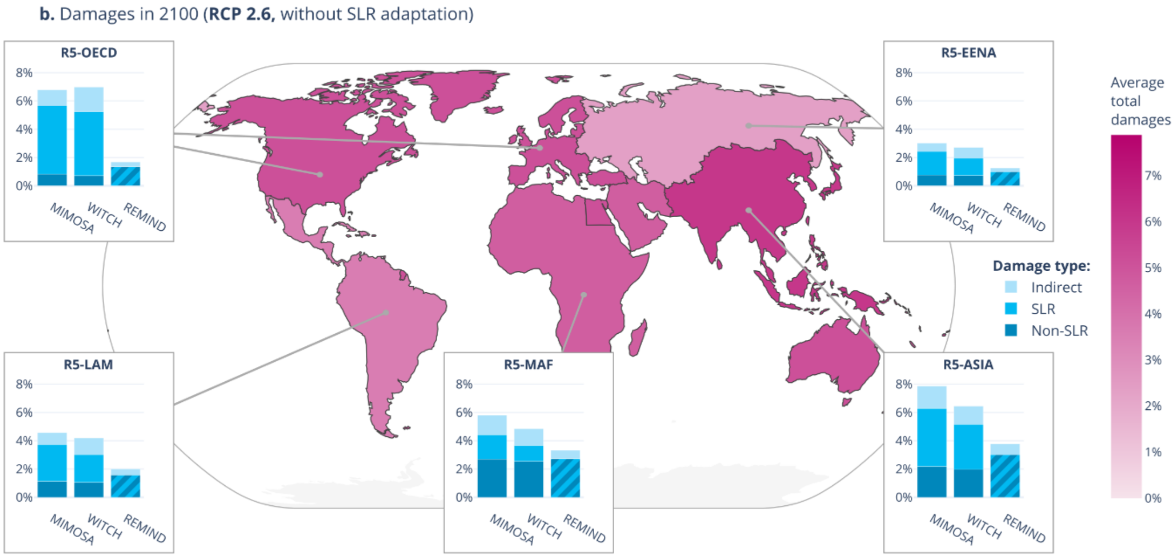


Figure SI.1.1. Regional damage cost decomposition for RCP6.0, without SLR adaptation. The REMIND model doesn't model sea-level rise damages explicitly and uses the combined damage function.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

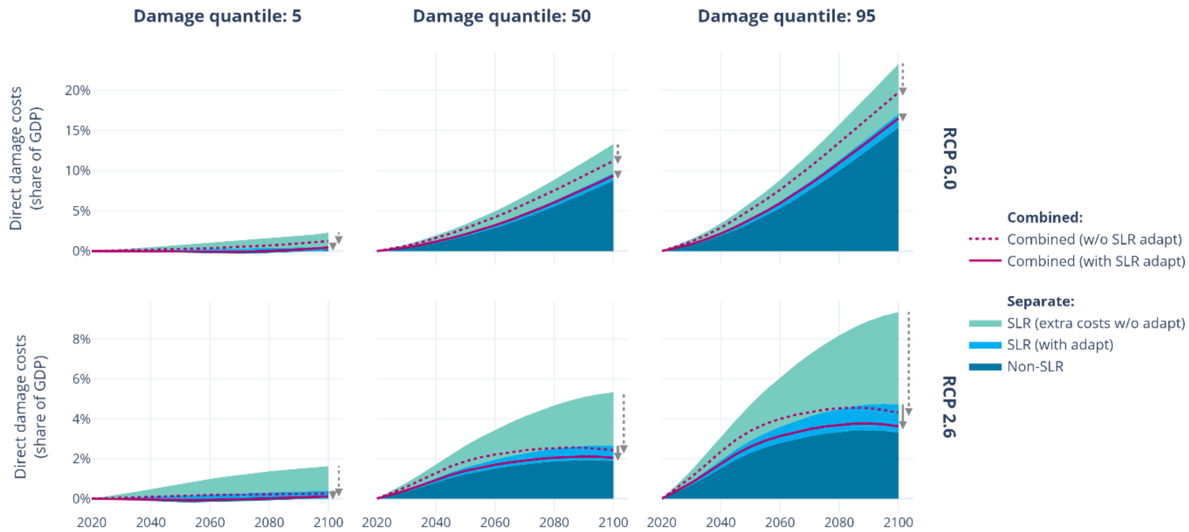


Figure SI.1.2. Comparison of the direct costs when modelling sea-level rise and non-sea-level rise separately (blue/green) versus combined in one damage function (pink lines). All these values are calculated with the same model (MIMOSA) and same scenario settings. The arrows indicate the differences between total separate and total combined, for the scenario with (solid arrow) and without (dotted arrow) SLR adaptation.

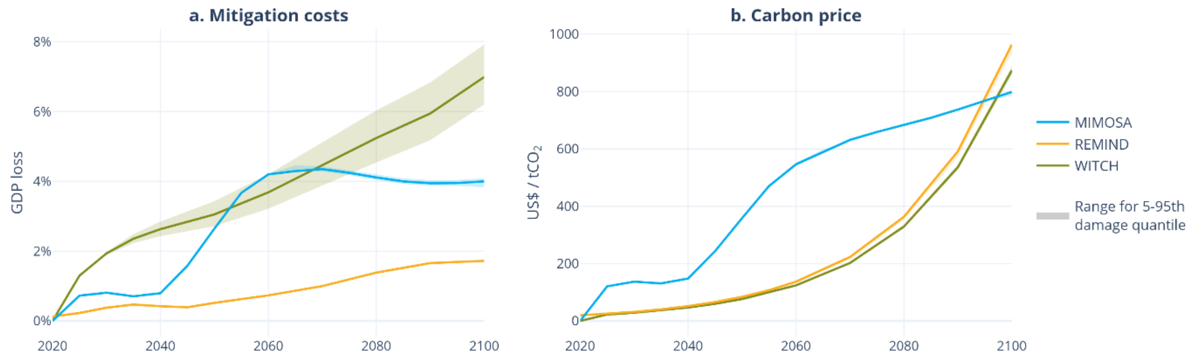
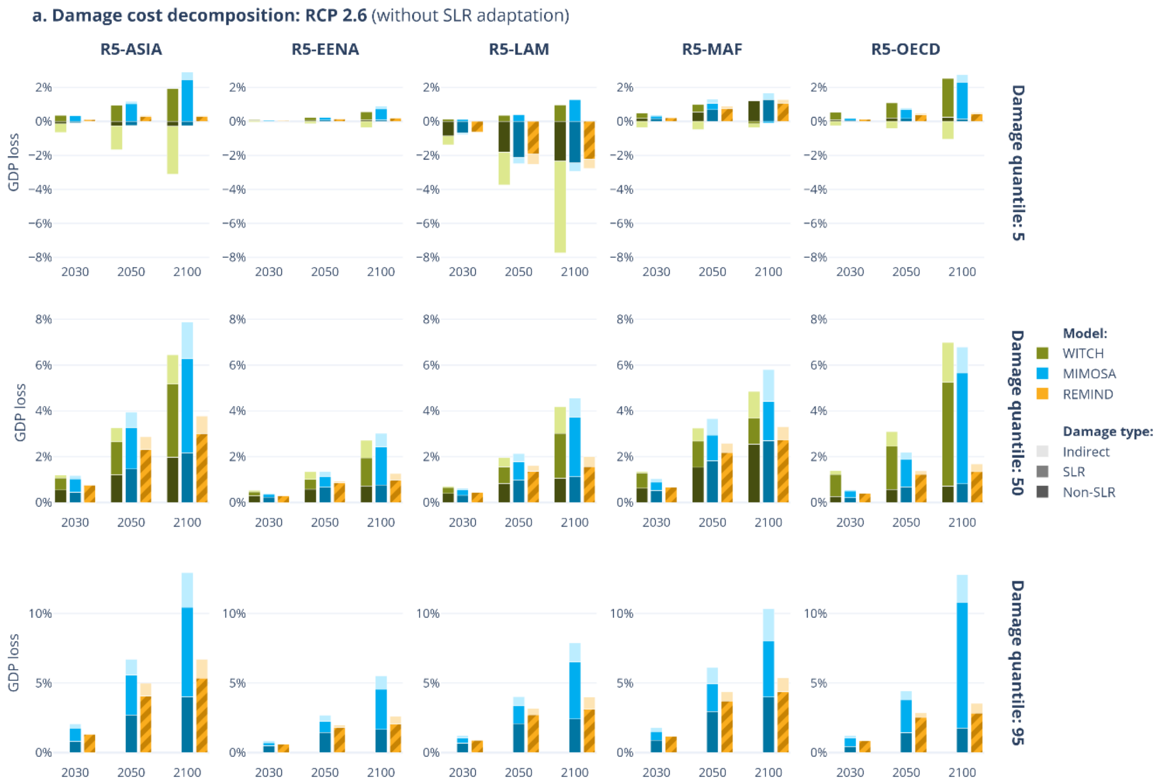
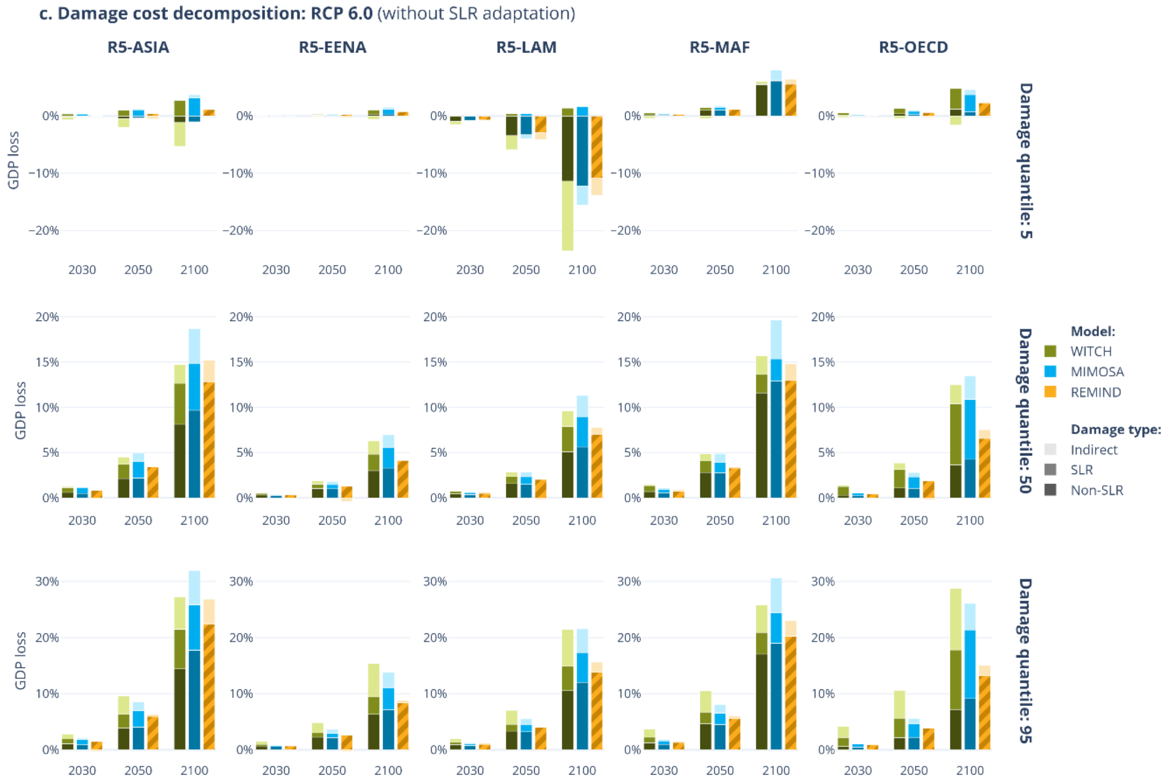


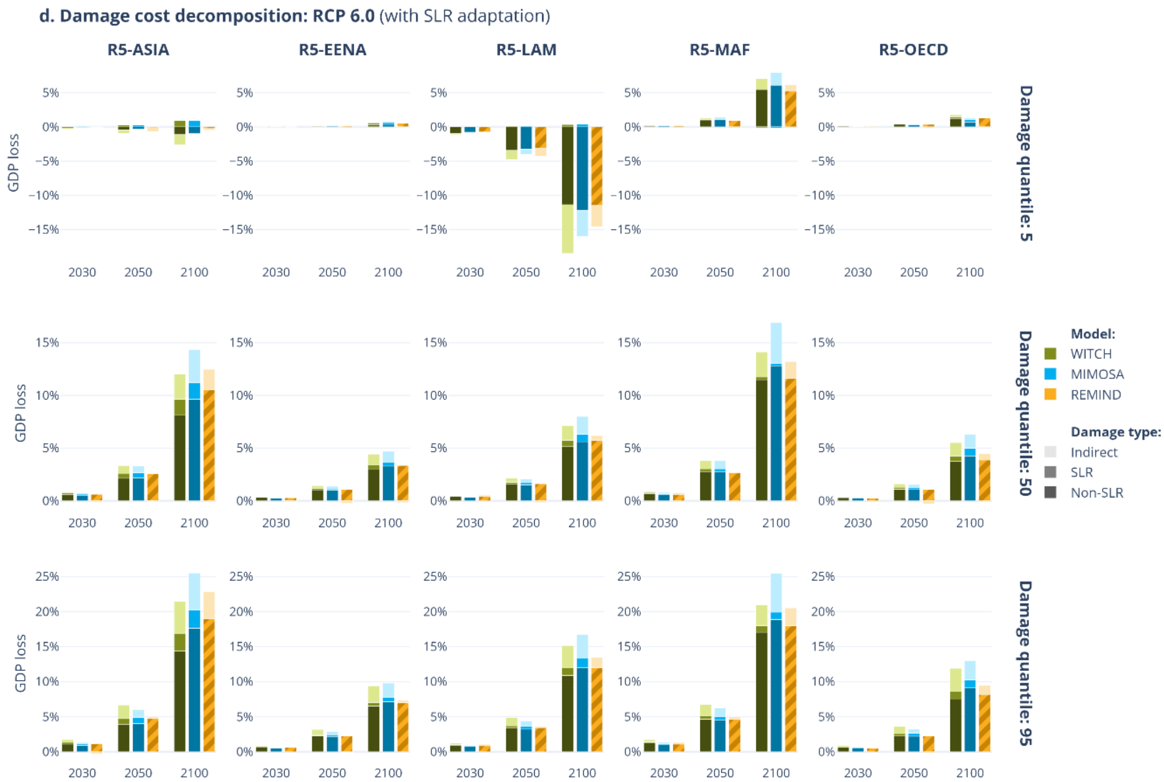
Figure SI.1.3. Mitigation costs and associated carbon prices per model for the RCP 2.6 scenario. The range indicates the ranges for the different damage quantiles.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***



*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***





*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Figure SI.1.4. Regional damages for RCP 2.6 (a, b) and RCP 6.0 (c, d) both with SLR adaptation (b, d) and without SLR adaptation (a, c).

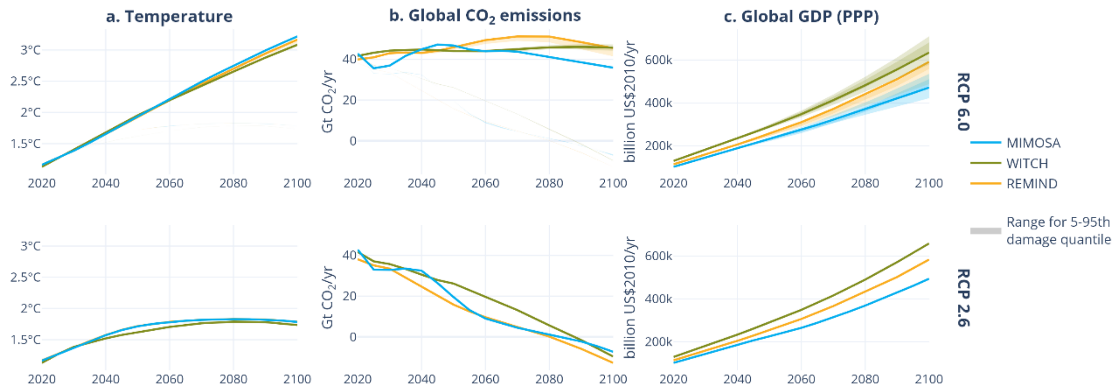


Figure SI.1.5. Temperature input, emission paths and GDP per RCP for each model.

SI.2. Extra figures experiment 2: cost-benefit analysis

No additional figures.

SI.3. Methodological details

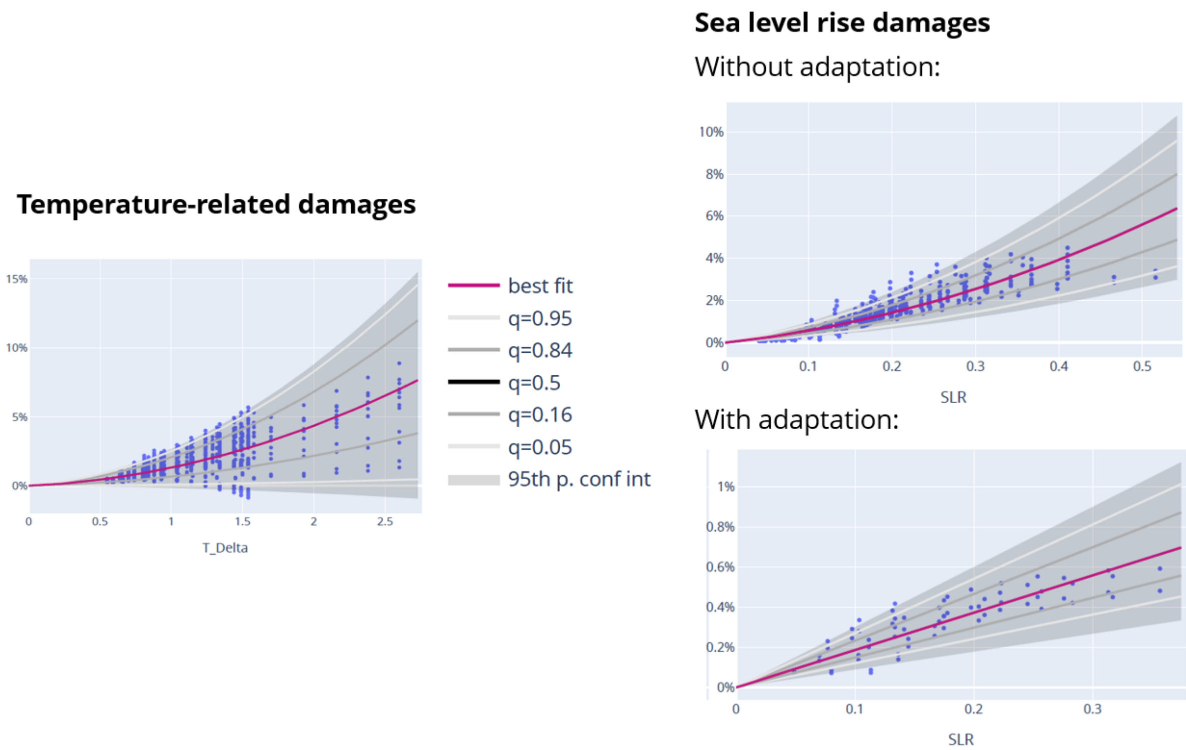


Figure SI.3.1. The COACCH damage functions, aggregated for this example to the world region. The dots represent the independent damage observations, through which various functions have been fitted. To account for uncertainty, different damage

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

quantiles are used: the 5th (low) and 95th (high) percentiles are shown in light grey, the 50th quantile (medium estimate) in pink. The damage functions are split in two components: temperature related damages (non-sea-level rise damages) (left) and sea-level rise (SLR) damages (right). The SLR can be used either with or without adaptation (top right vs bottom right).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

3. Local-scale climate damage functions for Europe

Authors:

Predrag Ignjacevic[*,1], Onno Kuik[1], Wouter Botzen[1]

[1] Institute for Environmental Studies (IVM), Vrije Universiteit (VU), Amsterdam
[*] Corresponding author

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

3.1. Introduction

Integrated assessment models of climate change often rely on the concept of damage functions for climate impact projections (Bosetti et al., 2007; Estrada & Botzen, 2021; Ignjacevic et al., 2020; Nordhaus, 2017b). Damage functions serve the purpose of translating changes in natural phenomena into economic impacts. Two most commonly explored phenomena are temperature change and sea-level rise (SLR). The spatial resolution of these damage functions is either global (Nordhaus, 1992) or regional (Anthoff & Tol, 2014; Nordhaus, 2017a). However, climate impacts affect local communities differently and impact assessment models could benefit from damage functions of a higher spatial resolution. For example, whereas some areas may experience negative initial impacts of climate change, others might experience a positive change due to, for example, increased agricultural productivity. Local scale vulnerabilities are not taken into account when using a single set of regional parameters. In this section, we use the newly developed COACCH damage function estimates on the NUTS-2 level for Europe. These damage functions relate temperature change w.r.t the baseline period 1986 – 2005 to climate impacts in the 21st century. The purpose of the new functions is to increase the accuracy of projecting local-scale results by accounting for local factors that influence climate vulnerability.

The new damage functions will be introduced into an existing IAM called CLIMRISK to improve the accuracy of local-scale results (Estrada & Botzen, 2021). Finally, additional urban heat island (UHI) damage functions will be introduced into the model to enhance our understanding of the local impacts and the inequalities that may exist between urban and rural areas as well as between different European cities.

3.2. Methods

The new damage functions are available for 138 NUTS-2 regions in Europe. The functional form of the damage functions is as follows:

$$D_{CMCC,r} = a * (b_{1,r} T_r + b_{2,r} T_r^2)$$

, where T is the regional (NUTS-2) change in temperature w.r.t. 1986-2005, a is the quantile regression factor and D represents the resulting impact expressed as a GDP equivalent loss (% GDP). $b_{1,r}$ and $b_{2,r}$ estimates are available in low, median and high versions, highlighting the uncertainty bounds of the damage function estimation process.

Figure 3.1 presents the estimates of the updated damage function coefficients made in COACCH. An interesting first observation of the figure is that certain local areas have negative temperature coefficients, implying that such areas could expect positive impacts of climate change at certain temperature points. This is in contrast to the previously used damage function for Europe in CLIMRISK that was derived from the RICE model which is positive for all temperature values:

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

$$D_{RICE,\,EU} = 0.1591 * T^2$$

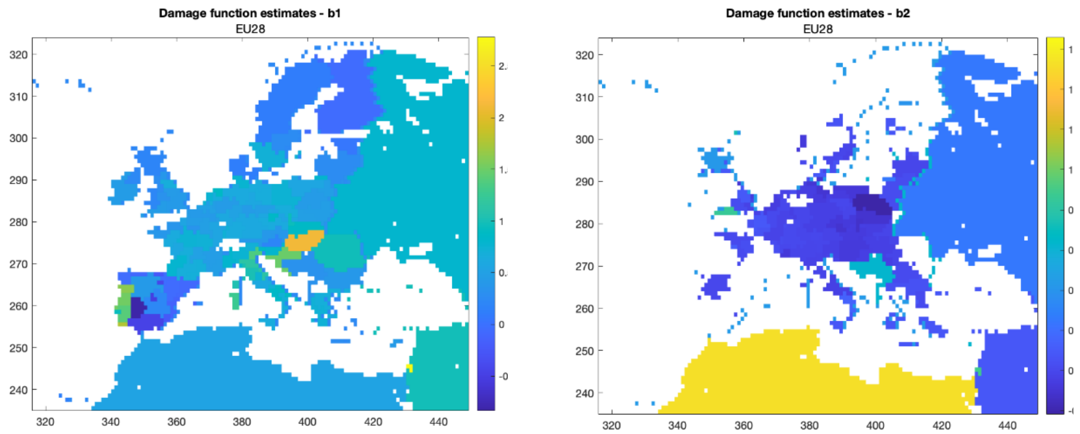


Figure 3.1: Damage function estimates for temperature change, excluding SLR. Estimates include b1 temperature coefficient (left panel) and b2 temperature squared coefficients (right panel).

The IAM used with the new damage functions is CLIMRISK (Estrada & Botzen, 2021; Ignjacevic et al., 2020, 2021) which makes use of the local-scale temperature projections to generate climate impact projections on a 0.5° x 0.5° scale[11]. The main change refers to the damage function for Europe where, instead of the single parameter estimate, we introduce NUTS-2 region-specific parameters which are expected to improve the precision of local-scale estimates.

To aid the presentation of results, an annual discount rate of 2% was used to illustrate the expected discounted climate damage over the course of the 21st century. The choice of the discount rate is entirely flexible in the model and results can be explored with alternative rate specifications.

3.3. Results

In this section, we present impact estimates for different climate and socioeconomic scenario combinations for Europe. Finally, we highlight cities in Europe that are projected to experience the highest climate-related impacts.

First, it is important to place the results using the new damage function in the context of previous modelling results. Figure 3.2 outlines the difference between the previously used RICE model damage function for Europe and the newly developed NUTS-2-level

[11] For more details about the complete methodology of the CLIMRISK model, please refer to the original papers' supplementary information (Estrada & Botzen, 2021).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

functions. The estimates are similar for a moderate mitigation scenario (RCP4.5), but the difference is more apparent for a low mitigation scenario (RCP8.5) whereby the new COACCH estimates lead to a lower overall impact estimate in Europe. This difference can be explained by the fact that some areas experience positive impacts of climate change, an effect that was impossible to capture through the EU-wide RICE damage function.

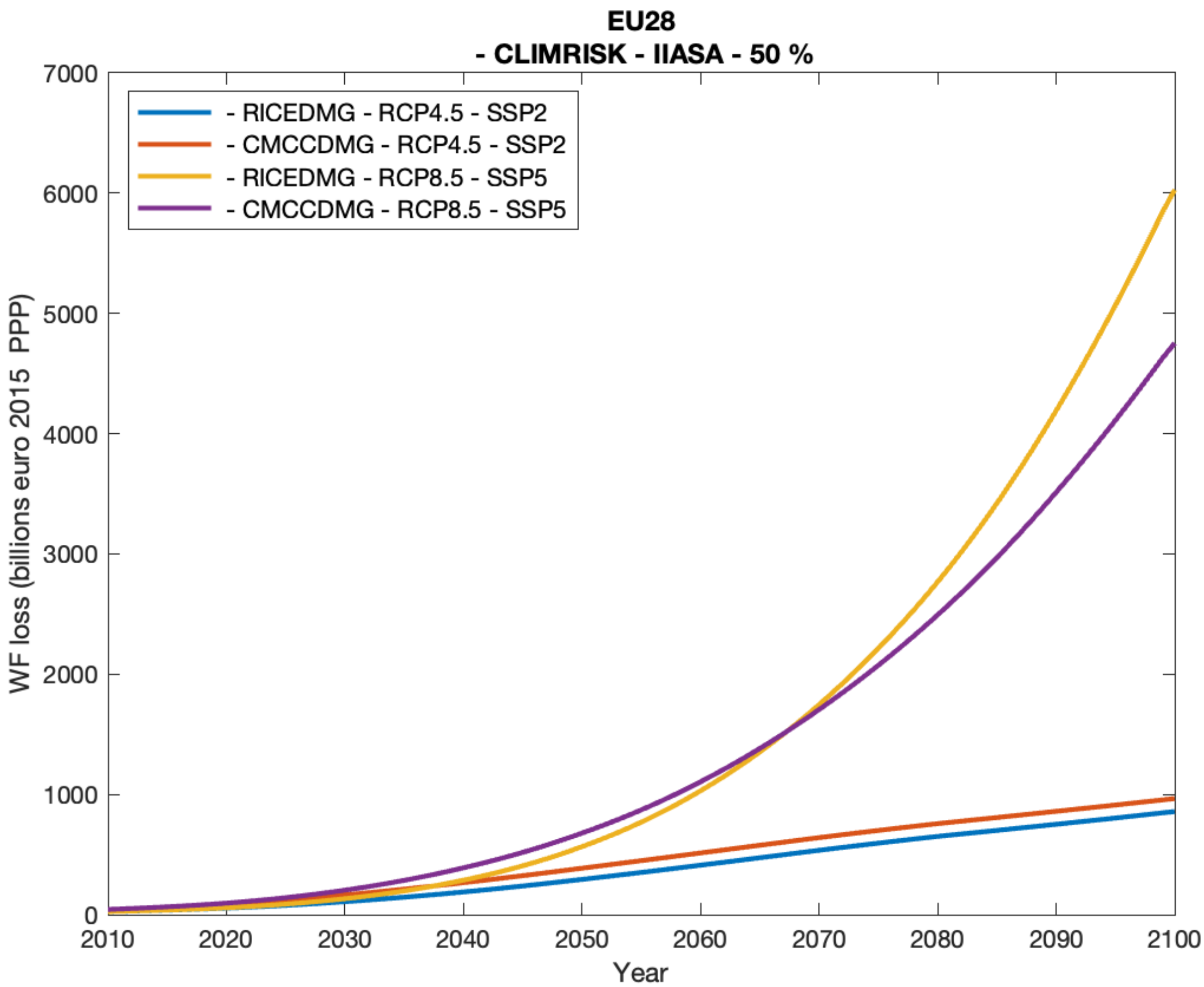


Figure 3.2: Difference in total climate impact projections between using RICE and CMCC damage functions in Europe for RCP4.5 and RCP8.5 scenarios.

A more local comparison between the two damage function specifications is made in Figure 3.3. It appears that the damage estimates are higher in more urban areas. In the RCP8.5 example, it is evident that estimates are lower on average in central and western europe. Spain represents an interesting example as several regions experience positive impacts of climate change initially, leading to lower estimates (dark blue) than previously thought (light blue). However, areas that represent centers of economic activity (eg. Madrid) experience higher damages than previously modelled. In comparing figures 3.2 and 3.3, we can conclude that although the total EU projected damages are not drastically different between the new and the old specifications, local

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

differences emerge due to accounting for local-scale vulnerability through the new damage functions.

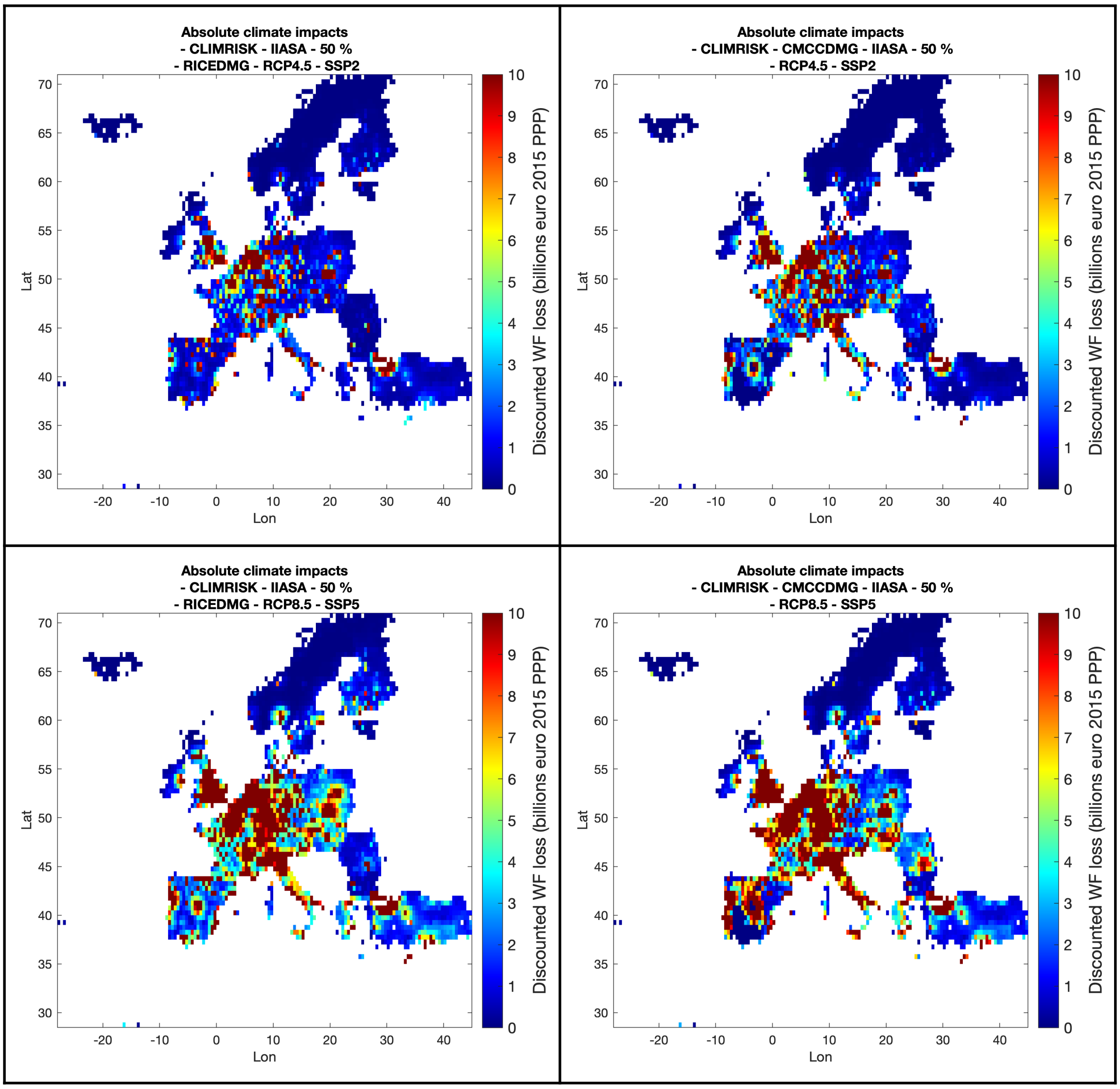


Figure 3.3: Difference between using RICE and COACCH damage functions in Europe.

There is a degree of uncertainty with respect to the damage function specification. In other words, local-scale uncertainties exist in how severely climate change would impact a particular area. Figure 3.4 presents the difference in choice between the low and high parameter estimates. The low case represents the low 5th percentile of the estimates whereas the high case represents the 95th percentile of the estimated parameters, each leading to lower and higher estimates compared to the median, respectively. In the remainder of the results presentation, only the median estimate will be used but it is important to note that uncertainty can also be explored in the damage function parameterization space.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

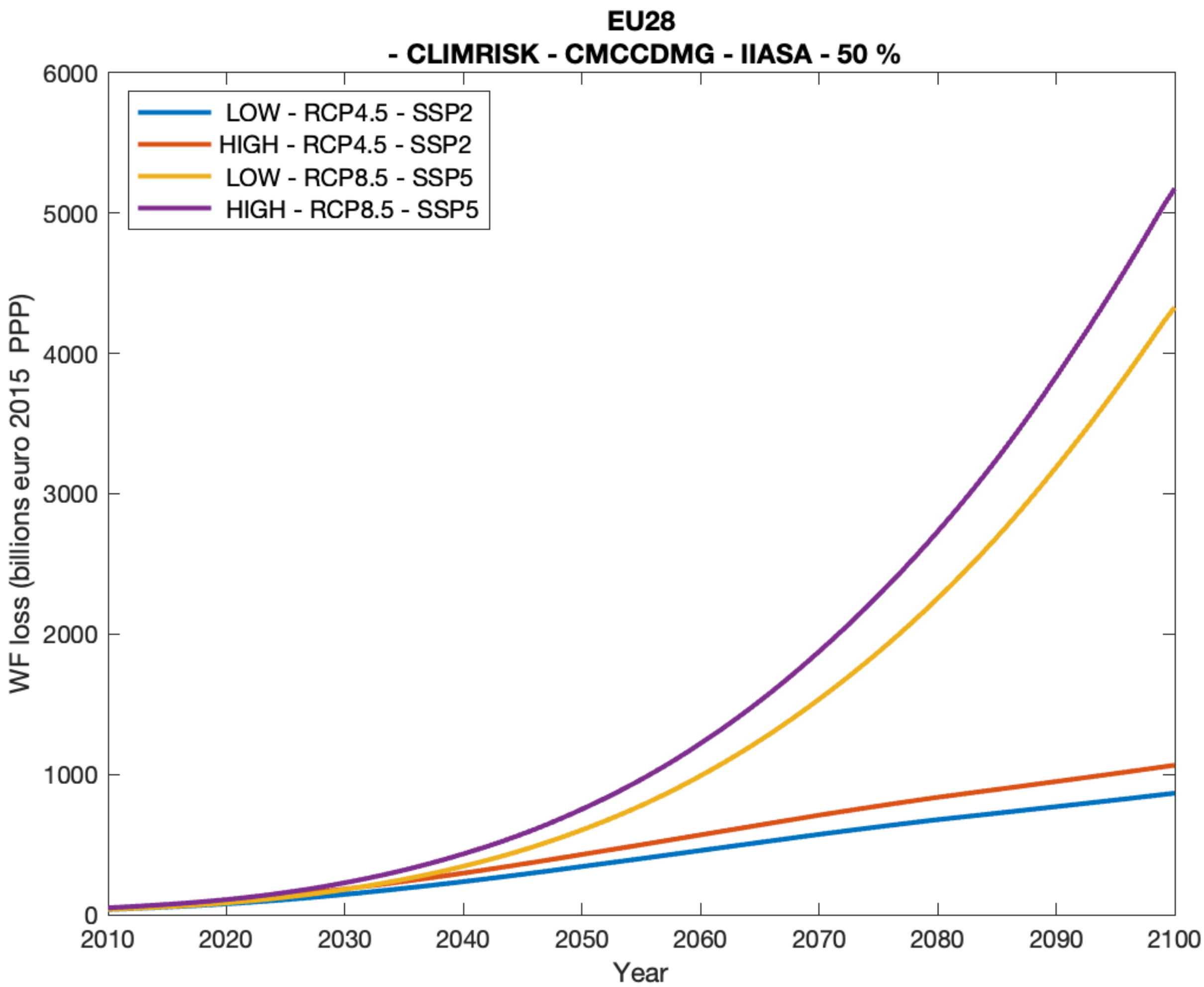


Figure 3.4: Damage function uncertainty explored through the use of low (5th percentile) and high (95th percentile) coefficient estimates (b1 and b2) for RCP4.5 - SSP2 and RCP8.5 - SSP5 scenario combinations.

If we zoom into the local-scale results, local differences in climate impact projections emerge. Figure 3.5 shows discounted estimates of total impacts of climate change in Europe over this century. The choice of the climate scenario is paramount to the severity of climate impacts as abiding by the Paris agreement is expected to yield the lowest amount of discounted damages. Nevertheless, urban areas still experience higher impacts compared to the rural areas due to higher exposure.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

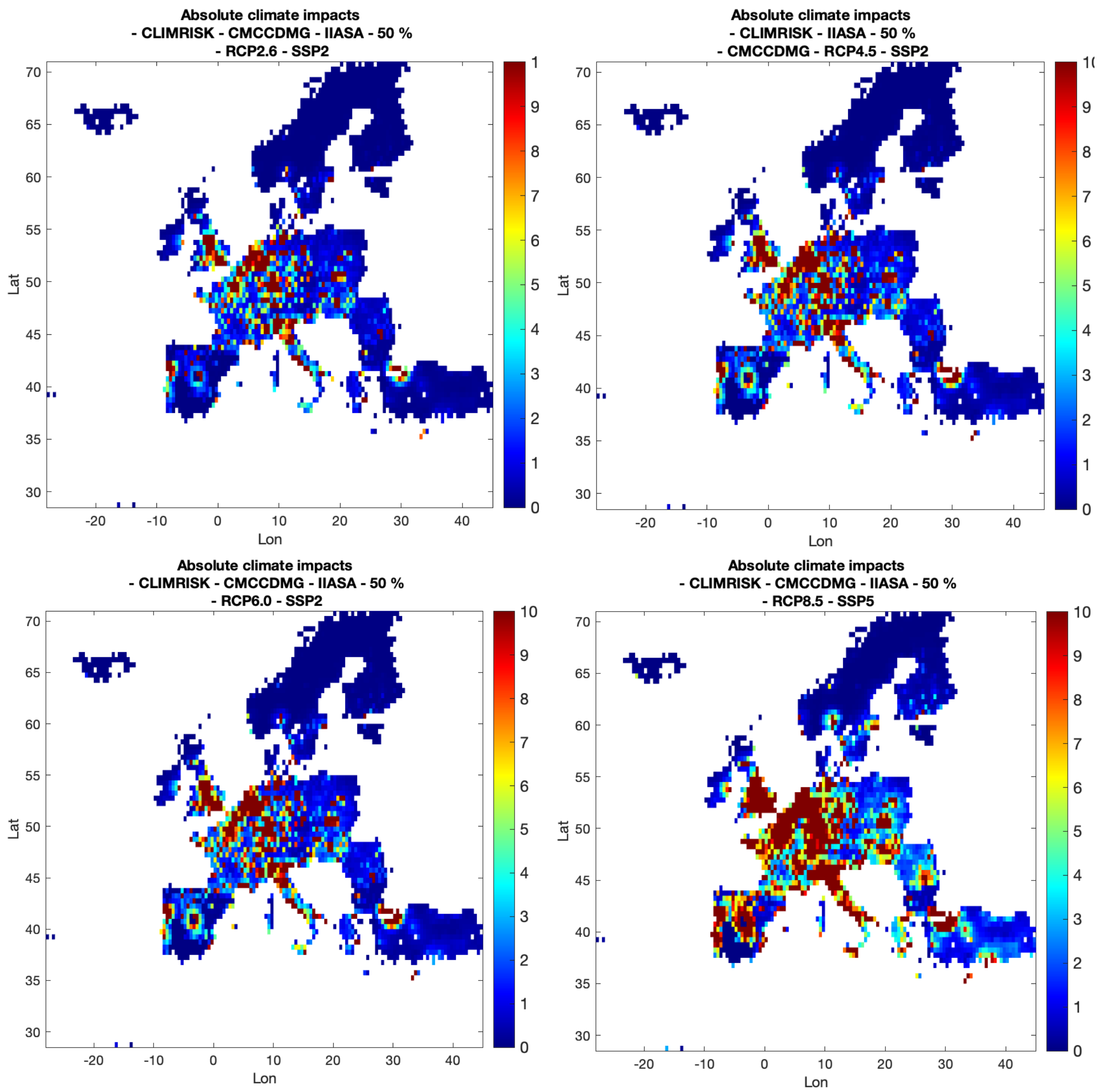


Figure 3.5: Grid cell-level impacts of climate change in Europe. Scenario combinations RCP2.6 - SSP2 (top-left), RCP4.5 - SSP2 (top left), RCP6.0 - SSP2 (bottom left) and RCP8.5 - SSP5 (bottom right).

The most important determinant of the severity of climate impacts is the choice/realization of the climate and socioeconomic scenario. Figure 3.6 shows such results for a standard set of scenario combinations, each of whom represent a different treatment of the climate change crisis. Major differences start to emerge only in the second half of the 21st century whereby total climate impacts in Europe over this century reach €1 trillion in 2055 alone under the RCP8.5 scenario. This impact could be kept below €250 billion under the high mitigation scenario of RCP2.6. The difference is more severe in the long-term, when such impacts exceed €2.5 trillion and €350 billion respectively in 2080 and become 10x as high at the end of the century.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

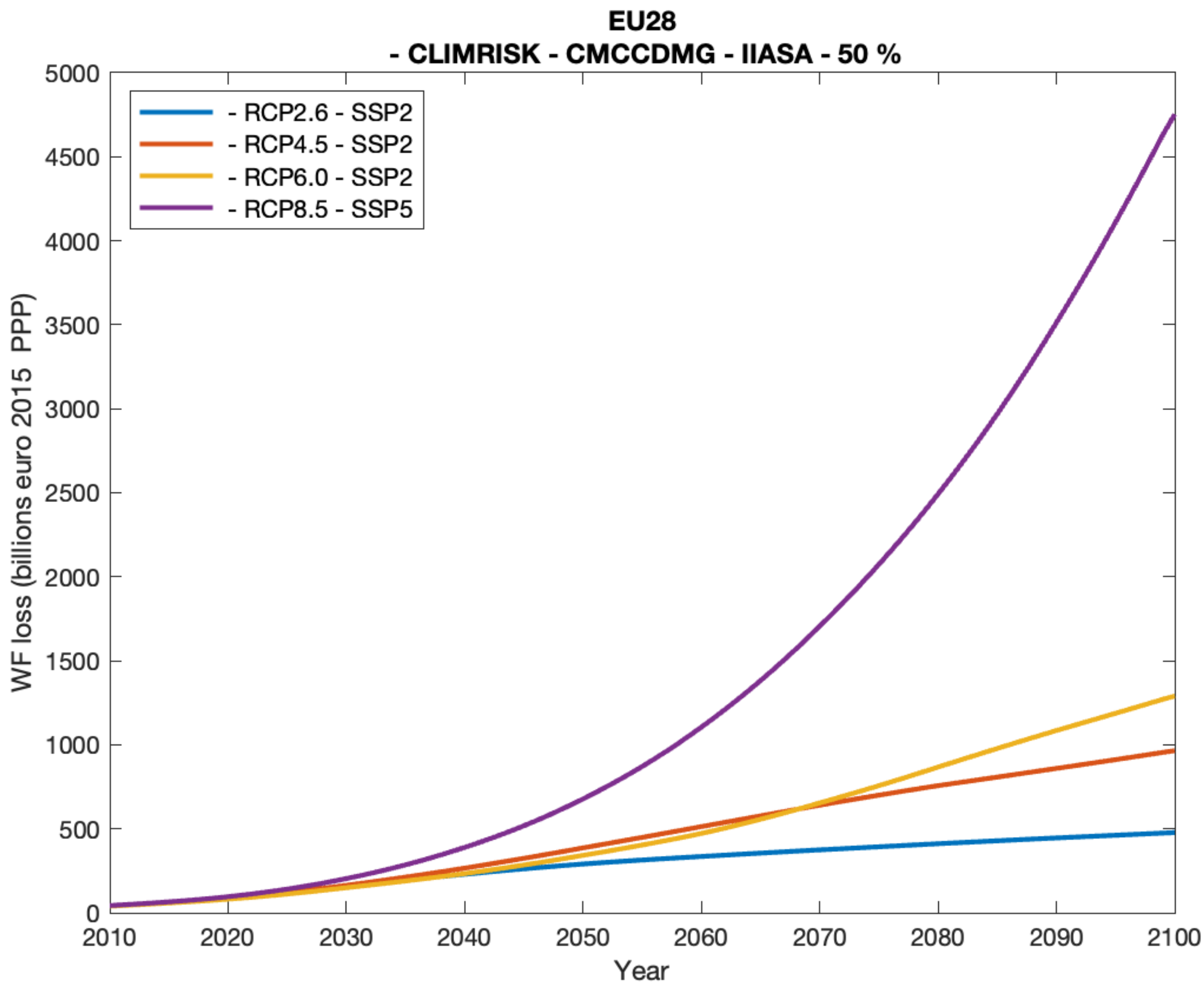


Figure 3.6: Evolution of climate impacts in the 21st century Europe for various climate and socioeconomic scenarios. Significant damage could be prevented when abiding by the Paris Agreement, about 10x less damage in 2100 compared to the RCP8.5 scenario. Socioeconomic projections sourced from IIASA, median realization of climate projections.

Now that the EU-wide results have been explored, we move on to the country-level aggregation using total discounted impacts over this century. Table 1 ranks European countries by the severity of projected climate impacts whereby Germany ranks highest with discounted total impacts ranging from €2 trillion to over €6 trillion until 2100. The situation is similar in France and Italy with somewhat smaller impacts under the RCP8.5 scenario. Given that the impacts presented refer to absolute values, it is no surprise that smaller countries with less economic output populate the bottom of the table (e.g., Iceland, Estonia, Cyprus etc.) with the most severe discounted impacts not exceeding €100 billion.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Table 1: Discounted (2%) total climate impacts in Europe over this century, in decreasing order of severity, for different climate and socioeconomic scenario combinations. Discounted impacts are most severe in Germany (>6 trillion) and least severe in Iceland (~7 billion) under the low-mitigation scenario (RCP8.5).

Europe Discounted climate impacts (€ bil, 2015 PPP)	**RCP2.6** SSP2	**RCP4.5** SSP2	**RCP6.0** SSP2	**RCP8.5** SSP5
Germany	2114.77	2897.53	2928.37	6526.62
France	1488.06	2143.35	2193.29	5568.13
Italy	1478.74	1995.37	2002.64	4005.31
UK	911.68	1320.58	1355.57	3654.87
Netherlands	408.43	567.83	575.75	1367.15
Hungary	396	529.25	534.05	901.85
Poland	363.79	502.47	513.06	869.99
Turkey	300.11	681.02	783.11	2683.93
Portugal	271.78	370.94	375.31	939.01
Romania	250.15	355.18	362.87	824.81
Belgium	186.96	252.32	253.86	583.14
Sweden	180.98	282.04	292.41	849.35
Spain	179.21	510.2	580.84	2417.69
Greece	144.25	221.04	229.81	713.88
Czechia	140.5	185.72	186.82	303.9
Austria	136.51	179.21	178.94	380.61
Slovakia	91.13	120.42	121.15	210.41
Switzerland	88.55	155.09	163.46	517.36
Slovenia	44.65	59.06	59.18	113.97
Finland	44.12	94.75	103.64	404
Bulgaria	39.67	52.07	51.64	98.98
Norway	36.09	72.83	78.81	278.36
Ireland	31.07	46.47	47.87	129.75
Denmark	27.56	51.67	55.42	192.01
Luxembourg	19.92	27.71	28.14	66.66
Cyprus	16.05	29.55	32.03	109.86
Estonia	1.36	2.23	2.37	7.21
Iceland	0.79	1.62	1.77	6.86
Total	9392.88	13707.52	14092.18	34725.67

Given the local nature of the newly estimated damage function, it is important that we place special focus on urban areas with significant economic exposure. The main advantage of the CLIMRISK model is the special treatment of the urban heat island (UHI) effect (Estrada & Botzen, 2021; Ignjacevic et al., 2020) which can be added on top of the existing damage functions which do not account for such an effect to capture the combined impacts from local and global warming. In case of using additional urban heat island (UHI) damage functions in our case, the total projected local impacts increase drastically. Table 2 presents the results with, and without, additional UHI damage functions. Using Paris as an example, under the RCP8.5 – SSP5 scenario, the discounted impacts with UHI functions is almost three times higher (€4 trillion) than

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

without (€1.8 trillion). Such results illustrate the potential danger urban areas are facing when the UHI effect is accounted for; not only is the local temperature in the urban area expected to be higher than the surrounding rural area but the exposure is also much higher. In other words, climate change is more severe and there is more to be lost.

Table 2: Discounted impacts of top10 most affected European cities, ranked by the severity of total discounted climate impacts over this century under the no mitigation (RCP8.5) scenario. The results are with (bottom table) and without (top table) the UHI damage functions. Western European cities are at most risk, of which many could experience damages exceeding 1 trillion euros in total discounted losses by 2100.

Top 10 EU-28 cities Discounted climate impacts (€ bil, 2015 PPP)	**RCP2.6** SSP2	**RCP4.5** SSP2	**RCP6.0** SSP2	**RCP8.5** SSP5
Paris	422.63	638.2	660.12	1826.63
Cologne	548.43	767.43	780.03	1775.87
London	303.99	438.64	449.51	1184.91
Milan	457.35	598.72	596.92	1103.31
Madrid	58.97	204.85	238.05	1025.52
Frankfurt	327.98	449.42	454.38	1006.39
Amsterdam	251.08	351.65	357.32	855.77
Istanbul	81.39	183.23	210.09	771.03
Budapest	297.04	395.83	399.02	624.56
Leeds	168.28	236.04	240.39	604.08

Top 10 EU-28 cities + UHI Discounted climate impacts (€ bil, 2015 PPP)	**RCP2.6** SSP2	**RCP4.5** SSP2	**RCP6.0** SSP2	**RCP8.5** SSP5
Paris	1248.79	1604.55	1640.96	4083.68
Cologne	841.28	1188.48	1229.09	3257.22
London	582.19	791.65	816.11	2253.81
Istanbul	658.84	883.96	926.8	2154.45
Madrid	370	554.85	581.51	1516.52
Milan	454.94	631.68	644.61	1513.84
Frankfurt	338.59	495.65	513.61	1404.7
Amsterdam	266.56	375.91	387.59	1046.33
Manchester	196.54	275.91	285.6	828.02
Leeds	202.23	282.45	291.81	827.79

If cities are ranked based on severity of impacts in years 2050 and 2080, the results would resemble Table 3. Paris and Cologne could both exceed €100 billion in climate impacts in 2080 alone. The results are also high in 2050 with all top 10 cities exceeding €10 billion under the RCP8.5 scenario. The benefits of climate mitigation are also seen in cities in the second half of the century; Madrid, for example, is only looking at €3 billion in estimated impacts in 2080 under the RCP2.6 scenario compared to almost €90 billion with no climate mitigation in place.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Table 3: European cities with the highest estimates of climate impact across different climate and socioeconomic scenario combinations. Estimates for years: 2050 (top panel) and 2080 (bottom panel).

Top 10 EU-28 cities, 2050 Climate impacts (€ bil, 2015 PPP)	**RCP2.6** SSP2	**RCP4.5** SSP2	**RCP6.0** SSP2	**RCP8.5** SSP5
Cologne	17.03	22.13	19.8	37.79
Paris	13.09	17.91	15.66	34.82
Milan	13.99	17.57	15.97	27.38
London	9.27	12.3	10.9	23.36
Frankfurt	10.17	13.04	11.74	22.38
Amsterdam	7.66	9.99	8.92	17.53
Budapest	9.11	11.2	10.28	13.45
Leeds	5.11	6.64	5.94	12.49
Berlin	6.15	7.77	7.05	12.45
Bucharest	5.13	6.69	5.98	12.3

Top 10 EU-28 cities, 2080 Climate impacts (€ bil, 2015 PPP)	**RCP2.6** SSP2	**RCP4.5** SSP2	**RCP6.0** SSP2	**RCP8.5** SSP5
Paris	17.97	35.19	41	132.47
Cologne	23.36	40.59	45.78	121.16
Madrid	3.15	15.4	20.62	88.51
London	12.94	23.64	27.04	83.36
Milan	18.01	28.79	31.66	68.72
Frankfurt	13.89	23.38	26.12	67.17
Istanbul	4.53	13.3	16.78	65.67
Amsterdam	10.55	18.51	20.94	60.61
Budapest	15.78	23.84	25.71	45.09
Leeds	7.2	12.56	14.19	41.72

3.4. Conclusion

In this section, we explored climate impact estimates in Europe using the recently developed NUTS-2-level damage functions. The EU-wide estimates are comparable in magnitude to the previously used set of damage functions (RICE model), but local differences emerge due to the higher spatial resolution of the functions and the possibility of accounting for the positive impacts of climate change in certain regions.

Absolute impacts are projected to be the highest in most developed countries in Europe such as Germany, France, Italy and the UK. This storyline is matched by the high impacts expected to occur in most populated cities such as Paris, Cologne, London and Milan, all of which could see discounted total impacts exceeding €1 trillion in the 21st century. All in all, the new damage estimates contribute to the increasing precision of the local scale results. The uncertainty range of the functions (low, median and high)

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

contributes to an already existing set of uncertainties involving climate and socioeconomic developments.
Future research could focus on generating local-scale estimates for other world regions in order to further improve our understanding of the local impacts of climate change.

3.5. References

Anthoff, D., & Tol, R. S. J. (2014). The Climate Framework for Uncertainty, Negotiation and Distribution (FUND), Technical Description, Version 3.9. *Www.Fund-Model.Org*, *26*, 1–69. http://www.fund-model.org/versions

Bosetti, V., Massetti, E., & Tavoni, M. (2007). The WITCH Model: Structure, Baseline, Solutions. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.960746

Estrada, F., & Botzen, W. J. W. (2021). Economic impacts and risks of climate change under failure and success of the Paris Agreement. *Annals of the New York Academy of Sciences*, nyas.14652. https://doi.org/10.1111/nyas.14652

Ignjacevic, P., Botzen, W. J. W., Estrada, F., Kuik, O., Ward, P., & Tiggeloven, T. (2020). CLIMRISK-RIVER: Accounting for local river flood risk in estimating the economic cost of climate change. *Environmental Modelling and Software*, *132*, 104784. https://doi.org/10.1016/j.envsoft.2020.104784

Ignjacevic, P., Estrada, F., & Botzen, W. J. W. (2021). Time of emergence of economic impacts of climate change. *Environmental Research Letters*, *16*(7), 074039. https://doi.org/10.1088/1748-9326/AC0D7A

Nordhaus, W. D. (1992). The “DICE” Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming. In *Cowles Foundation Discussion Paper*. https://doi.org/DOI:

Nordhaus, W. D. (2017a). Revisiting the social cost of carbon. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(7), 1518–1523. https://doi.org/10.1073/pnas.1609244114

Nordhaus, W. D. (2017b). The social cost of carbon: updated estimates. *Proceedings of the US National Academy of Sciences, January*, *31*.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

4. Macroeconomic assessment of national adaptation strategies

Authors:

Eva Preinfalk (Uni Graz), Nina Knittel (Uni Graz), Birgit Bednar-Friedl (Uni Graz), Elisa Sainz de Murieta (BC3), Max Tesselaar (VU), Gabriel Bachner (Uni Graz)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

In this chapter, we first assess current and future public adaptation expenditures in three case study countries: Austria, Spain, and the Netherlands. Second, we assess the economy-wide consequences of these policies by 2050 to assess whether adaptation is cost-effective not only from a sectoral but also from a macroeconomic stance. Third, we analyse the consequences of these adaptation expenditure pathways for government budgets, both from a mainstreaming perspective and from the perspective of public austerity. In addition to direct effects of public adaptation expenditures on government budgets also indirect effects are considered, e.g. changes in the tax base resulting from alterations in economic output, labour and capital income.

There is growing evidence suggesting that the economy-wide consequences of climate change in Europe are substantial (Ciscar et al., 2011; Dellink et al., 2019; Koks et al., 2019; Szewczyk et al., 2020, 2018) and that effective adaptation is needed to reduce these risks. The public sector plays a substantial role in promoting and facilitating adaptation action as the owner of critical infrastructure and as the provider of important information and services facilitating and coordinating private adaptation action (Eakin and Patt, 2011; Stern, 2007). This strong role of the public sector is also reflected by the European Union's Green and White paper on adaptation and the pursuing EU adaptation strategy issued in 2013, with an overhaul in 2021 (European Commission 2007, 2009, 2013,2021) and the European Commission's climate action spending targets in its Regional Cohesion and Structural Investment Funds (European Commission 2018).

This study addresses this important research gap by assessing the macroeconomic viability and budgetary effects of public adaptation in three EU case study countries. To be of relevance for adaptation decision making in practice (Hinkel and Bisaro, 2016; Warren et al., 2018), we consider actually implemented as well as planned or proposed measures as part of a comprehensive adaptation strategy. In the first part, we shed light on the practical implementation of public adaptation in three EU Member States: Austria, Spain and the Netherlands. Not only do these countries differ with respect to their historical background in dealing with climate risk and the institutional framework promoting adaptation, but based on their geographical locations, they are exposed to a wide range of climate risks. The continuous retreat of glaciers, longer vegetation periods and an increase in temperature extremes make climate change in Austria easily observable (BMNT, 2017). By 2020, annual climate change induced damages aggregate to € 2 billion in Austria, a number that is expected to more than double by mid-century (Steininger et al., 2020). Located in the Mediterranean basin, Spain is exposed to a wide range of climate risks, such as water scarcity, floods, heat waves and prolonged droughts (Vargas-Amelin and Pindado, 2014). As a result of a changing climate, an increase in the frequency and magnitude of such hazards can be expected (Vargas-Amelin and Pindado, 2014). With almost 60% of the country and about 9 million people prone to flooding, Dutch water management is a long-lived tradition (Van Alphen, 2016). Thus, the selected case study countries are a representative sample of the adaptation landscape among Member States, as well as of the range of climate impacts Member States are adapting to. In line with the most frequently addressed climate risks by EU Member States (EEA, 2020), we focus on adaptation action addressing the risks of riverine and coastal flooding, as well as the impact of climate change in the agricultural and forestry sector.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Besides taking stock of the practical implementation of public adaptation strategies in three Member States, the second objective of this study is to analyse the macroeconomic viability of planned adaptation actions. Based on a review of existing literature and consultation with national experts and stakeholders, indicative adaptation cost pathways until 2050 are developed. For the analysis of the direct and indirect budgetary and economic consequences of adaptation, the pathways are introduced to a multi-sectoral, multi-regional comparative static computable general equilibrium (CGE) model. Due to the sectoral detail and differentiation between economic agents, the CGE model allows for a detailed assessment of various types of adaptation activities, taking into account economic feedback effects and budgetary implications of the implemented actions. Following the modelling directions for adaptation proposed by Fisher-Vanden et al. (2013), as well as the refined modelling of public costs of adaptation by Bachner and Bednar-Friedl (2019), we account for different types of adaptation (infrastructural, informational, ecosystem-based adaptation) and types of costs (investment, maintenance and operating costs), as well as different developments of these expenditure components over time. To account for the benefits of adaptation, we model the economic consequences of climate change in 2050 across a set of climatic and socioeconomic scenarios and consider the effectiveness of different adaptation options based on literature and expert assessment (Kolström et al., 2011; Kuik et al., 2016; Schönhart et al., 2016; Tröltzsch et al., 2012).

4.1. Public climate change adaptation in the EU – presenting the level of current and future public adaptation action in three case study countries

National adaptation strategies and plans across EU Member States (European Commission 2018; Leitner et al. 2020) show that despite differences with respect to the historical background of dealing with climate risk and the institutional framework promoting climate resilience, adaptation is a present and well-established issue in public policy across the EU.
Climate adaptation action is often suggested to be mainstreamed into all policy areas, as adapting in many cases means doing things differently, rather than doing different things. This implies that from a budgetary perspective, adaptation tracking faces the additional challenge of identifying relevant action and projects, which are rarely stand-alone projects. Based on available information on public adaptation projects and a consultation of national experts from ministries and the scientific community, we collected and synthesized data on public adaptation finance, as well as the types of actions pursued to address a range of climate risks until 2050. Adhering to common classifications of adaptation actions (e.g. European Environment Agency 2013; Goldstein et al. 2019; Noble et al. 2014), we differentiated by adaptation sectors (energy, infrastructure, agriculture etc.), risks addressed (e.g. riverine flooding, sea level rise, drought) and types of adaptation actions (grey/infrastructural; soft/informational; green/ecosystem-based). With the base year of our dataset being 2011 and the target year of investigation being 2050, we collected information on (i) the past and current level of public adaptation expenditures (i.e. 2011-2019); (ii) the planned or announced adaptation expenditures (i.e. 2020-2030); and (iii) additional adaptation expenditures beyond the current budgetary planning period (i.e. 2030-2050). While we reviewed realized budget or project reports for the first category of observed adaptation expenditures up to 2019, we investigated budget plans or announced projects for the period up to 2030. As there is hardly any information available beyond 2030, we relied on expert consultation and suggestions from the literature regarding sound adaptation pathways to extrapolate adaptation costs up to 2050, following the approach in Bachner et al. (2019). The combination of this information allowed us

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

to construct indicative adaptation pathways until 2050 for each of the case study countries, which are discussed in the following.

Austria

The continuous retreat of glaciers, longer vegetation periods and an increase in temperature extremes make climate change in Austria easily observable (BMNT, 2017). In 2020, annual climate change induced losses aggregated to € 2 billion, a number that is expected to more than double by mid-century (Steininger et al., 2020). In response to the clear signs of climate change in Austria, the Austrian Federal Ministry of Agriculture, Forestry, Environment and Water Management developed the first strategy for adaptation in 2012, followed by an update in 2017 (BMNT, 2017). Based on scientific findings and a broad stakeholder process, the strategy identified 14 key areas of action, ranging from agriculture, forestry, water resources and water management to tourism, industry and settlements (BMNT, 2017). The enhancement and communication of knowledge and scientific information on climate change, as well as the integration of adaptation into instruments and decision-making processes in the public and private sector constitutes a major objective of the Austrian adaptation strategy (BMNT, 2017).

Adhering to the idea of adaptation mainstreaming into all (policy) domains, no dedicated budget is foreseen for the implementation of adaptation. Instead, the implementation occurs within the existing jurisdictions and funding should be provided by a careful prioritization and reallocation of available resources (BMNT, 2017). In the absence of aggregated figures or detailed information on adaptation costs provided by the Austrian government, we employ a top-down approach proposed by Knittel et al. (2017), combined with the consultation of experts in the relevant ministries to determine and assess the annual public budget share attributed to adaptation. In our assessment, we focus on three key impact fields: flood risk management, forestry and agriculture, as Bachner et al. (2015) find that the costs of inaction are most severe in these sectors. Furthermore, funding under the Austrian Climate and Energy Fund is included, given the pivotal role attributed to knowledge generation in the Austrian adaptation strategy (BMNT, 2017).

We find that expenditures directed at adaptation in forestry and agriculture, as well as flood risk management and research on vulnerability and resilience, amounted to approximately € 550 million in 2017 (2017 is the latest year available for the Austrian budget report at the time of analysis), corresponding to about 0.15% of Austrian GDP and 0.3% of total public expenditures. Green, or ecosystem-based measures constitute the most dominant category of Austrian adaptation measures, especially in the agricultural sector, where the public sector incentivizes the utilization of more resilient crop and plant varieties. Grey or infrastructural measures are important mainly in forestry and water management and comprise the construction of flood barriers or torrent control systems in mountains and valleys. Expert appraisal suggests that the need for adaptation in the forestry sector will grow, as a result of the increasing threat of forest fires, storm damages and pests. Also, the afforestation of protective forests and the adaptation of tree species is increasing the importance of green measures in the forestry sector. Soft measures, such as the establishment of monitoring and early warning systems or the mapping of risk zones, are important for raising awareness to climate risks, and are likely to gain in importance over time. Expert appraisal furthermore suggests that the share attributed towards the maintenance of flood protection infrastructure will increase in the medium to long run, keeping the share of grey measures comparatively high. A prioritization of green and soft measures in the Austrian flood risk management plan (BMNT, 2018) is likely to result in higher expenditures in these categories until 2050. The last expenditure category considered refers to publicly funded adaptation research under the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Austrian Climate and Energy Fund (KLIEN). In the current funding period, a fifth of the available budget is attributed towards adaptation. According to expert appraisal, adaptation has emerged into an important pillar in the KLIEN. We assume a steady increase in the adaptation-relevant budget of the KLIEN, as increasing awareness of the consequences of climate change may lead to an increased prioritization of adaptation related research.

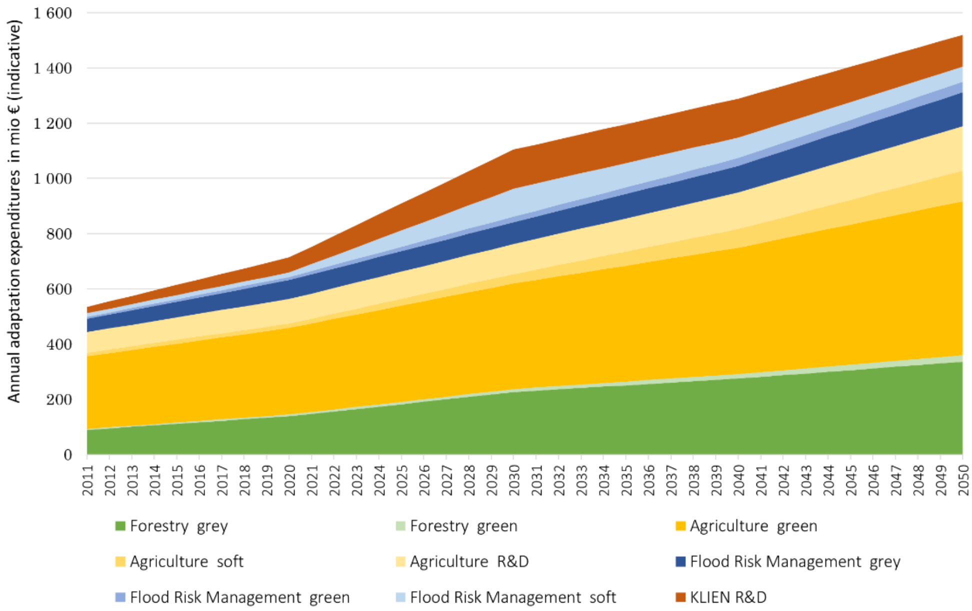


Figure 4.1: Expenditures on flood risk management, adaptation in forestry & agriculture and R&D in Austria between 2011 and 2050. Numbers are based on the Austrian budget report and export consultation.

Spain

Located in the Mediterranean basin, Spain is exposed to a wide range of climate risks, such as water scarcity, floods, heat waves and prolonged droughts (Vargas-Amelin and Pindado, 2014). Causing a decrease in precipitation and runoff, climate change is likely to aggravate already existing conflicts over water use between a powerful agricultural sector and other economic agents (Francés et al., 2017). Moreover, with more 7800 km of coastline, Spain will be exposed to sea level rise, an increase in storminess and storm surges (Losada et al., 2019). The increasing risk of water stress and other climate risks such as pests, invasive species or changes in vegetative cycles is expected to pose difficulties also in the Spanish agricultural and forestry sector (Vargas-Amelin & Pindado, 2014).

In 2006, Spain was among the first EU Member States to compile a national adaptation plan, focusing on coasts, water and biodiversity (Francés et al., 2017). Since 2009, the plan also incorporates health agriculture, forestry and desertification (Losada et al., 2019). The experience of floods, water scarcity, heat waves, droughts and changes in temperatures have left the Spanish water sector highly politicized. Thus, water has developed into a key element in Spanish climate change adaptation. Drought management plans are in place since 2007 and serve as tools for prioritizing water allocations among the water using sectors in case of water scarcity (Francés et al., 2017). Spanish coastal management has been regulated for over 25 years, with legally established instruments for addressing the problem of climate change. Until 2008, Spain's expenditures on coastal protection were among the highest in Europe, constituting approximately € 52 million annually. Coinciding with the peak of the last economic crisis, this budget has decreased significantly since 2009 (López-Dóriga et al., 2020). In the agricultural sector, farmers are encouraged to adapt to changing conditions by providing

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

financial support for the modernization of farm machinery and irrigation systems (Vargas-Amelin and Pindado, 2014). To reduce erosion and desertification of forest areas, reforestation and afforestation is promoted, alongside the improvement of infrastructures necessary in case of forest fires.

Based on an aggregated list on past, current and planned adaptation actions in Spain provided by the Basque Centre for Climate Change and assessment by national experts in the field of adaptation, we extrapolate an adaptation cost pathway until 2050 (see Figure 4.2). In light of the increasing frequency and intensity of droughts, we expect that investments in irrigation remain important. Under the Hydrological Plans, Spain has attributed a considerable share of public resources towards the management of hydrological resources in agriculture and flood risk, with a large share of structural measures. Given that among the many projects implemented under the Hydrological Plans, climate change adaptation constitutes only a secondary goal, a share of 40% of total expenditures under the Hydrological Plans is considered as adaptation costs, in line with the EU tracking mechanism (European Court of Auditors, 2016).

Over the years, ecosystem-based actions have increased in importance in managing riverine flood risk, promoting the reforestation of riverbanks and ecosystem-restoration of rivers. With an increase of droughts and heat spells, the prevention of forest fires will remain an important pillar in the adaptation of the forestry sector, comprising a large share of structural measures for improving the infrastructure necessary to prevent and extinguish fires. Expenditures on coastal management have been heavily fluctuating over the past years, with about half of the resources directed towards the implementation of hard and soft structural measures, such as sea walls and beach nourishments. A significant share of resources was used for the analysis of vulnerabilities and the synthesis of regional adaptation plans. Given the coast’s vulnerability to climate change, we expect an increase in the implementation of hard structural measures.

The expenditures considered correspond to approximately 0.02% of Spanish GDP, or 0.09% of overall government expenditures in 2019 (as a pre-covid-19 reference year). Besides funding from the national government and autonomous communities, EU funding plays a prominent role in financing adaptation, especially in the agricultural and forestry sector, constituting 42% of the total resources provided that go beyond the Hydrological Plans.

*This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

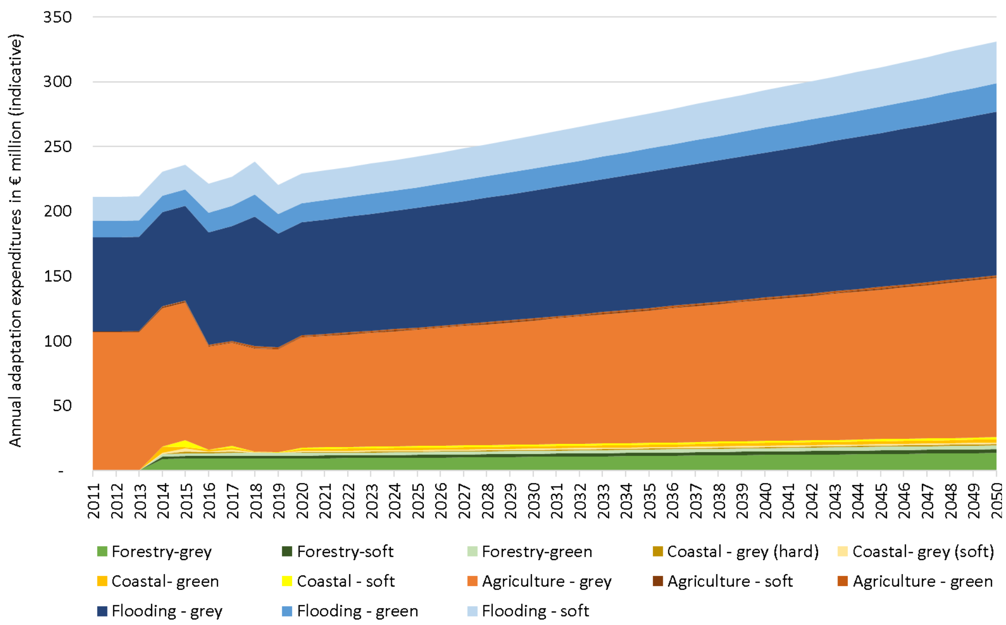


Figure 4.2: Expenditures on riverine and coastal flood risk management, adaptation in forestry & agriculture and R&D in Spain between 2011 and 2050. Based on a comprehensive list of adaptation projects synthesized by the Basque Centre for Climate Change (BC3) and expert consultation.

Netherlands

With almost 60% of the country and almost 9 million people prone to flooding, the Netherlands has a history of living with and also defending itself from floods (Van Alphen, 2016). Following a major flood in 1953, with 1800 casualties and direct losses of a tenth of total GDP, the first Delta Committee was appointed by the government to design necessary flood protection measures (Kind, 2014). Under the Dutch Delta Program, national, regional and local authorities are required to develop strategies and implement measures that ensure long-term flood protection in the Netherlands, keeping the design flexible to climate conditions and options open to avoid lock-ins (Van Alphen, 2016). The legally binding flood protection standards require that the probability of fatality caused by a flood should be no more than 1 in 10 0000 years (Delta Programme Commissioner, 2019) and that therefore infrastructure needs to withstand up to 100 000 year floods (Van Alphen, 2016). To ensure that these legally established standards are met by 2050, funding is provided by the Delta Fund, a stable budget of over € 1 billion annually (Van Alphen, 2016), corresponding to 0.3% of total government expenditures or 0.13% of GDP in 2019. By earmarking financial resources under the Delta Fund, the government reduces dependencies on economic or political circumstances (Delta Programme Commissioner, 2019; Van Alphen, 2016).

In consultation with the Delta Commissioner's office, we identified the flood related expenses under the Delta Fund and were able to gather detailed information on each of the expenditure

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

categories (Delta Programme Commissioner, 2019). In 2019, a share of 80% of the overall Delta Fund was attributed towards the management of flood risk, a share that will have increased to 90% by 2033 (Figure 4.3). According to expert appraisal, structural measures account for the majority of investments, with only 10% of investments directed towards green measures. The share of the total Delta Fund budget attributed to the maintenance, replacement & renovation of existing structures is expected to increase over the next years, given the increase in infrastructural measures. The remaining budget is used for the provision of information and communication technology (ICT) and other public services, as well as for further R&D and planning of future actions.

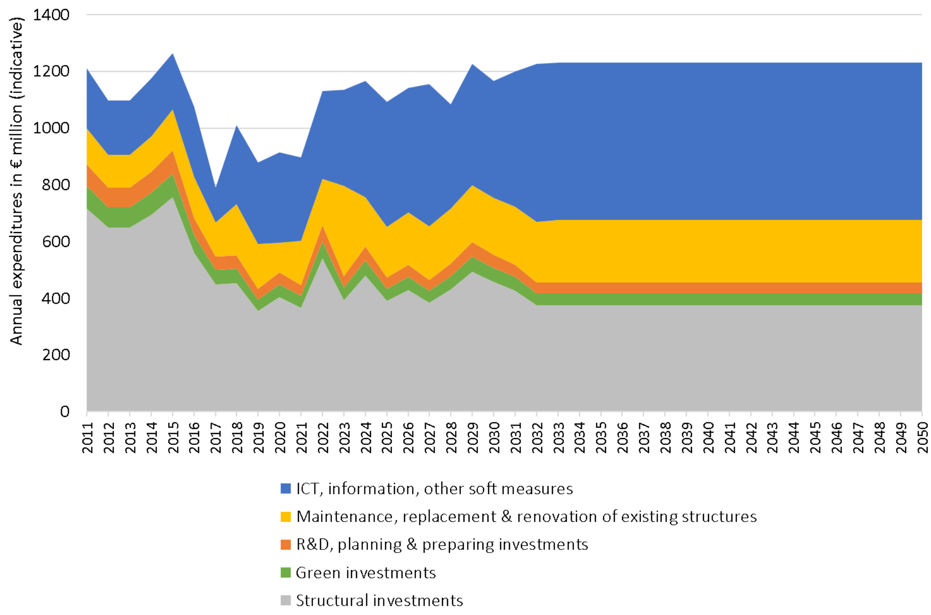


Figure 4.3: Expenditures on riverine and coastal flood risk management under the Dutch Delta programme between 2011 and 2050. Based on information disclosed in the Delta Programme and consultation with experts from the Delta Commissioner's office.

4.2. Methodology

For the macroeconomic assessment of climate change impacts and public adaptation strategies, we employ a multi-sectoral, multi-regional comparative static CGE model that is introduced in Deliverable 3.4. For a more detailed regional and sectoral resolution necessary for the underlying study, the model's disaggregation has been adjusted. The modified regional and sectoral resolution of the model employed is discussed in deliverable 4.2.
Moreover, we extend this model to account for the climate change impacts relevant for the national adaptation actions considered (sea level rise, riverine flooding, productivity changes in agriculture and forestry), as well as towards a detailed account of adaptation measures to reduce these risks. For the modelling approach of the latter, we draw on our national scale impact and adaptation model for Austria (Bachner et al., 2019; Bachner and Bednar-Friedl, 2019; Steininger et al., 2016, 2015).
To take account of uncertainty about socioeconomic and climatic development until

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

mid-century, the scenarios applied in the following analysis are in line with the RCP-SSP framework (Knutti and Sedláček, 2013; O'Neill et al., 2014). While SSPs (shared socioeconomic pathways) describe potential developments of socioeconomic indicators, such as GDP and population growth or land use change, the RCPs (representative concentration pathways) consist of different emission scenarios leading to different levels of warming until the end of the century.

Throughout the analysis, we differentiate between three main scenarios, describing socioeconomic and climatic conditions in 2050: (i) the *baseline scenario*, which considers only socioeconomic development according to the SSP scenario in the absence of climate change, (ii) the *impact scenario*, adding climate change impacts for the underlying RCP to the SSP *baseline* and (iii) the *adaptation scenario,* which introduces adaptation measures to the RCP-SSP framework, including policy costs arising from the implementation of measures and the benefits of adaptation actions. Eventually, we are interested in the potential of climate change adaptation to reduce impacts. Thus, in the results section, we compare the *impact scenario* to the *adaptation scenario*, which are described in the following two paragraphs.

The impact scenario

Climate change enters the model via a range of impact chains that describe how the occurrence of physical climate impacts affects economic systems and public budgets. Quantified by various physical and biophysical impact models, we introduce the impacts of sea level rise, flood risk, as well as changes in agriculture and forestry to the CGE model (see Table 1). Following state-of-the-art approaches in impact modelling (Bosello et al., 2012; Ciscar et al., 2018; Parrado et al., 2020; Roson and Van der Mensbrugghe, 2012), we implement climate change impacts by (i) changing affected production cost structures, (ii) changing productivity levels of certain sectors, (iii) adjusting government demand for investments and (iv) changing the structure of government expenditures. Table 1 provides detailed information on the economic implication and model implementation of each impact chain, as well as the underlying (bio-)physical impact model for each impact field. Riverine flood risk is implemented in two ways: first, as expected annual damage (EAD) considering a range of probabilities of certain exceedance levels and the corresponding annual damages, and second as a 100-year flood, which has a 1% probability of occurrence each year.

Table 1: Implementation of climate change impacts in the CGE model

Climate change impact	Economic implication	Model implementation	Underlying impact model
Riverine flooding **Expected annual damages (EAD)** **100-year flood**	Damage to private and public infrastructure in flooded areas. The maintenance of current protection levels requires government resources.	Reduction of capital endowment as a result of flood damage. Public investment demand for the maintenance of protection levels.	GLOFRIS (Ward et al., 2017; Winsemius et al., 2016)
Sea level rise	Damage to private and public infrastructure along coastlines. The maintenance of current protection levels	see riverine flooding	DIVA (Hinkel et al., 2014)

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

	requires government resources		
Impacts on agricultural yield	Climate change affects the agricultural sector in two ways: (i) direct impact on agricultural yields, (ii) change in available farmland for crop production	The change in agricultural yields is caused by a change in the productivity level of land. Changes in available farmland affect the level of land endowment.	GLOBIOM (Havlík et al., 2011)
Impacts on the forestry sector	Change in the biomass produced in commercial forests due to changes in precipitation patterns and temperature.	Change in the productivity level of the forestry sector.	MAgPIE (Dietrich et al., 2019)

The adaptation scenario

For the *adaptation scenario*, we implement the indicative adaptation cost pathways in the CGE model. The public demand for implementing and maintaining adaptation is modelled by changing the structure of government consumption, leaving the overall level of government consumption unchanged. Green measures constitute reductions in the private endowment of natural resources, as they are converted to protective forests or retention zones for the protection of society. Given that we are working in a comparative-static environment, the development of the green and grey capital stock (e.g. protective forests, sea walls, etc.) resulting from changes in annual investment levels cannot be taken account for explicitly. Thus, we consider the accumulation effect of additional annual investments due to adaptation, by adjusting the level of annual capital costs, i.e. depreciation, of green and grey capital. A range of actions is considered in each impact category, distinguishing between structural investments and the accumulation effect thereof, as well as public demand for maintenance and informational measures. See Appendix B for the specific cost vectors implemented for Austria, Spain and the Netherlands.

The second important building block for the *adaptation scenario* is the expected effectiveness of the implemented measures, expressed in avoided damages or, in case of positive impacts of climate change, amplified benefits from climate change. Given the comprehensive approach to Dutch delta management, the benefits from adaptation arise from the collectively implemented measures, whereas actions directed at flood risk management implemented in Austria and Spain are considered separately, differentiating between the expected effectiveness of grey, green and soft measures. Cost-benefit ratios for flood risk management in Austria and Spain are synthesized from estimated mean cost-benefit ratios of a list of comparable measures, taking into account also lower bound and upper bound ratios (Kuik et al., 2016; Tröltzsch et al., 2012). Similarly, uncertainties concerning the effectiveness of adaptation in the agricultural and forestry sector are taken into account by considering a bandwidth of values, suggested by literature and expert assessment. The underlying assumptions regarding the expected effectiveness of each type of adaptation used throughout this analysis are included in the last column of the cost vectors in Appendix B.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

4.3. Results

After introducing all building blocks necessary for setting up the macroeconomic model, this section discusses the key results of the macroeconomic assessment of public adaptation strategies in Austria, Spain and the Netherlands. Conclusions about the net benefits of adaptation are drawn by comparing the overall level of economic output in terms of GDP, sectoral effects, as well as absolute changes in the revenue and expenditure side of the public budget in the *impact scenario* and the *adaptation scenario.* All impact scenarios discussed in the following section are based on a RCP8.5 and SSP5 development path until 2050 (with GCM HadGEM2-ESM). The results for a RCP4.5 SSP2 (with GCM HadGEM2-ESM) development are included in Appendix B.

Net-benefits of Austrian adaptation action

The types of adaptation actions analysed in Austria are manifold, addressing the risk of riverine flooding, impacts in agriculture and forestry. The impact scenario considers EAD from riverine flooding, productivity changes in agriculture and forestry in 2050 for the scenario RCP8.5 and SSP5 (and with GCM HAD-GEM2; see Appendix B for results for RCP4.5 SSP2) with adaptation actions introduced in the adaptation scenario.

Macroeconomic implications

In 2050, the *impact* scenario with EAD from riverine flooding and changes in the sectoral productivity of the agricultural and forestry sector reduce GDP by 1.16%, relative to the *baseline* in Austria*.* By reducing direct capital damages from riverine flooding and enhancing sectoral productivity levels in agriculture and forestry, adaptation allows for a higher level of economic activity, reducing the GDP losses by 58%. This result is robust for a range of benefit-cost-ratios applied (indicated by the error bar in the adaptation scenario in Figure 4.4). While benefits increase significantly when upper bound effectiveness assumptions of adaptation are applied, there are clear benefits also for lower bound effectiveness levels. See Table A 1 for the underlying estimations concerning the expected effectiveness of adaptation.

Changes in the forestry sector constitute the largest contributor to the negative impacts in Austria, with negative impacts magnified by capital losses due to riverine flooding and productivity losses in agriculture. The implementation of climate impacts in forestry shows that the economy-wide effects of this impact change are substantial for the Austrian forestry sector and woodworking industry (i.e., furniture, paper, etc.). As the output of the forestry sector is almost exclusively used as an intermediate input in the woodworking industry, changes in the sectoral productivity of the forestry sector trigger significant economic feedback effects in the industries employing this input intensively. As a result, GDP losses in the *impact scenario* considering only impacts in forestry constitute 0.97%, relative to the *baseline.* With direct capital damages from riverine flooding amounting to € 700 million, despite the maintenance of current protection levels in 2050, GDP is reduced by 0.11%, compared to the *baseline*. The underlying impact model suggests that climate impacts have a small, yet negative impact on the Austrian agricultural sector, with a decrease in GDP by 0.07% in the *impact scenario* in 2050, relative to the *baseline scenario.*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

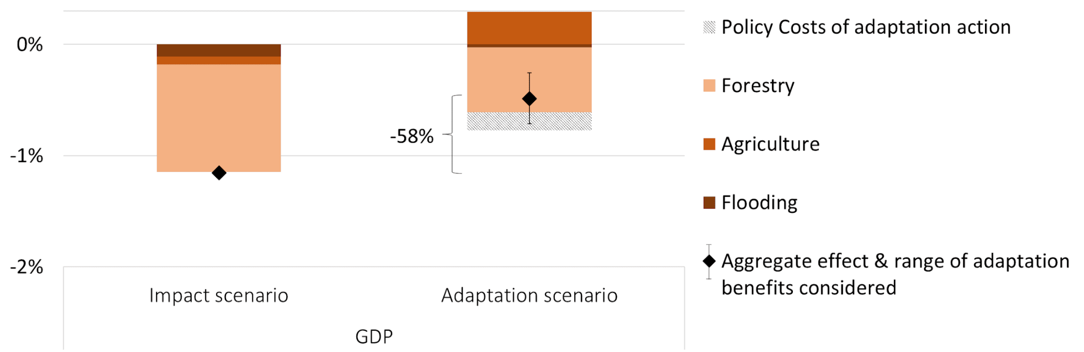


Figure 4.4: Macroeconomic effect in terms of GDP of mean changes from riverine flooding (expected annual damage, EAD), impacts in agriculture & forestry in SSP5 RCP8.5 in Austria in 2050. Note: Bars indicate the percentage change in the impact and adaptation scenario relative to the baseline. Results are based on GCM HadGem2-ESM.

In the *adaptation scenario*, a number of different adaptation actions is considered in each impact category, giving rise to a range of macroeconomic feedback effects (the costs thereof are included as *Policy costs of adaptation action* in Figure 4.4). Adaptation action in the forestry sector is manifold. Structural investments, such as the improvement of roads to access forests in case of disaster, securing mountain torrents or landslide protection increase the public investment demand and increase capital intensity of the forestry sector. Moreover, the reforestation of protective forests or diversification of tree species increases the protective role of forests, reducing the quantity available for economic activities. Combining these effects with climate impacts in the forestry sector and expected benefits of implemented adaptation actions shows that adaptation can mitigate the negative effects of climate change on the forestry sector. By muting the impact of climate change on the forestry sector, adaptation reduces the GDP losses by a third, relative to the *impact scenario.*

Flood risk management constitutes a mix of grey, green and soft measures. Yet, its economy-wide and budgetary implications are twofold. Firstly, the implementation of measures requires public resources, changing the composition of public demand. As structural measures raise the level of investments, higher savings are necessary, reducing private consumption levels. Moreover, public demand for the maintenance of existing infrastructure and improvement of early warning systems or evacuation plans reduces consumption opportunities of the public sector. While the economic implications of grey and soft measures arise more on the public side, our results show that the implementation of green flood risk adaptation is more likely to affect land-using sectors, such as agriculture. The re-zoning of land used by the private sector to natural flood retention basins increases the scarcity of land available for economic activities, raising the rental price of land. This affects the production of land-using sectors, wielding influence on the overall output level of the economy. As the second building block for the *adaptation scenario*, the *benefits of adaptation* reduce the direct impacts of climate change, mitigating the economy-wide and budgetary consequences. We find that despite these macroeconomic feedback effects of implementation, Austrian flood risk management reduces the GDP effects from riverine flooding, creating distinct net-benefits of adaptation.

The implementation of adaptation action foreseen in the Austrian agricultural sector affects sectoral activity levels. Because of changes in the crop varieties employed, or the exploration of more resilient plant species, the agricultural sector becomes more labor intensive, changing the composition of inputs. This affects the level of agricultural output, wielding impacts on the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

level of economic activity. Despite these economy-wide effects of implementing adaptation in agriculture, we find that the introduction of adaptation action and the benefits arising thereof, lead to an increase in agricultural output, allowing for economy-wide benefits in the *adaptation scenario*, more than offsetting the losses observed in the *impact scenario.*

Sectoral implications

Figure 4.5 illustrates the absolute changes in sectoral output levels in the *impact* and *adaptation scenario*, relative to the *baseline*. As mentioned above, the Austrian forestry sector is particularly affected by climate change, with a reduction in output by €3bn, corresponding to a 41% fall, relative to the *baseline.* As the output of the forestry sector is largely used as an input in the woodworking sectors (e.g. paper, furniture), we see that the manufacturing industry, the sector including wood and paper products, is also severely affected with output levels falling by €1.4bn or 14% compared to the *baseline*. Adaptation can mitigate these impacts, by reducing the output losses in forestry significantly. Moreover, a distinct winner in the *adaptation scenario* is Austrian crop production. Adaptation offsets climate change induced productivity losses in agriculture completely, increasing overall crop production compared to the *baseline*. As crop production becomes more profitable, the competing sector for land input - livestock production – loses in terms of production in the *adaptation scenario.* As the implementation of adaptation action raises the demand for private and public services, as well as construction, a large share of climate change induced reductions in the activity level of these sectors are reduced in the *adaptation scenario*.

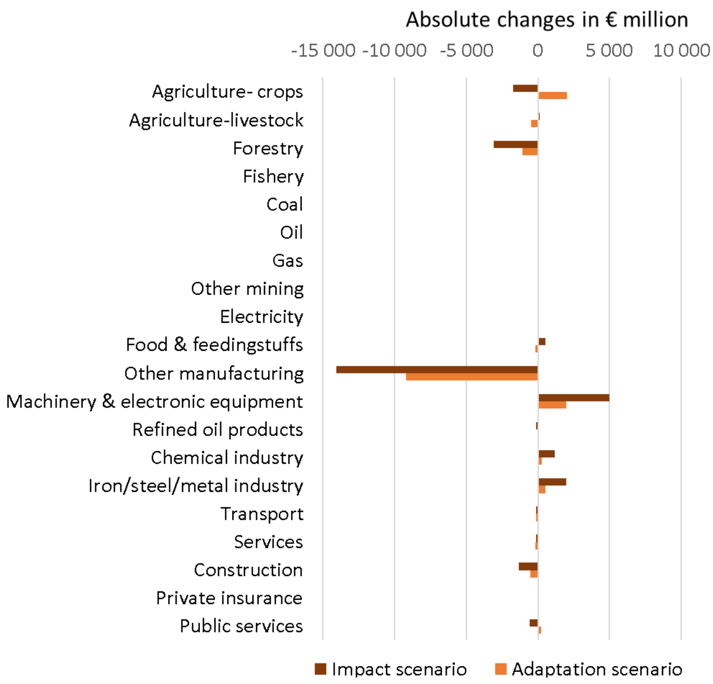


Figure 4.5: Absolute changes in sectoral output levels in the impact and adaptation scenario of mean changes from riverine flooding (expected annual damage, EAD), impacts in agriculture & forestry in Austria in 2050 in SSP5 RCP8.5. Note: Results are based on GCM HadGem2-ESM.

Budgetary implications

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

The economy-wide effects caused by climate change also put stress on the public budget, both on the revenue and the expenditure side. As a result of lower economic activity in the impact scenario, government revenues from taxes in total fall by 1.19%, relative to the baseline, constituting a reduction of €2bn in absolute terms. Assuming a balanced budget without incurring debt, this reduces the level of government consumption and public transfers to the private households, affecting private consumption levels. The largest driver of the reduction on the income side is a reduced income from factor taxes, as less factors are employed in production. Also, a lower level of economic activity in the impact scenario reduces household incomes and thus leads to a lower level of consumption, which in turn reduces the government income from consumption taxes, while a lower level of economic output reduces revenues from output taxation. The effect on trade is only marginal, where a loss in competitiveness for Austria leads to a slight increase in trade activities leaving tax income from trade taxes virtually unaffected.

Figure 4.6 illustrates the absolute difference in the revenue and expenditure side of the public budget between the impact and adaptation scenario, considering the capital damages from riverine flooding and impacts in agriculture and forestry in Austria in 2050 under RCP8.5 SSP5.

We find that a higher level of economic activity in the adaptation scenario increases government revenue from consumption, factor and output taxation, relative to the impact scenario. Especially the higher activity level of the agricultural sector achieved under the adaptation scenario increases factor tax income significantly, compared to the impact scenario. However, the economic feedback effects resulting from the implementation of public adaptation action and the shift in the government's consumption structure also reduce government revenues. Yet, these costs are more than offset by the benefits of adaptation on the revenue side of the Austrian public budget.

In the *adaptation scenario*, the expenditure side incurs additional expenditures for adaptation activities on the one hand, but achieves to reduce the adverse effects on government consumption on the other. In addition, the climate change induced reduction of transfer payments from the public to the private household, a result of a smaller public budget, can be largely prevented (70%). A higher level of economic activity in the *adaptation* scenario, raises the source of government revenue, increasing public consumption opportunities, as well as private consumption levels, due to higher government transfers. This shows that additional public expenditures lead to overall macroeconomic benefits including the effects on the public budget.

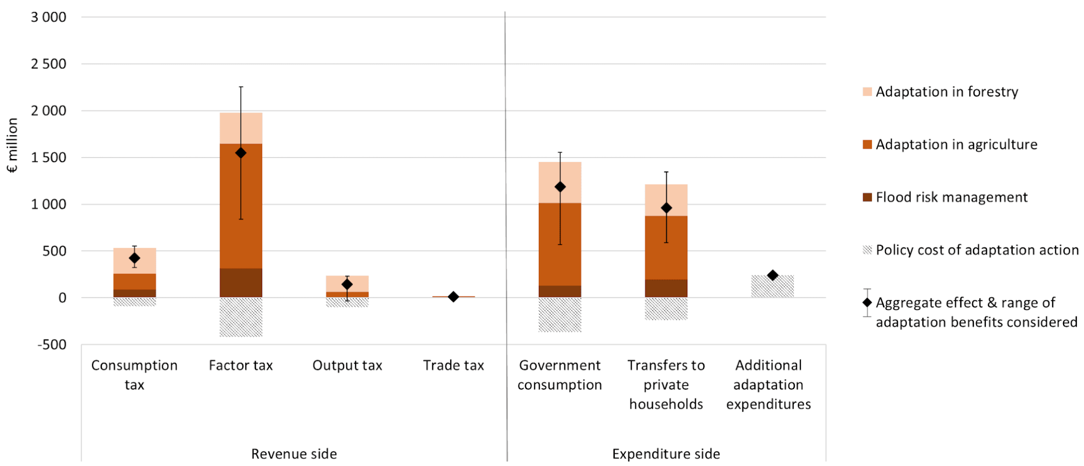


Figure 4.6: Absolute difference between the impact and adaptation scenario on the expenditure side of the Austrian public budget in 2050 in SSP5 RCP8.5 in Austria in 2050 considering mean changes from riverine flooding (expected annual damage, EAD), impacts in agriculture & forestry. Note: Results are based on GCM HadGem2-ESM.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Net-benefits of Spanish adaptation action

The following section considers climate change impacts through riverine and coastal flooding, as well as changes to the productivity levels of the agricultural and forestry sector in Spain in 2050 for the scenario RCP8.5-SSP5 (and with GCM HAD-GEM2; see Appendix B for results for RCP4.5 SSP2) with adaptation actions introduced in the adaptation scenario.

Macroeconomic implications

In 2050, capital damages from sea level rise, EAD from riverine flooding and sectoral productivity losses in the agricultural and forestry sector reduce GDP by 1.6%, relative to the *baseline.* Results show that in the *adaptation scenario*, adverse economy-wide effects are mitigated by reducing the effects on GDP by 70%. These results are robust for a range of benefit-cost-ratios applied (indicated by the error bar in the *adaptation scenario* in Figure 4.7). While benefits become even more distinct when upper bound effectiveness assumptions of adaptation are applied, effects of adaptation are also positive for the lower bound benefit-cost-ratios of adaptation

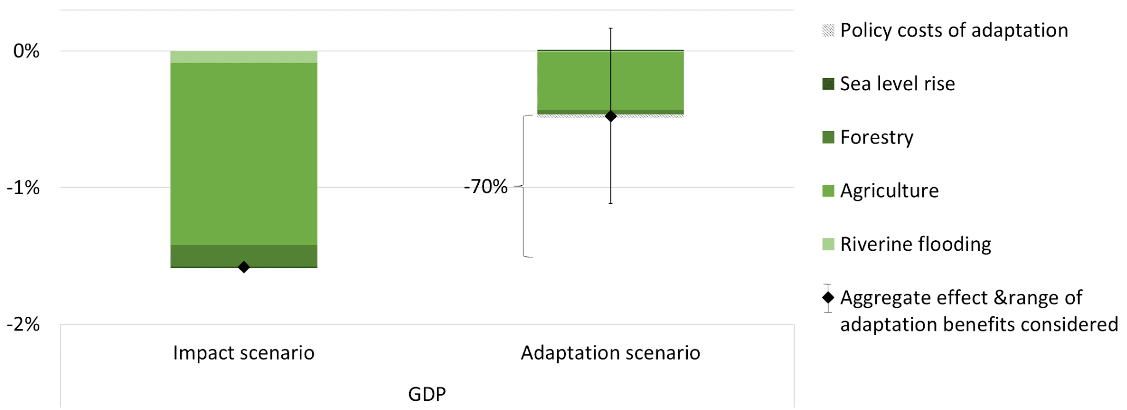


Figure 4.7: Macroeconomic effect in terms of GDP of mean changes from riverine flooding (expected annual damage, EAD), coastal flooding, impacts in agriculture & forestry in SSP5 RCP8.5 in Spain in 2050. Note: Bars indicate the percentage change in the impact and adaptation scenario relative to the baseline. Results are based on GCM HadGem2-ESM.

Among all impacts considered in Spain, climate-induced changes in agricultural yields and cropland lost due to changing climatic conditions constitute the largest contributors to negative impacts in Spain. Given the importance of the Spanish agricultural sector, macroeconomic feedback effects of sectoral productivity losses are significant, reducing GDP by 1.3%, compared to the *baseline* in 2050. Despite the maintenance of current flood protection standards, capital costs from riverine and coastal flooding in 2050 amounting to €300 and €2040 million in 2050 respectively, aggravate GDP losses. As the size of the Spanish forestry and woodworking sector is small, compared to Austria, the macroeconomic effect of similarly dimensioned productivity losses in the forestry sector are marginal.

In the *adaptation scenario*, a range of structural, ecosystem-based and informational adaptation actions is implemented. Given the severity of climate impacts in the agricultural sector, a significant share of public adaptation expenditure is directed towards the construction and improvement of irrigation structures until 2050. This does not only imply additional public investment demand, but also an increase in the capital intensity of the agricultural sector. By

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

alleviating the productivity losses due to changes in the climatic conditions until 2050, adaptation through the implementation of irrigation structures reduces GDP losses by more than 50%.
Under the Hydrological Plans, Spanish flood risk management is manifold, pursuing strategies to prevent capital damages from riverine flooding via structural measures, as well as supporting the natural defence mechanism of the ecosystems alongside rivers and in riverbeds. Despite the significant sum of government expenditures directed towards riverine flood risk protection, results show that GDP effects of adaptation are positive. Similarly, the construction of coastal protection infrastructure and ecosystem-based measures successfully reduce the macroeconomic impacts of sea level rise along the Spanish coastline.
We find that macroeconomic impacts in the Spanish forestry sector can be significantly reduced by adaptation. Although the impact data considered in our analysis includes damages from natural forest fires, anthropogenic forest fires are not considered. Therefore, the underlying analysis may underestimate the effective damage reduction potential of the implemented measures, given the increasing threat not only from natural, but also from anthropogenic forest fires.

Sectoral implications
Sectoral implications of climate change impacts in the *impact* and *adaptation scenario,* relative to the *baseline* are illustrated in Figure 4.8. Due to the significant impact on the productivity of the agricultural crop producing sector, sectoral output levels fall by 28%, constituting an absolute loss in sectoral output of €36bn. With agricultural products used as an important intermediate input in the food industry, sectoral output in the Food & feeding stuffs sector falls by almost 1%, or €2bn in absolute terms. A lower level of production in the agricultural and food sectors frees up resources, reducing the factor price of labour, which in turn allows for higher sectoral activity in other sectors such as the chemical sector, machinery & electronics, the iron/steel/metal industry and other manufacturing in the *impact scenario*. In the *adaptation scenario,* sectoral effects in agriculture can be reduced, however output losses of €13bn in the crop sector remain. On the one hand, this is driven by residual damages, given that productivity losses cannot be prevented completely by assumption, on the other hand, an increase in irrigation infrastructure makes agricultural production more expensive.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

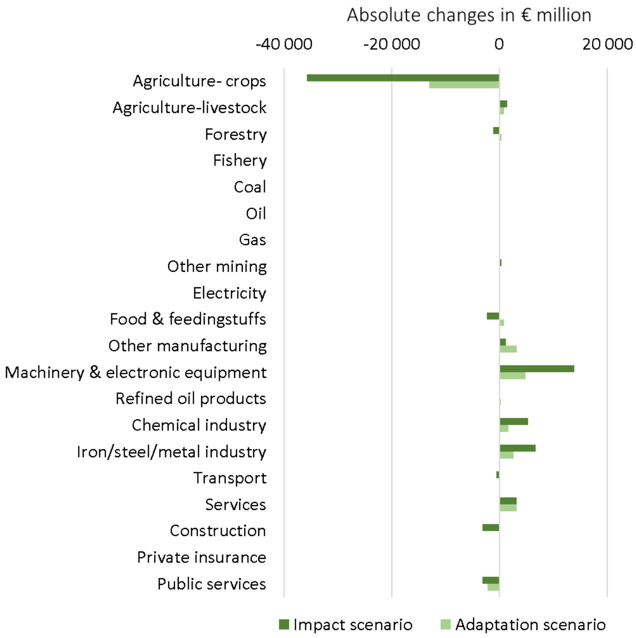


Figure 4.8: Absolute changes in sectoral output levels in the impact and adaptation scenario in Spain in 2050 in SSP5 RCP8.5. Note: Results are based on GCM HadGem2-ESM.

Budgetary implications

The budgetary effects of climate impacts and adaptation reflect the macroeconomic developments in the Spanish economy in 2050. A lower level of economic activity in the *impact scenario* reduces the public income from consumption, factor and output taxes, due to a reduction of factors employed in production and a lower level of overall demand. As a result of lower economy-wide production levels, income from the taxes levied on output falls in the *impact scenario,* relative to the *baseline.* In total, government revenue from taxes falls by €10bn, or 2% in the *impact scenario,* relative to the *baseline* in 2050. As we assume that governments pursue a balanced budget to avoid additional debt, this results in a reduction of government consumption and public transfers to private households.

Due to a higher level of economic activity, the tax income generated in the *adaptation scenario* exceeds public revenues in the *impact scenario* by a total of €7bn. In the *adaptation scenario*, the expenditure side incurs additional expenditures for adaptation activities, but achieves to reduce the adverse effects on government consumption and public transfers to private households by 60% and 66%, respectively. Figure 4.9 illustrates the absolute difference in government revenue and expenditure between the *impact* and *adaptation scenario.* We see that especially adaptation in agriculture generates significant benefits to both the revenue and the expenditure side of Spain's public budget. This demonstrates that although adaptation constitutes additional financial burden on the public budget, benefits prevail.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

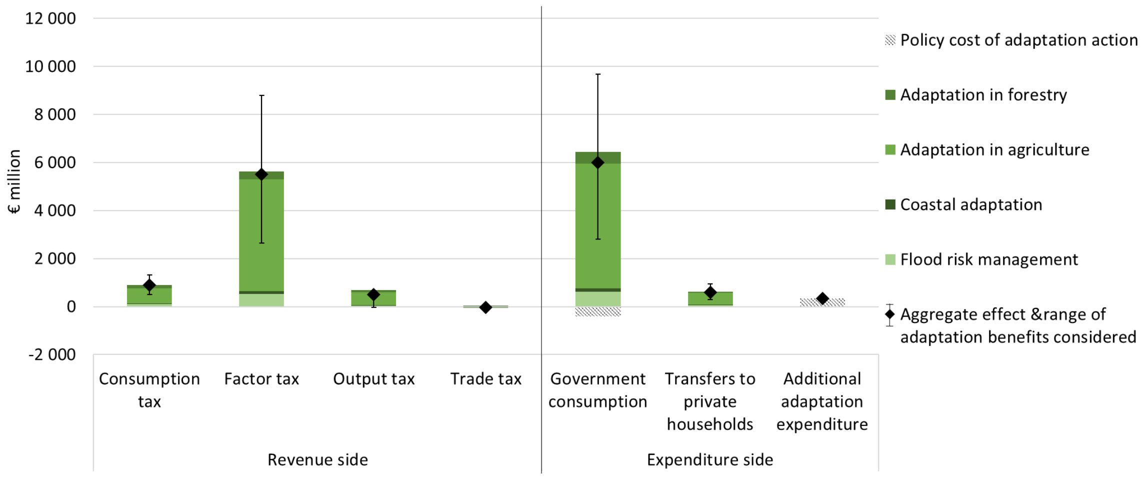


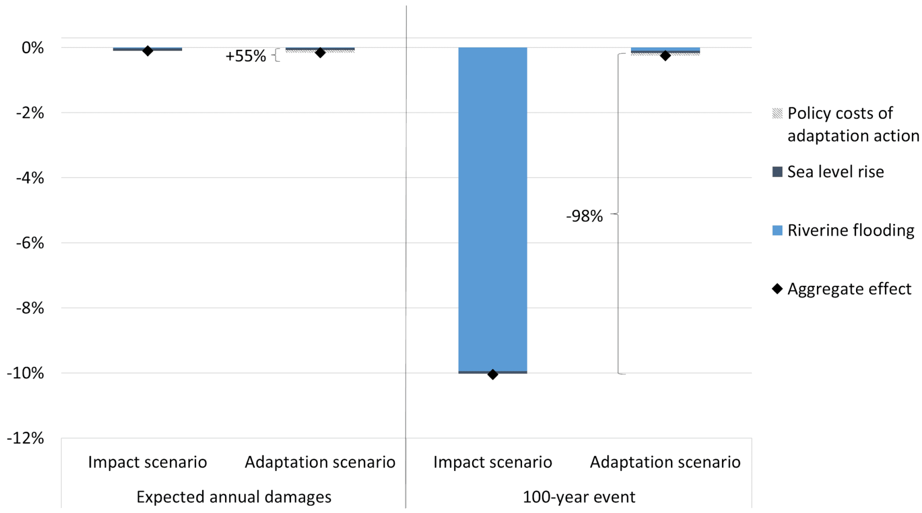
Figure 4.9: Absolute difference between the impact and adaptation scenario on the expenditure side of the Austrian public budget in 2050 in SSP5 RCP8.5 in Spain in 2050. Note: Results are based on GCM HadGem2-ESM.

Net-benefits of Dutch Delta management

Given the comprehensive approach to Dutch Delta management and the extremely high protection levels pursued by the Delta commission until 2050, the underlying analysis for the Netherlands is twofold. In addition to riverine flood damages quantified by mean annual capital costs in terms of EAD, we investigate a scenario in which a 100-year flood occurs alongside the impacts of sea level rise in 2050.

Macroeconomic implications

The impact scenario displayed in the left panel of Figure 4.10 considers expected annual damages (EAD) from riverine flooding, as well as costs from sea level rise in 2050 for the scenario RCP8.5-SSP5 (and with GCM HadGem2-ESM). Results show that Dutch GDP is reduced by 0.1%, relative to the *baseline scenario* in 2050, suggesting that capital damages are relatively small. Losses increase significantly when the occurrence of a 100-year flood and sea level rise are considered (right panel of Figure 4.8). Due to a high level of assets at risk of flooding, the direct economic damages of a 100-year flood and sea level rise amount to approximately 6% of GDP in 2050, which leads to macroeconomic damages in terms of GDP losses of 10%, relative to the *baseline*. This economy-wide effect is caused by the large-scale destruction of private and public infrastructure.



*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Figure 4.10: Macroeconomic effect in terms of GDP of changes from riverine flooding (measured by expected annual damages, EAD) and sea level rise (left panel) and the occurrence of a 100-year flood and sea level rise (right panel) in SSP5 RCP8.5 in the Netherlands in 2050. Note: Results are based on GCM HadGem2-ESM.

In the *adaptation scenario*, we introduce adaptation measures and their effectiveness in reducing damages from riverine and coastal flooding in 2050. For a discussion of the economy-wide implications of the implementation of adaptation actions, see the previous section on Austrian flood risk management. The Dutch Delta project, planned to be fully implemented by 2050, ensures protection from 100-year floods and higher. In consultation with national experts, we expect that the direct economic damage caused by a 100-year flood in 2050 can be avoided almost entirely, apart from a limited number of houses scattered outside dike rings (i.e. 99% of direct impacts are mitigated). The comparison between the *impact* and *adaptation scenario* in Figure 4.10 shows that the economy-wide impacts of adaptation are ambiguous. Although adaptation mitigates the direct EAD that arise from riverine flooding and capital costs from sea level rise in 2050, the macroeconomic costs that arise from implementation and maintenance of protective measures cannot fully be offset by the benefits from adaptation (although they are very small). When the occurrence of a 100-year flood is considered, we find that adaptation succeeds in mitigating the adverse economy-wide effects by reducing GDP losses by 98%, compared to the *impact scenario.*

Sectoral implications

Due to the low level of direct damages from riverine and coastal flooding in a scenario with EAD from riverine flooding and sea level rise; sectoral effects are marginal in the *impact scenario*. We therefore focus our discussion on the 100-year flood case. As a result of the high level of capital destroyed during the occurrence of a 100-year flood, the rental price of capital increases considerably, affecting especially capital-intensive sectors, such as the chemical, iron/steel/metal and the manufacturing industry and construction. Due to its size, the services sector is affected most heavily in absolute terms, with losses exceeding €200bn, relative to the *baseline*.

As a result of the high effectiveness of adaptation, and therefore overall higher economic activity, negative sectoral effects can be avoided almost entirely, with a handful of sectors experiencing gains from adaptation, such as the chemical industry, the iron/steel/metal industry and machinery and electronics. The comparative advantage of the land-using agricultural sectors compared to the capital-intensive sectors in the *impact scenario* vanishes in the *adaptation scenario,* where we observe a marginal decrease in sectoral output of the agricultural sectors relative to the *baseline*, because of the re-zoning of agricultural land into retention zones.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

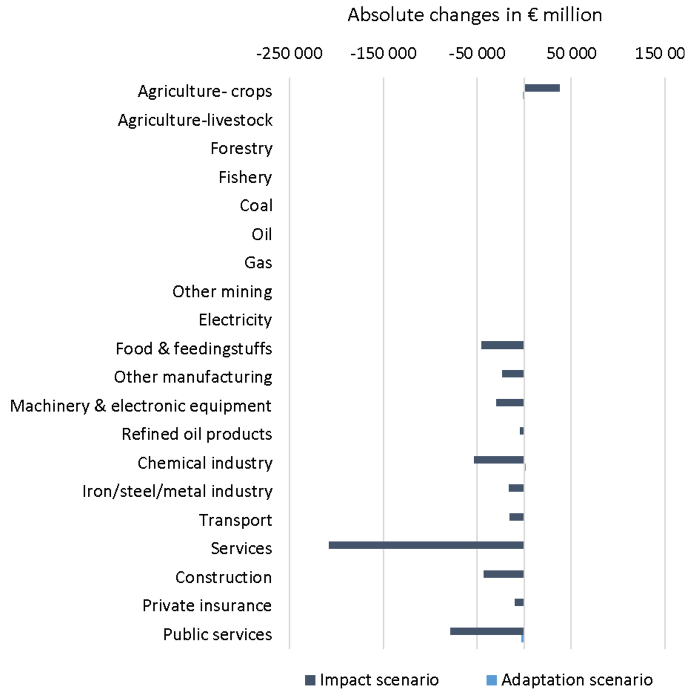
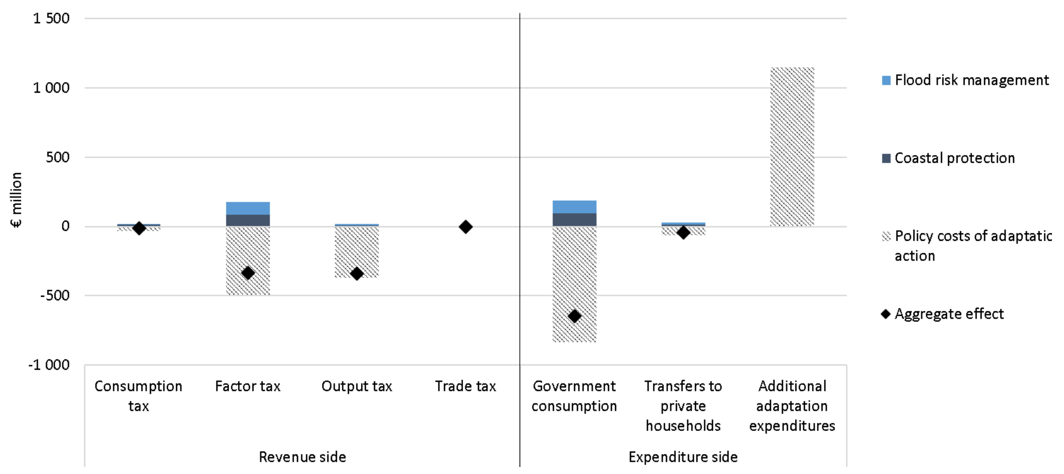


Figure 4.11: Absolute changes in sectoral output levels in the impact and adaptation scenario in the Netherlands from the occurrence of a 100-year flood and sea level rise in 2050 in SSP5 RCP8.5. Note: Results are based on GCM HadGem2-ESM.

Budgetary implications

Figure 4.12 illustrates the effects of riverine flooding quantified by EAD and sea level rise on Dutch tax income from different sources and public expenditure across different categories in terms of the absolute difference between the *impact* and *adaptation scenario*. We see that the budgetary benefits from additional adaptation expenditures in the *adaptation scenario* cannot compensate the budgetary effects that arise from the implementation of these actions. In this case, the construction of protective measures under the Delta programme crowds other government consumption, to an extent where the benefits from avoided damages in the *adaptation scenario* do not compensate for the direct and indirect costs of implementation that arise on the revenue and expenditure side of the public budget.

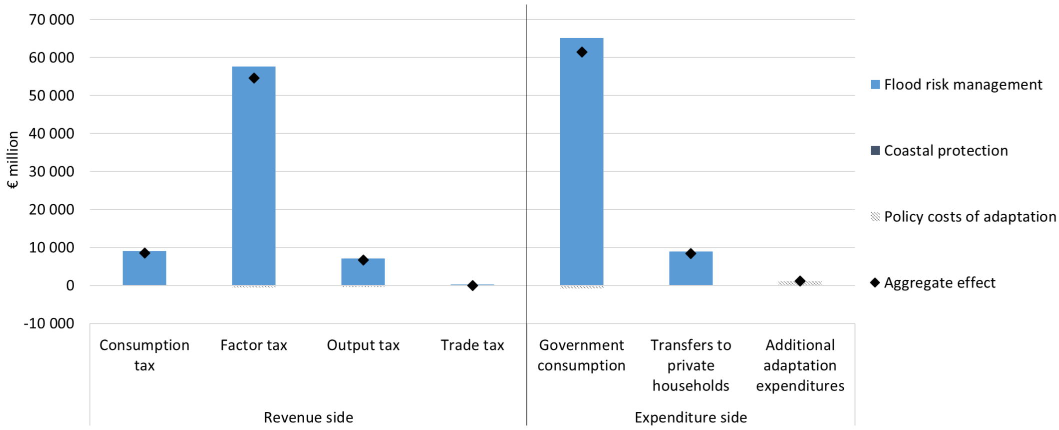


*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Figure 4.12: Absolute difference between the impact and adaptation scenario on the expenditure side of the public budget in 2050 in SSP5 RCP8.5 in the Netherlands in 2050 accounting for impacts from riverine flooding in terms of expected annual damages (EAD) and sea level rise. Note: Results are based on GCM HadGem2-ESM.

However, adaptation under the Dutch Delta programme is clearly beneficial when the occurrence of a 100-year flood event is analysed. A higher level of economic activity in the *adaptation scenario* due to the mitigation of direct flood damages reduces the losses in tax revenues almost entirely, compared to the *impact scenario*. Therefore, we also find a higher level of public expenditures in the *adaptation scenario*, increasing government consumption and transfers to private households, compared to the *impact scenario*. Thus, for the case of a 100-year flood, we find that despite the public expenditures arising from the implementation of the Delta project, the economy-wide and budgetary net-benefits from adaptation are clearly positive.

Figure 4.13: Absolute difference between the impact and adaptation scenario on the expenditure side of the public



budget in 2050 in SSP5 RCP8.5 in the Netherlands in 2050 accounting for impacts from riverine flooding in terms of the occurrence of a 100-year flood and sea level rise. Note: Results are based on GCM HadGem2-ESM.

In contrast to the Austrian or Spanish case, where adaptation is always beneficial, we find that the adaptation actions undertaken by the Netherlands clearly prepare for a 100-year event, rather than the expected annual damages (EAD).

4.4. Discussion

The three case study countries illustrate that adaptation planning and implementation differs across countries and sectors. Detailed information on long-term strategies of dealing with climate risk, alongside a list of measures implemented or planned and necessary government expenditure is only available in the Netherlands. Spain discloses some information concerning the costs and types of past and current projects, as well as some projects scattered over the near future (up to 2030). In Austria, adaptation progress and planning is regularly monitored, but information on public adaptation expenditures can only be deduced from the medium term forecast for the federal general budget, where policy goals and objectives need to be specified for budget subdivisions. While adaptation is a well-established policy area in all three countries under investigation, harmonization regarding the collection and reporting of information disclosed on past, current and future adaptation projects is necessary for a more systematic analysis.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

Moreover, the institutionalisation of adaptation varies strongly by the climate impact considered. The past exposure of floods and droughts has left the water sector highly institutionalized in all three countries. Risk assessment and adaptation planning are carried out by legally established institutions, with measures and protection levels being revaluated regularly, responsive to new scientific insights. In contrast, adaptation in the agricultural and forestry sector seems less firmly established, with adaptation concerns being mainstreamed into already existing policies and funding programs, under a distinct influence of EU policies. While including objectives of adaptation and resilience into sectoral policies may catalyze a broad range of adaptation action and allow for co-benefits, this makes adaptation action also dependent on political and economic situations, with adaptation subordinating to other societal objectives.

Considering the types of measures and associated funding volumes, our analysis has shown that the composition of measures varies between countries and impact categories, demonstrating that effective adaptation is not determined by a one-size fits all strategy, but that national adaptation is manifold, taking account of a range of climate impacts, exposed sectors and institutional differences. While adaptation to flood risk exhibits a large share of grey measures in all case study countries, accompanied by a significant share of ecosystem-based measures in Austria and Spain, we observe differences in the composition of adaptation action in agriculture and forestry between Austria and Spain. The Spanish agricultural sector is adapting to more frequent droughts and heat spells, requiring an improvement and expansion of irrigation infrastructure. Similarly, adaptation to an increased risk of forest fires in the Spanish forestry sector is capital-intensive, comprising a large share of structural measures. In contrast, the Austrian adaptation strategy foresees a large share of green measures in the Austrian agricultural and forestry sector, by promoting a shift towards more resilient crop and tree species, to prepare for climatic changes and an increase in diseases and pests.

The macroeconomic and budgetary effects of impacts and adaptation strategies in the three countries are summarised in Table 2. The magnitude of economy-wide effects depends on the number and severity of climate risks relevant in each of the three countries. Austria is exemplary of a country with a diverse set of potential climate change impacts, with mostly negative effects on the economy. Output is reduced in those sectors that are directly affected by climate change, such as the forestry and wood processing sectors, but also in large economic sectors that are only indirectly affected, such as other manufacturing sectors. Similarly, also Spain is exposed to a range of climate impacts along coastlines, riverbeds, and forestry, with climate impacts being most severe in agriculture. The Netherlands, on the other hand, is traditionally a country that prepares for high impact, low probability flood events. If such an event would occur, as exemplified by a 100-year flood event, and no further adaptation beyond the current protection measures would be set, the Dutch economy would shrink by 10% in 2050, compared to a *baseline scenario* without climate change. A flood of such magnitude would destroy capital, negatively affecting capital intensive sectors such as the chemical industry, but also private and public service sectors.

Adaptation is effective in reducing both the macroeconomic effect and ameliorating the effect on those sectors that are particularly negatively hit by climate change impacts. In addition, some sectors are even positively affected by climate change adaptation, such as construction in the Netherlands (because of higher public adaptation expenditures) or agriculture in Austria (because of realized chances of higher yields). However, adaptation, particularly high levels of it, can eventually also negatively affect some sectors: in the Netherlands, we find that the

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

expansion of ecosystem-based solutions (green adaptation) requires land, reducing the level of land available for agricultural crop and livestock sectors. As a consequence, those sectors are negatively affected by adaptation in the Netherlands. The magnitude of this effect depends strongly on how much land is set aside for ecosystem-based solutions and whether some agricultural activity is still feasible on this land (e.g. grazing, but not crop production).

The effect on public budgets on the revenue side is reflective of macroeconomic developments: with lower economic activity, the tax base is reduced and so are government revenues; this is particularly strong in the *impact scenario*s and with the 100-year flood. As adaptation mitigates the macroeconomic effect of climate impacts, allowing for a higher economic activity level, also the effects on the revenue side of the public budget can be reduced to a considerable extent. But the budgetary burden of adaptation also depends on the development of the expenditure side. Adaptation requires public expenditures, which at least partly need to be diverted away from other expenditures, i.e. government consumption and transfers to households. The effect of adaptation on the budgetary burden depends on whether the positive effect on the revenue side in the *adaptation scenario* compared to the *impact scenario* more than compensates the additional pressure on the expenditure side. When comparing the EAD case to the 100-year flood case in the Netherlands, we find that adaptation is reducing the budgetary burden substantially in case of a 100-year flood event, but not in the EAD case. This can be explained by the different adaptation approaches, protection levels and the associated costs: The implementation of the Austrian and Spanish adaptation strategy follows the concept of adaptation mainstreaming and no additional budget (funded out of the general budget of the different ministries); in contrast, the Dutch Delta program has a very high protection target that corresponds to a case of preparing for high impact, low probability events and a dedicated program budget.

In light of these findings, public action may become increasingly important not only for promoting adaptation to gradual impacts of climate change (e.g. changes in precipitation patterns, average temperatures), but also to extreme events with the potential to cause significant disruptions to the socioeconomic system. Our analysis shows that the effects of a 100-year flood may be severe, causing significant losses in GDP levels. Moreover, the ultimate damage of extreme events or climate impacts might not be fully captured by the economic damage they cause. People living in flood prone areas might suffer psychological stress of being exposed to floods or even having to relocate and abandon their family homes. Also, important ecosystems might be damaged or fully lost. Thus, the ultimate goal of public adaptation might not be economic efficiency, but ensuring a socially acceptable level of protection at least economy-wide cost.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Table 2: Comparison of macroeconomic and fiscal effects of impacts and adaptation in 2050

		Austria	Spain	Netherlands
Impact fields & adaptation considered		• Riverine flood risk • Changes agriculture & forestry	• Riverine & coastal flood risk • Changes agriculture & forestry	• Extreme riverine (100-year flood) flood risk • Coastal flood risk
GDP effect*	*Impact scenario*	-1.2%	-1.6%	-9.9%
	Adaptation scenario	-0.7%	-0.8%	-12.8%
Sectoral losers* of climate impacts		• Forestry • Other manufacturing • Construction • Electricity	• Agriculture-crops • Food industry • Public Services • Construction	• Services • Public services • Chemical industry • Construction • Food industry • Machinery & electronics
Sectoral winners* of climate impacts		• Machinery and electronics • Iron/metal/steel ind. • Chemical ind. • Refined oil products	• Machinery & electronics • Iron/steel/metal ind. • Chemical ind. • Other mining • Other manufact.	• Agriculture crops • Agriculture livestock • Gas
Sectoral winners* of adaptation		• Agriculture-crops • Forestry • Machinery & electronics	• Machinery & electronics • Iron/steel/metal ind. • Other manufacturing	• Chemical industry • Machinery and electronics • Iron/steel/metal ind. • Refined oil prod. • Construction • Manufacturing ind.
Tax income*	*Impact scenario*	-1.19%	-2.05%	-17.51%
	Adaptation scenario	-0.30%	-0.77%	-0.63%

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Government consumption*	*impact scenario*	-1.26%	-2.05%	-17.51%
	adaptation scenario	-0.41%	-0.83%	-0.63%
Transfers to households*	*impact scenario*	-1.10%	-1.95%	-17.41%
	adaptation scenario	-0.32%	-0.66%	-0.47%
Additional public adaptation expenditure in 2050 *(adaptation scenario)***		€ 0.24 bn	€ 0.33 bn	€ 1.15 bn

4.5. Conclusion

Adaptation is a well-established policy area in all three countries under investigation, but there are distinct differences. The Netherlands have adopted a comprehensive approach to protect from the risk of riverine and coastal flooding, with a strong focus on grey measures and creating space for rivers. While structural measures are important also in Spanish and Austrian flood risk management, the Austrian adaptation strategy foresees a prioritization of green measures, leading to a relatively higher share of ecosystem-based measures. Moreover, adaptation in agriculture and forestry differs between case study countries, with adaptation in the Austrian forestry and agriculture focusing mainly on green and soft measures. In contrast, adaptation in the Spanish agricultural and forestry sector is capital intensive, focusing on measures to face more frequent droughts and heat spells.

The macroeconomic assessment of national adaptation strategies for Austria, Spain and the Netherlands shows that adaptation is highly effective in reducing the negative sectoral and economy-wide effects of riverine and coastal flooding (especially in the case of an extreme event exemplified by a 100-year flood). Moreover, we find that adaptation is successful in reducing climate change induced productivity losses in forestry and agriculture in Spain and Austria. The joint analysis of flood risk management and public adaptation in the agricultural and forestry sectors shows that actions are beneficial for the Austrian and Spanish economy, even for lower bound effectiveness assumptions of adaptation. This shows that the overall effects on GDP expected from adaptation measures are positive for a range of assumptions on the effectiveness of adaptation, offsetting the macroeconomic effects and public costs that emerge from the implementation of the respective measures.

Although our analysis shows that adaptation creates economy-wide and budgetary net-benefits, we find that residual damages remain in all cases considered. Moreover, the results show that residual damages might be particularly high where impacts are most distinct. This is seen by the remaining GDP losses after adaptation in the Austrian forestry sector and in Spanish agriculture. Given prevailing uncertainties concerning climatic developments, especially with regard to the occurrence of high impact, low probability events and the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

effectiveness of adaptation action for different levels of exposure to climate risk, the limits of adaptation may vary across scenarios. Another important caveat when discussing the prevalence of residual damages is the assumption of linear adaptation benefits employed throughout our analysis. In practice, additional adaptation may become less effective in reducing the impacts of climate change, as the stock of adaptation increases. This decreasing effectiveness of adaptation may in some cases lead to adaptation limits, where a reduction of residual damages of climate change is no longer feasible.

The macroeconomic assessment also shows that adaptation to high magnitude floods is costly and requires a reallocation of government resources, causing significant economy-wide and budgetary feedback effects. Using the example of the Netherlands, we see that large-scale projects such as the comprehensively planned Dutch Delta program can considerably decrease the economic and social impacts of extreme events. In case of a 100-year flood, benefits from adaptation fully compensate for the costs of implementing and maintaining adaptive measures. However, the uncertainty concerning the occurrence and magnitude of high impact, low probability events and the considerable costs of large-scale adaptation action might restrain governments from implementing actions, especially when adaptive capacities are limited and scarce public means are directed towards other topics on the political agenda.
One critical difference between adaptation in agriculture and flood risk management is the timing of costs and benefits. While the benefits from a transition towards more resilient crop species occurs immediately once these changes have been made, dykes strengthened to withstand 100-year floods can only unfold their damage reduction potential in case such extreme events strike. While the challenge of accounting for climate change in the planning and timing of long-lived investments as already been addressed in the literature (Haasnoot et al., 2020; Kwakkel et al., 2015; Lempert and Schlesinger, 2000), the intertemporal heterogeneity of economy-wide costs and benefits from adaptation action deserves further analysis (Fankhauser et al. 1999; Osberghaus et al. 2010). This also holds for the budgetary effects of adaptation, where the stage of implementation is affecting especially the short-term balance of public budgets. Future research could also explore how balanced public budgets can be ensured – by cutting expenditures elsewhere, raising taxes or incurring debt, and what this implies for the economic and budgetary appraisal of adaptation.

4.6. References

Aguiar, A., Narayanan, B., McDougall, R., 2016a. An Overview of the GTAP 9 Data Base. Journal of Global Economic Analysis 1, 181–208. https://doi.org/10.21642/JGEA.010103AF
Aguiar, A., Narayanan, B., McDougall, R., 2016b. An overview of the GTAP 9 data base. Journal of Global Economic Analysis 1, 181–208.
Anagnostopoulos, K.P., Petalas, C., 2011. A fuzzy multicriteria benefit–cost approach for irrigation projects evaluation. Agricultural Water Management 98, 1409–1416. https://doi.org/10.1016/j.agwat.2011.04.009
Bachner, G., Bednar-Friedl, B., 2019. The effects of climate change impacts on public budgets and implications of fiscal counterbalancing instruments. Environmental Modeling & Assessment 24, 121–142.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Bachner, G., Bednar-Friedl, B., Knittel, N., 2019. How does climate change adaptation affect public budgets? Development of an assessment framework and a demonstration for Austria. Mitigation and Adaptation Strategies for Global Change 24, 1325–1341.
Bachner, G., Bednar-Friedl, B., Nabernegg, S., Steininger, K.W., 2015. Macroeconomic evaluation of climate change in Austria: a comparison across impact fields and total effects, in: Economic Evaluation of Climate Change Impacts. Springer, pp. 415–440.
BMNT, 2018. Flood Risk Management in Austria: Objectives - Measures - Good practice.
BMNT, 2017. The Austrian strategy for adaptation to climate change.
Bosello, F., Nicholls, R.J., Richards, J., Roson, R., Tol, R.S., 2012. Economic impacts of climate change in Europe: sea-level rise. Climatic change 112, 63–81.
Ciscar, J., Ibarreta, D., Soria, A., Dosio, A., Toreti, A., Ceglar, A., Fumagalli, D., Dentener, F., Lecerf, R., Zucchini, A., others, 2018. Climate Impacts in Europe: Final Report of the JRC PESETA III Project. Joint Research Centre Science for Policy Report.
Ciscar, J.-C., Iglesias, A., Feyen, L., Szabo, L., Van Regemorter, D., Amelung, B., Nicholls, R., Watkiss, P., Christensen, O.B., Dankers, R., Garrote, L., Goodess, C.M., Hunt, A., Moreno, A., Richards, J., Soria, A., 2011. Physical and economic consequences of climate change in Europe. Proceedings of the National Academy of Sciences 108, 2678–2683. https://doi.org/10.1073/pnas.1011612108
Dellink, R., Lanzi, E., Chateau, J., 2019. The sectoral and regional economic consequences of climate change to 2060. Environmental and resource economics 72, 309–363.
Delta Programme Commissioner, 2019. Delta Programme 2020 - Continuing the work on the delta: down to earth, alert and prepared.
Dietrich, J.P., Bodirsky, B.L., Humpenöder, F., Weindl, I., Stevanović, M., Karstens, K., Kreidenweis, U., Wang, X., Mishra, A., Klein, D., Ambrósio, G., Araujo, E., Yalew, A.W., Baumstark, L., Wirth, S., Giannousakis, A., Beier, F., Chen, D.M.-C., Lotze-Campen, H., Popp, A., 2019. MAgPIE 4 – a modular open-source framework for modeling global land systems. Geosci. Model Dev. 12, 1299–1317. https://doi.org/10.5194/gmd-12-1299-2019
Eakin, H.C., Patt, A., 2011. Are adaptation studies effective, and what can enhance their practical impact? Wiley Interdisciplinary Reviews: Climate Change 2, 141–153.
EEA, 2020. Monitoring and evaluation of national adaptation policies throughout the policy cycle. European Environmental Agency.
European Comission, 2018. Evaluation of the EU Strategy on adaptation to climate change Accompanying the document REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL on the implementation of the EU Strategy on adaptation to climate change (Comission Staff Working Document. Impact Assessment No. SWD/2018/461 final). Brussels, Belgium.
European Commission, 2009. White Paper “Adapting to climate change in Europe : Towards a European framework for action.” COM 147 final.
European Commission, 2007. Green Paper ’ Adapting to climate change in Europe - options for EU action’. COM 354 final.

*This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

European Court of Auditors, 2016. Spending at least one euro in every five from the EU budget on climate action: ambitious work underway, but at serious risk of falling short. European Union.
European Environment Agency (Ed.), 2013. Adaptation in Europe: addressing risks and opportunities from climate change in the context of socio-economic developments, EEA report. European Environment Agency [u.a.], Copenhagen.
Fisher-Vanden, K., Sue Wing, I., Lanzi, E., Popp, D., 2013. Modeling climate change feedbacks and adaptation responses: recent approaches and shortcomings. Climatic Change 117, 481–495. https://doi.org/10.1007/s10584-012-0644-9
Francés, G.E., Quevauviller, P., González, E.S.M., Amelin, E.V., 2017. Climate change policy and water resources in the EU and Spain. A closer look into the Water Framework Directive. Environmental Science & Policy 69, 1–12.
Global Commission on Adaptation, 2019. Adapt now: a global call for leadership on climate resilience. Global Commission on Adaptation.
Goldstein, A., Turner, W.R., Gladstone, J., Hole, D.G., 2019. The private sector's climate change risk and adaptation blind spots. Nature Climate Change 9, 18–25. https://doi.org/10.1038/s41558-018-0340-5
Haasnoot, M., van Aalst, M., Rozenberg, J., Dominique, K., Matthews, J., Bouwer, L.M., Kind, J., Poff, N.L., 2020. Investments under non-stationarity: economic evaluation of adaptation pathways. Climatic Change 161, 451–463. https://doi.org/10.1007/s10584-019-02409-6
Havlík, P., Schneider, U.A., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., Cara, S.D., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A., Sauer, T., Obersteiner, M., 2011. Global land-use implications of first and second generation biofuel targets. Energy Policy 39, 5690–5702. https://doi.org/10.1016/j.enpol.2010.03.030
Hinkel, J., Bisaro, A., 2016. Methodological choices in solution-oriented adaptation research: a diagnostic framework. Regional Environmental Change 16, 7–20. https://doi.org/10.1007/s10113-014-0682-0
Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proceedings of the National Academy of Sciences 111, 3292–3297.
Kind, J.M., 2014. Economically efficient flood protection standards for the Netherlands: Efficient flood protection standards for the Netherlands. J. Flood Risk Manage 7, 103–117. https://doi.org/10.1111/jfr3.12026
Knittel, N., Bednar-Friedl, B., Leitner, M., Bachner, G., 2017. THE COSTS OF CLIMATE CHANGE ADAPTATION FOR THE AUSTRIAN FEDERAL BUDGET.
Knutti, R., Sedláček, J., 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nature Climate Change 3, 369–373.
Koks, E.E., Thissen, M., Alfieri, L., De Moel, H., Feyen, L., Jongman, B., Aerts, J.C.J.H., 2019. The macroeconomic impacts of future river flooding in Europe. Environmental Research Letters 14, 084042. https://doi.org/10.1088/1748-9326/ab3306
Kolström, M., Lindner, M., Vilén, T., Maroschek, M., Seidl, R., Lexer, M.J., Netherer, S., Kremer, A., Delzon, S., Barbati, A., Marchetti, M., Corona, P., 2011. Reviewing the

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Science and Implementation of Climate Change Adaptation Measures in European Forestry. Forests 2, 961–982. https://doi.org/10.3390/f2040961
Kontogianni, A., Tourkolias, C.H., Damigos, D., Skourtos, M., 2014. Assessing sea level rise costs and adaptation benefits under uncertainty in Greece. Environmental Science & Policy 37, 61–78. https://doi.org/10.1016/j.envsci.2013.08.006
Kuik, O., Scussolini, P., Mechler, R., Mochizuki, J., Hunt, A., Wellman, J., 2016. Assessing the economic case for adaptation to extreme events at different scales (No. Deliverable 5.1), EconAdapt.
Kwakkel, J.H., Haasnoot, M., Walker, W.E., 2015. Developing dynamic adaptive policy pathways: a computer-assisted approach for developing adaptive strategies for a deeply uncertain world. Climatic Change 132, 373–386. https://doi.org/10.1007/s10584-014-1210-4
Leitner, M., Mäkinen, K., Vanneuville, W., Mysiak, J., Deacon, A., Torresan, S., Vikstrom, S., Ligtvoet, W., Prutsch, A., 2020. Monitoring and evaluation of national adaptation policies throughout the policy cycle. Publications Office, LU.
Lempert, R., Schlesinger, M., 2000. Robust Strategies for Abating Climate Change. Climatic Change 45, 129–161.
López-Dóriga, U., Jiménez, J., Bisaro, A., Hinkel, J., 2020. Financing and implementation of adaptation measures to climate change along the Spanish coast. Science of The Total Environment 712, 135685.
Losada, I.J., Toimil, A., Muñoz, A., Garcia-Fletcher, A.P., Diaz-Simal, P., 2019. A planning strategy for the adaptation of coastal areas to climate change: The Spanish case. Ocean & Coastal Management 182, 104983.
Nisbet, T., Roe, P., Marrington, S., Thomas, H., Broadmeadow, S., Valatin, G., 2015. Multi-objective Flood Management Demonstration Project. DEFRA.
Noble, I.R., Huq, S., Anokhin, Y.A., Carmin, J., Goudou, D., Lansigan, F.P., Osman-Elasha, B., Villamizar, A., 2014. Adaptation Needs and Options, in: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (Eds.)]. United Kingdom and New York, NY, USA, pp. 833–868.
O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic change 122, 387–400.
Parrado, R., Bosello, F., Delpiazzo, E., Hinkel, J., Lincke, D., Brown, S., 2020. Fiscal effects and the potential implications on economic growth of sea-level rise impacts and coastal zone protection. Climatic Change 1–20.
Roson, R., Van der Mensbrugghe, D., 2012. Climate change and economic growth: impacts and interactions. International Journal of Sustainable Economy 4, 270–285.
Schönhart, M., Schauppenlehner, T., Kuttner, M., Kirchner, M., Schmid, E., 2016. Climate change impacts on farm production, landscape appearance, and the environment: Policy scenario results from an integrated field-farm-landscape model in Austria. Agricultural Systems 145, 39–50. https://doi.org/10.1016/j.agsy.2016.02.008

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Steininger, K.W., Bednar-Friedl, B., Formayer, H., KÃ¶nig, M., 2016. Consistent economic cross-sectoral climate change impact scenario analysis: Method and application to Austria. Climate Services 1, 39–52. https://doi.org/10.1016/j.cliser.2016.02.003
Steininger, K.W., Bednar-Friedl, B., Knittel, N., Kirchengast, G., Nabernegg, S., Williges, K., Mestel, R., Hutter, H.-P., Kenner, L., 2020. Klimapolitik in Österreich: Innovationschance Coronakrise und die Kosten des Nicht-Handelns.
Steininger, K.W., König, M., Bednar-Friedl, B., Kranzl, L., Loibl, W., Prettenthaler, F. (Eds.), 2015. Economic evaluation of climate change impacts: development of a cross-sectoral framework and results for Austria, Springer climate. Springer Verlag, Cham.
Stern, N., 2007. . The Economics of Climate Change: The Stern Review.
Szewczyk, W., Ciscar, J.C., Mongelli, I., Soria, A., 2018. JRC PESETA III project: Economic integration and spillover analysis (No. EUR 29456 EN). Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/514048
Szewczyk, W., Feyen, L., Matei, A., Ciscar, J.C., Mulholland, E., Soria, A., 2020. Economic analysis of selected climate impacts: JRC PESETA IV project : Task 14. Publications Office of the European Union, Luxembourg.
Tröltzsch, J., Görlach, B., Lückge, H., Peter, M., Sartorius, C., 2012. Kosten und Nutzen von Anpassungsmaßnahmen an den Klimawandel - Analyse von 28 Anpassungs-maßnahmen in Deutschland (No. FKZ 3709 41 121). Ecologic.
Van Alphen, J., 2016. The Delta Programme and updated flood risk management policies in the Netherlands. Flood Risk Management 9, 310–319. https://doi.org/10.1111/jfr3.12183
Vargas-Amelin, E., Pindado, P., 2014. The challenge of climate change in Spain: Water resources, agriculture and land. Journal of Hydrology 518, 243–249.
Ward, P.J., Jongman, B., Aerts, J.C., Bates, P.D., Botzen, W.J., Loaiza, A.D., Hallegatte, S., Kind, J.M., Kwadijk, J., Scussolini, P., others, 2017. A global framework for future costs and benefits of river-flood protection in urban areas. Nature climate change 7, 642–646.
Warren, R.F., Wilby, R.L., Brown, K., Watkiss, P., Betts, R.A., Murphy, J.M., Lowe, J.A., 2018. Advancing national climate change risk assessment to deliver national adaptation plans. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 376, 20170295. https://doi.org/10.1098/rsta.2017.0295
Winsemius, H.C., Aerts, J.C., Van Beek, L.P., Bierkens, M.F., Bouwman, A., Jongman, B., Kwadijk, J.C., Ligtvoet, W., Lucas, P.L., Van Vuuren, D.P., others, 2016. Global drivers of future river flood risk. Nature Climate Change 6, 381–385.

4.7. Appendix

4.7.1. Appendix A: Adaptation cost vectors and effectiveness estimates

Tables A 1-A 3 describe the annual cost vectors implemented in the CGE model synthesised from the adaptation cost pathways discussed in 2.2.1 for Austria, Spain and the Netherlands in 2050. Thereby we differentiate public expenditure volumes and adaptation benefits between climate impacts and types of adaptation actions. The effectiveness of adaptation is quantified in two ways: (i) by benefit-cost-ratios,

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

which express the relationship between relative adaptation costs of a specific action and the direct damages that can be avoided by this action, and (ii) by the damage reduction potential of a set of measures, expressed as relative changes in the magnitude of direct climate impacts. Benefit-cost ratios for flood risk management in Austria and adaptation in Spain are synthesised from estimated mean benefit-cost ratios of a list of comparable measures, where lower bound and upper bound ratios refer to the 10^{th} and 90^{th} percentile respectively. Similarly, uncertainties concerning the effectiveness of adaptation in the agricultural and forestry sector are taken into account by considering a bandwidth of values, suggested by literature and expert assessment. Given the comprehensive approach to Dutch delta management, the benefits (quantified by the damage reduction potential) arise from the collectively implemented measures, whereas actions directed at flood risk management in Austria and Spain, or adaptation in agriculture and forestry in Spain are considered separately, differentiating between the expected effectiveness of grey, green and soft measures. Similar to Dutch flood risk management, the benefits of Austrian adaptation in agriculture and forestry arise from the bundle of measures foreseen in the adaptation strategy. As a result, the benefits are expressed in terms of damage reduction potential, specified for the measures currently foreseen, given the current state of knowledge on the development of climate risk.

Table A 1: Cost vector implemented in the CGE model resulting from the Austrian adaptation cost pathway illustrated in Figure 4.1 for the impact fields of riverine flooding, agriculture and forestry and expected effectiveness of adaptation of the individual measures with underlying sources in 2050.

Impact field	**Type of adaptation action**	**Annual costs in 2050 in EUR million**	**Estimated effectiveness of adaptation**
Riverine flooding	Structural investments	15	benefit-cost-ratio: 3.8 (lower bound: 1.2, upper bound: 7.5) (Kuik et al., 2016; Tröltzsch et al., 2012)
	Accumulation effect of structural investments	1	
	Green investments	16	benefit-cost-ratio: 2.8 (lower bound: 1.2, upper bound: 5.5) (Kuik et al., 2016; Tröltzsch et al., 2012)
	Accumulation effect of green investments	3	
	Implementation of soft measures	52	benefit-cost-ratio: 10.3 (lower bound: 1.6, upper bound: 12.6) (Kuik et al., 2016; Tröltzsch et al., 2012)
Agriculture	Green measures	33	Yield increase: 10% (lower bound: 5%, upper bound: 15%) (Schönhart et al. 2016)
	Soft measures	49	
Forestry	Structural investments	53	Damage reduction to commercial forests: 40% (lower bound: 35%, upper bound: 45%) (Kolström et al. 2011)
	Accumulation effect of structural investments	8	
	Green investments	10	
	Accumulation effect of green investments	1	

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Table A 2: Cost vector implemented in the CGE model resulting from the Spanish adaptation cost pathway illustrated in Figure 4.2 for the impact fields of riverine flooding, coastal flooding, agriculture and forestry and expected effectiveness of adaptation of the individual measures with underlying sources in 2050.

Impact field	**Type of adaptation action**	**Annual costs in 2050 in EUR million**	**Estimated effectiveness of adaptation**
Riverine flooding	Structural investments	126	benefit-cost-ratio: 3.5 (lower bound: 5.1, upper bound: 2.1) (Kuik et al., 2016; Nisbet et al., 2015; Tröltzsch et al., 2012)
	Accumulation effect of structural investments	14	
	Green investments	22	benefit-cost-ratio: 4 (Kuik et al., 2016; Nisbet et al., 2015; Tröltzsch et al., 2012)(Kuik et al., 2016; Tröltzsch et al., 2012)
	Accumulation effect of green investments	2	
	Implementation of soft measures	33	benefit-cost-ratio: 10.3 (lower bound: 1.6, upper bound: 12.6) (Kuik et al., 2016; Nisbet et al., 2015; Tröltzsch et al., 2012)(Kuik et al., 2016; Tröltzsch et al., 2012)
Sea level rise	Structural investments (hard & soft)	2	benefit-cost-ratio: 3 (lower bound: 2.3, upper bound: 3.3) (Global Commission on Adaptation, 2019; Kontogianni et al., 2014; Tröltzsch et al., 2012)
	Accumulation effect of hard structural measures	<1	
	Green coastal management	2	benefit-cost-ratio: 10 (Global Commission on Adaptation, 2019; Kontogianni et al., 2014; Tröltzsch et al., 2012)
	Planning & management of further actions	2	benefit-cost-ratio: 4.8 (Global Commission on Adaptation, 2019; Kontogianni et al., 2014; Tröltzsch et al., 2012)
Agriculture	Structural investments	307	benefit-cost ratio: 1.3 (lower bound: 0.5, upper bound: 2.2) (Anagnostopoulos and Petalas, 2011)
	Accumulation effect of structural investments	35	
	Green measures	3	
	Implementation of soft measures	2	
Forestry	Structural investments	14	benefit-cost-ratio: 2

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

	Accumulation effect of structural measures	3	(Tröltzsch et al., 2012)
	Green investments	3	benefit-cost-ratio: 4.8 (Tröltzsch et al., 2012)

Table A 3: Cost vector implemented in the CGE model resulting from the adaptation cost pathway under the Dutch Delta Programme illustrated in Figure 4.3 for the impact fields of riverine flooding and coastal flooding and expected effectiveness of adaptation with the underlying source in 2050.

Type of adaptation action	**Annual costs in 2050 in EUR million**	**Estimated effectiveness of adaptation**
Structural investments	370	
Accumulation effect of structural investments	65	
Green investments	41	
Accumulation effect of green investments	7	
Government demand for maintenance & the implementation of soft measures	708	99% for up to 1/100 per year flood events and sea level rise (Van Alphen, 2016)

4.7.2. Appendix B: Results for SSP2 RCP4.5 HadGEM2-ESM

The following figures present the *impact* and *adaptation scenario* for a socioeconomic development under SSP2 and an emission pathway following RCP 4.5 in 2050 for GCM HadGem2-ESM.

B.1. Austria

Figures B.1.1.-B.1.3 represent the results for the *impact* and *adaptation scenario* in Austria for a SSP2-RCP4.5 scenario combination. Compared to the results discussed in 2.2.3, we find that under this scenario combination, impacts in agriculture are positive in 2050, leading to an increase in the sectoral output level and therefore economic activity, which lowers overall GDP losses caused by productivity changes in forestry and capital damages from riverine flooding. Adaptation increases climate induced productivity gains in agriculture, enabling an overall positive effect on GDP in the *adaptation scenario.* A higher economic activity in the *adaptation* scenario, compared to the *baseline,* also allows for a higher level of government revenue, resulting in an increase of government consumption and transfers to private households in the *adaptation scenario.*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

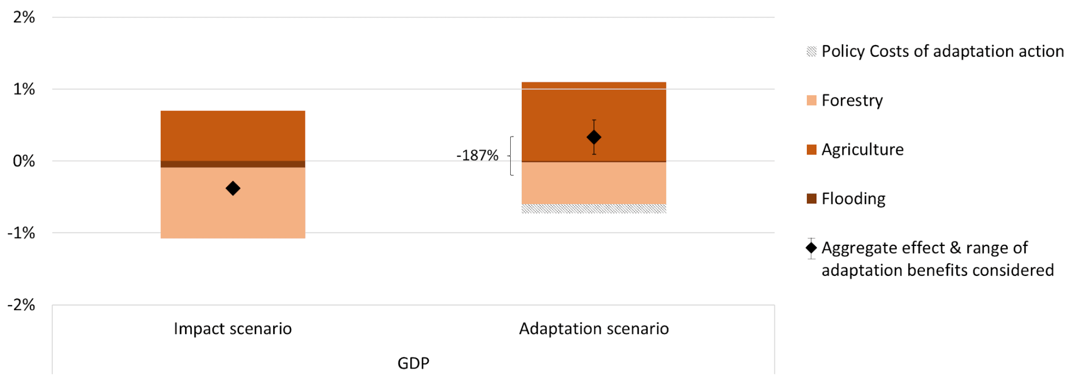


Figure B.1.1. Macroeconomic effect in terms of GDP of mean changes from riverine flooding (expected annual damage, EAD), impacts in agriculture & forestry in SSP2 RCP4.5 in Austria in 2050. Note: Results are based on GCM HadGem2-ESM.

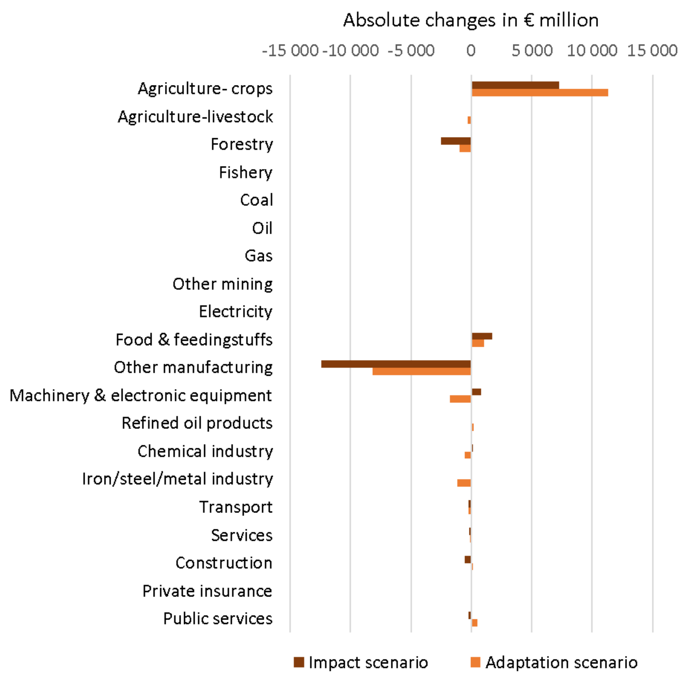


Figure B.1.2. Absolute changes in sectoral output levels in the impact and adaptation scenario of mean changes from riverine flooding (expected annual damage, EAD), impacts in agriculture & forestry in Austria in 2050 in SSP2 RCP4.5. Note: Results are based on GCM HadGem2-ESM.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***

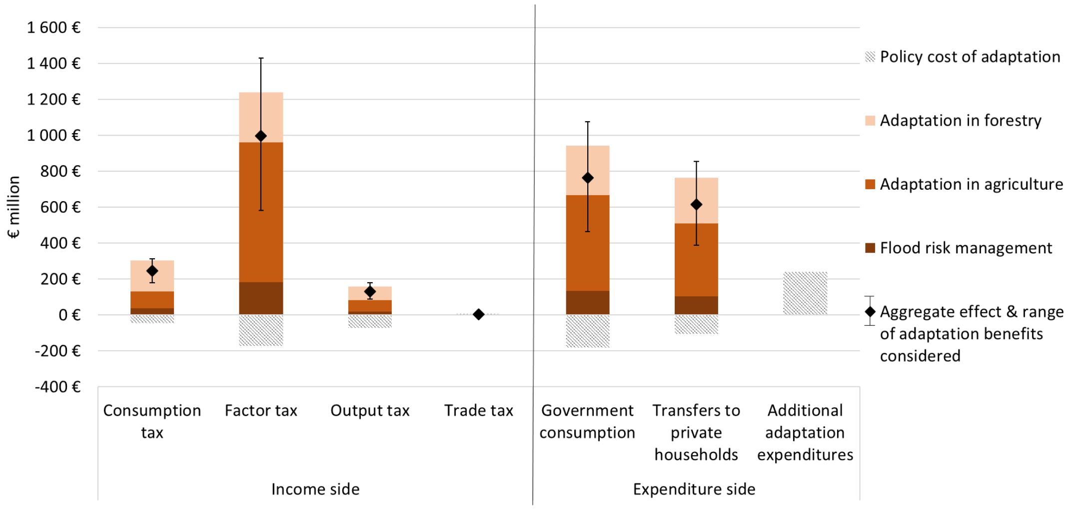


Figure B.1.3. Absolute difference between the impact and adaptation scenario on the expenditure side of the public budget in 2050 in SSP2 RCP4.5 in Austria in 2050 considering mean changes from riverine flooding (expected annual damage, EAD), impacts in agriculture & forestry. Note: Results are based on GCM HadGem2-ESM.

B.2. Spain

Figures B.2.1.-B.2.3 represent the results for the *impact* and *adaptation scenario* in Spain for a SSP2-RCP4.5 scenario combination. Compared to the results discussed in 2.2.3, we find that economy-wide and budgetary disruptions of climate change impacts (especially due changes in agricultural productivity level) are less severe, with GDP effects of -1.1%, compared to a 1.6% loss in SPSP5-RCP8.5. Similarly, sectoral implications in the *impact scenario* are less distinct, with a lower reduction in the sectoral activity level of the agricultural crop production. Due to less severe climate impacts in SSP2-RCP4.5, disruptions to public tax revenues are less severe, resulting in smaller benefits of adaptation in absolute terms, compared to SSP5-RCP8.5. However, benefits of adaptation prevail also for this scenario combination and are robust across the range of benefit-cost ratios considered.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

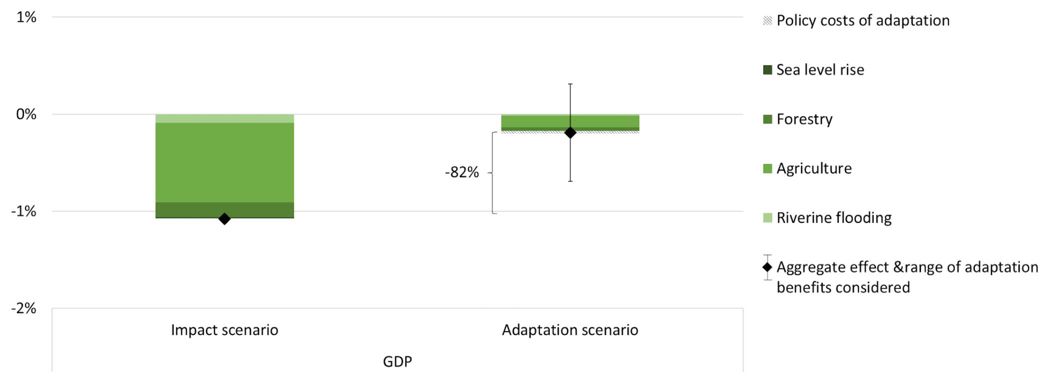


Figure B.2.1. Macroeconomic effect in terms of GDP of mean changes from riverine flooding (expected annual damage, EAD), sea level rise and impacts in agriculture & forestry in SSP2 RCP4.5 in Spain in 2050. Note: Results are based on GCM HadGem2-ESM.

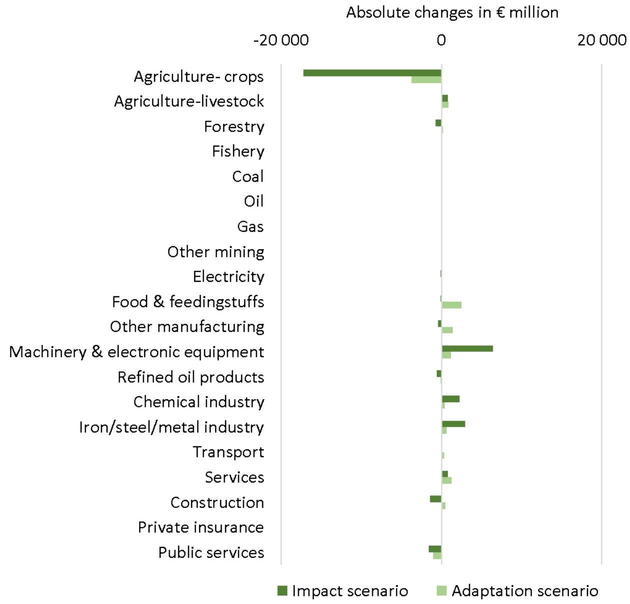


Figure B.2.2. Absolute changes in sectoral output levels in the impact and adaptation scenario of mean changes from riverine flooding (expected annual damage, EAD), sea level rise and impacts in agriculture & forestry in Spain in 2050 in SSP2 RCP4.5. Note: Results are based on GCM HadGem2-ESM.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

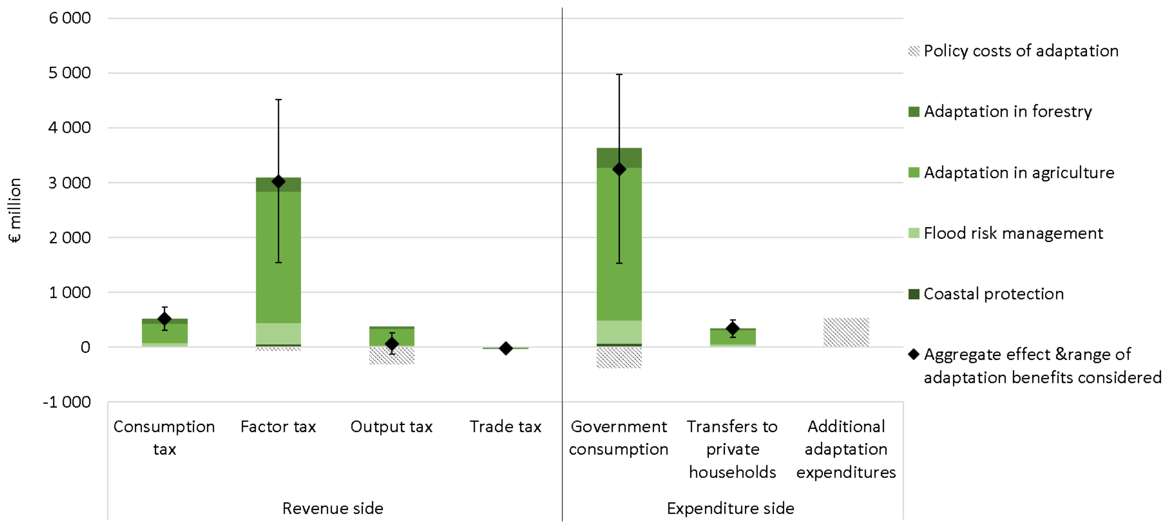


Figure B.2.3. Absolute difference between the impact and adaptation scenario on the expenditure side of the public budget in 2050 in SSP2 RCP4.5 in Spain in 2050 considering mean changes from riverine flooding (expected annual damage, EAD), sea level rise and impacts in agriculture & forestry. Note: Results are based on GCM HadGem2-ESM.

B.3. Netherlands

Figures B.3.1.-B.3.3 represent the results for the *impact* and *adaptation scenario* in the Netherlands for a SSP2-RCP4.5 scenario combination with EAD from riverine flooding and sea level rise. As discussed in 2.2.3, we find that economy-wide and budgetary disruptions remain low also in SSP2-RCP4.5. Again we find that adaptation under the Dutch Delta programme is costly, with adaptation benefits failing to compensate for the policy costs of implementation, leading to higher economy-wide and budgetary disruptions in the *adaptation scenario,* compared to the *impact scenario.*

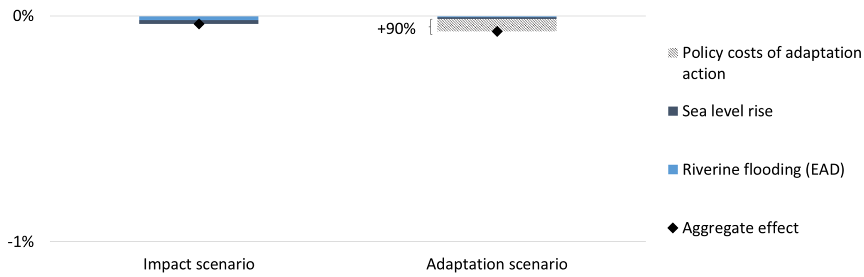


Figure B.3.1. Macroeconomic effect in terms of GDP of mean changes from riverine flooding (expected annual damage, EAD) and sea level rise in SSP2 RCP4.5 in the Netherlands in 2050. Note: Results are based on GCM HadGem2-ESM.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

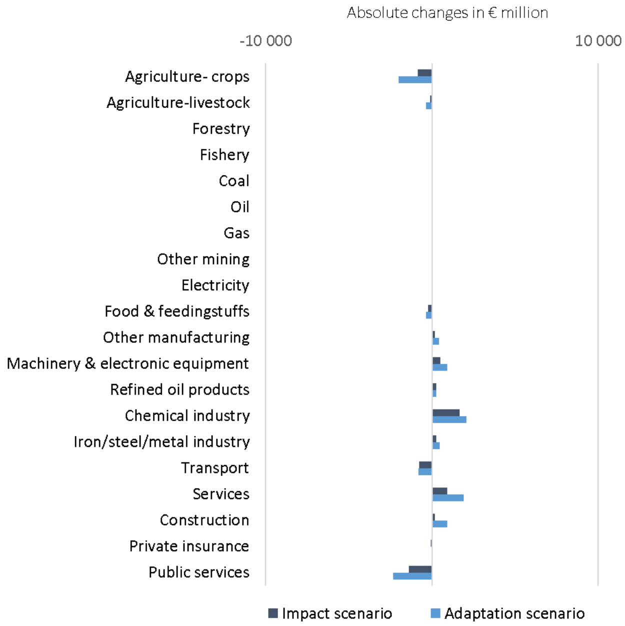


Figure B.3.2. Absolute changes in sectoral output levels in the impact and adaptation scenario of mean changes from riverine flooding (expected annual damage, EAD) and sea level rise in the Netherlands in 2050 in SSP2 RCP4.5. Note: Results are based on GCM HadGem2-ESM.

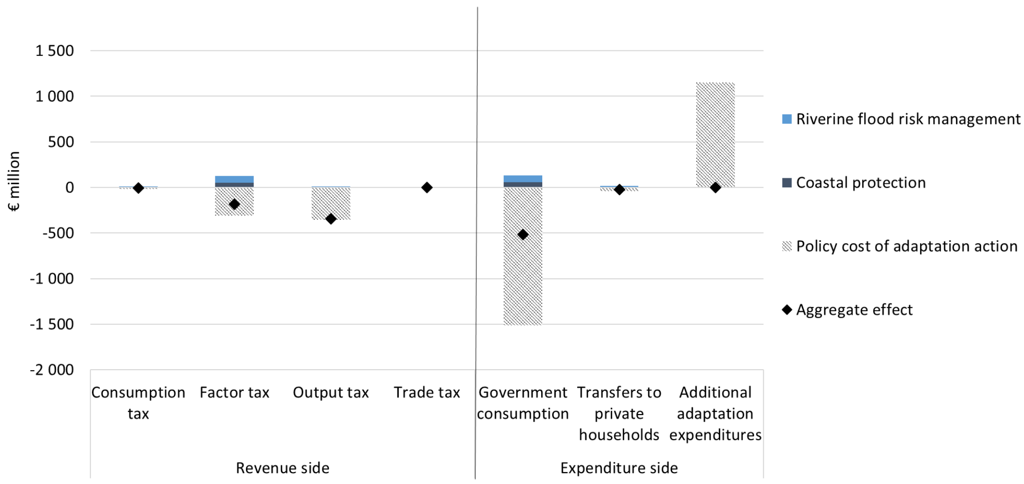


Figure B.3.3. Absolute difference between the impact and adaptation scenario on the expenditure side of the public budget in 2050 in SSP2 RCP4.5 in the Netherlands in 2050 considering mean changes from riverine flooding (expected annual damage, EAD) and sea level rise. Note: Results are based on GCM HadGem2-ESM.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

5. Annex with COACCH damage function coefficients

5.1. Annex I: CCDFs coefficients COACCH-WP4

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Table 2: Damage function parameters for IAMs: FAIR/IMAGE, REMIND and WITCH – All impacts except SLR – Quadratic Quantile Regression

Region	b1	b2	a (q=0.025)	a (q=0.05)	a (q=0.16)	a (q=0.25)	a (q=0.33)	a (q=0.5)	a (q=0.67)	a (q=0.75)	a (q=0.84)	a (q=0.95)	a (q=0.975)	b1_low	b2_low	b1_high	b2_high
World	0.445	0.863	-0.122	0.060	0.497	0.625	0.737	1.000	1.230	1.346	1.566	1.906	2.025	0.320	0.781	0.570	0.945
I_CAN	0.474	0.581	0.294	0.320	0.424	0.565	0.650	1.000	1.171	1.354	1.860	2.114	2.228	0.342	0.494	0.606	0.667
I_CEU	0.330	0.628	0.134	0.266	0.535	0.704	0.800	1.000	1.240	1.380	1.560	2.200	2.388	0.247	0.573	0.413	0.682
I_CHN	1.379	-0.071	-0.731	-0.418	0.376	0.601	0.774	1.000	1.284	1.447	1.569	1.775	1.900	1.251	-0.155	1.508	0.014
I_EastAsia	0.984	0.602	0.341	0.444	0.645	0.742	0.843	1.000	1.209	1.305	1.547	1.827	1.898	0.831	0.501	1.137	0.702
I_FSU	0.792	0.252	0.052	0.106	0.365	0.567	0.679	1.000	1.312	1.545	1.740	2.174	2.293	0.659	0.165	0.925	0.339
I_INDIA	2.323	1.660	-0.178	-0.093	0.334	0.472	0.616	1.000	1.172	1.299	1.491	1.861	2.006	1.860	1.356	2.786	1.964
I_JAP	0.069	0.821	0.254	0.319	0.559	0.675	0.784	1.000	1.237	1.346	1.666	2.216	2.361	-0.019	0.763	0.156	0.878
I_Laca	0.696	0.639	-2.650	-2.174	-0.173	0.219	0.511	1.000	1.213	1.390	1.807	2.150	2.262	0.533	0.532	0.859	0.746
I_MiddleEast	0.989	0.081	-0.184	-0.010	0.430	0.619	0.714	1.000	1.384	1.639	1.952	2.403	2.511	0.840	-0.017	1.138	0.179
I_NAF	0.532	1.521	-0.743	-0.509	0.274	0.417	0.581	1.000	1.282	1.576	1.970	2.438	2.542	0.276	1.353	0.788	1.690
I_OCE	0.351	0.916	-0.429	-0.288	0.258	0.567	0.708	1.000	1.226	1.333	1.626	1.973	2.070	0.223	0.832	0.480	1.001
I_RSAF	0.359	1.480	0.497	0.547	0.684	0.788	0.856	1.000	1.140	1.200	1.304	1.669	1.830	0.234	1.398	0.484	1.562
I_RSAS	2.781	0.890	0.043	0.125	0.486	0.613	0.744	1.000	1.188	1.263	1.389	1.686	1.790	2.452	0.674	3.111	1.107
I_SEAS	2.178	0.926	-0.538	-0.253	0.390	0.500	0.651	1.000	1.249	1.387	1.696	1.964	2.097	1.822	0.693	2.534	1.160
I_SSA	2.309	1.619	0.469	0.532	0.721	0.809	0.876	1.000	1.102	1.173	1.262	1.397	1.455	2.068	1.461	2.550	1.778
I_USA	0.472	0.448	0.369	0.467	0.688	0.757	0.816	1.000	1.189	1.294	1.477	1.743	1.823	0.391	0.395	0.553	0.501
I_WEU	0.231	0.429	0.197	0.313	0.596	0.733	0.801	1.000	1.280	1.408	1.611	2.445	2.669	0.172	0.391	0.290	0.468
R_CAZ	0.431	0.633	-0.047	0.106	0.501	0.612	0.713	1.000	1.331	1.497	1.831	2.179	2.284	0.307	0.552	0.555	0.715
R_CHA	1.379	-0.071	-0.731	-0.418	0.376	0.602	0.774	1.000	1.284	1.447	1.569	1.775	1.900	1.251	-0.155	1.508	0.014
R_EUR	0.235	0.467	0.191	0.310	0.596	0.739	0.823	1.000	1.269	1.412	1.596	2.423	2.620	0.175	0.428	0.295	0.507
R_IND	2.323	1.660	-0.178	-0.093	0.334	0.472	0.616	1.000	1.172	1.299	1.491	1.861	2.006	1.860	1.356	2.786	1.964
R_JON	0.069	0.821	0.254	0.319	0.559	0.675	0.784	1.000	1.237	1.346	1.666	2.216	2.361	-0.019	0.763	0.156	0.878
R_LAM	0.696	0.639	-2.650	-2.174	-0.173	0.219	0.511	1.000	1.213	1.390	1.807	2.150	2.262	0.533	0.532	0.859	0.746
R_MEA	0.776	0.427	-0.389	-0.176	0.380	0.569	0.744	1.000	1.386	1.656	2.022	2.511	2.653	0.617	0.323	0.935	0.532
R_NEU	0.212	0.062	-0.799	-0.450	0.088	0.331	0.584	1.000	1.787	2.800	3.659	5.009	5.724	0.160	0.028	0.264	0.096
R_OAS	1.393	1.153	-0.236	-0.011	0.468	0.593	0.714	1.000	1.242	1.354	1.602	1.908	2.001	1.112	0.968	1.674	1.337
R_REF	0.792	0.252	0.052	0.106	0.365	0.567	0.679	1.000	1.312	1.545	1.740	2.174	2.293	0.659	0.165	0.925	0.339
R_SSA	1.643	1.827	0.477	0.537	0.731	0.812	0.881	1.000	1.108	1.175	1.277	1.428	1.490	1.427	1.685	1.859	1.969
R_USA	0.472	0.448	0.369	0.467	0.688	0.757	0.816	1.000	1.189	1.294	1.477	1.743	1.823	0.391	0.395	0.553	0.501
W_canada	0.474	0.581	0.294	0.320	0.424	0.565	0.650	1.000	1.171	1.354	1.860	2.114	2.228	0.342	0.494	0.606	0.667
W_china	1.379	-0.071	-0.731	-0.418	0.376	0.602	0.774	1.000	1.284	1.447	1.569	1.775	1.900	1.251	-0.155	1.508	0.014
W_europe	0.253	0.436	0.197	0.313	0.591	0.734	0.813	1.000	1.282	1.406	1.594	2.435	2.644	0.192	0.396	0.313	0.475
W_india	2.323	1.660	-0.178	-0.093	0.334	0.472	0.616	1.000	1.172	1.299	1.491	1.861	2.006	1.860	1.356	2.786	1.964
W_jpnkor	0.349	0.743	0.323	0.370	0.610	0.769	0.845	1.000	1.260	1.353	1.657	2.097	2.203	0.243	0.673	0.456	0.813
W_laca	0.696	0.639	-2.650	-2.174	-0.173	0.219	0.511	1.000	1.213	1.390	1.807	2.150	2.262	0.533	0.532	0.859	0.746
W_mena	0.776	0.427	-0.389	-0.176	0.380	0.569	0.744	1.000	1.386	1.656	2.022	2.511	2.653	0.617	0.323	0.935	0.532
W_oceania	0.351	0.916	-0.429	-0.288	0.258	0.567	0.708	1.000	1.226	1.333	1.626	1.973	2.070	0.223	0.832	0.480	1.001
W_sasia	2.781	0.890	0.043	0.125	0.486	0.613	0.744	1.000	1.188	1.263	1.389	1.686	1.790	2.452	0.674	3.111	1.107
W_seasia	2.178	0.926	-0.538	-0.253	0.390	0.500	0.651	1.000	1.249	1.387	1.696	1.964	2.097	1.822	0.693	2.534	1.160
W_southafrica	0.359	1.480	0.497	0.547	0.684	0.788	0.856	1.000	1.140	1.200	1.304	1.669	1.830	0.234	1.398	0.484	1.562
W_ssa	2.309	1.619	0.469	0.532	0.721	0.809	0.876	1.000	1.102	1.173	1.262	1.397	1.455	2.068	1.461	2.550	1.778
W_te	0.792	0.252	0.052	0.106	0.365	0.567	0.679	1.000	1.312	1.545	1.740	2.174	2.293	0.659	0.165	0.925	0.339
W_usa	0.472	0.448	0.369	0.467	0.688	0.757	0.816	1.000	1.189	1.294	1.477	1.743	1.823	0.391	0.395	0.553	0.501

Note: The first letter of the region name indicates the Model: I = FAIR/IMAGE, R=REMIND, W=WITCH. Coloured rows highlight the suggested parameters for each IAM

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Table 3: Damage function parameters for IAMs: FAIR/IMAGE, REMIND and WITCH – SLR with incremental adaptation– Linear Quantile Regression

Region	b1	a (q=0.025)	a (q=0.05)	a (q=0.16)	a (q=0.25)	a (q=0.33)	a (q=0.5)	a (q=0.67)	a (q=0.75)	a (q=0.84)	a (q=0.95)	a (q=0.975)	b1_low	b1_high
World	1.859	0.480	0.650	0.800	0.864	0.908	1.000	1.095	1.142	1.251	1.454	1.611	1.712	2.007
I_CAN	2.635	0.286	0.416	0.829	0.879	0.926	1.000	1.107	1.149	1.244	1.383	1.484	2.420	2.849
I_CEU	0.426	0.334	0.337	0.429	0.496	0.603	1.000	3.499	3.582	4.190	4.771	5.321	0.156	0.697
I_CHN	2.506	0.651	0.664	0.749	0.811	0.877	1.000	1.224	1.280	1.529	2.129	2.369	2.167	2.845
I_EastAsia	3.490	0.303	0.415	0.730	0.874	0.891	1.000	1.055	1.153	1.196	1.334	1.340	3.216	3.764
I_FSU	0.714	0.538	0.721	0.768	0.861	0.883	1.000	1.048	1.077	1.237	1.459	1.561	0.660	0.768
I_INDIA	1.237	0.647	0.684	0.749	0.808	0.862	1.000	1.241	1.360	1.542	2.099	2.275	1.069	1.404
I_JAP	3.378	0.304	0.344	0.703	0.868	0.912	1.000	1.081	1.143	1.206	1.354	1.371	3.088	3.668
I_Laca	1.279	0.503	0.566	0.699	0.814	0.832	1.000	1.220	1.307	1.485	1.843	1.956	1.115	1.442
I_MiddleEast	3.095	0.457	0.561	0.864	0.894	0.947	1.000	1.087	1.160	1.250	1.425	1.466	2.868	3.321
I_NAF	6.450	0.456	0.508	0.878	0.911	0.928	1.000	1.057	1.164	1.208	1.363	1.478	6.002	6.898
I_OCE	2.172	0.432	0.596	0.827	0.878	0.938	1.000	1.140	1.166	1.274	1.481	1.565	1.992	2.351
I_RSAF	1.723	0.247	0.545	0.711	0.799	0.898	1.000	1.148	1.195	1.354	1.542	1.752	1.546	1.901
I_RSAS	0.508	0.402	0.450	0.541	0.615	0.703	1.000	1.739	2.123	2.542	3.487	4.471	0.308	0.708
I_SEAS	9.292	0.475	0.524	0.881	0.907	0.926	1.000	1.059	1.119	1.199	1.323	1.417	8.686	9.898
I_SSA	-0.633	1.809	1.687	1.431	1.358	1.239	1.000	0.037	-0.505	-0.921	-1.489	-1.748	-0.877	-0.389
I_USA	1.395	0.213	0.348	0.753	0.852	0.904	1.000	1.122	1.158	1.181	1.399	1.431	1.266	1.523
I_WEU	0.147	0.134	0.141	0.176	0.201	0.242	1.000	9.863	9.952	11.266	13.303	13.532	-0.127	0.422
R_CAZ	2.441	0.342	0.484	0.828	0.872	0.908	1.000	1.099	1.157	1.220	1.394	1.508	2.249	2.634
R_CHA	2.506	0.651	0.664	0.749	0.811	0.877	1.000	1.224	1.280	1.529	2.129	2.369	2.167	2.845
R_EUR	0.142	-0.725	-0.661	-0.573	-0.558	-0.505	1.000	9.834	10.324	11.330	13.481	13.710	-0.141	0.426
R_IND	1.237	0.647	0.684	0.749	0.808	0.862	1.000	1.241	1.360	1.542	2.099	2.275	1.069	1.404
R_JON	3.378	0.304	0.344	0.703	0.868	0.912	1.000	1.081	1.143	1.206	1.354	1.371	3.088	3.668
R_LAM	1.279	0.503	0.566	0.699	0.814	0.832	1.000	1.220	1.307	1.485	1.843	1.956	1.115	1.442
R_MEA	3.864	0.435	0.513	0.876	0.901	0.915	1.000	1.045	1.161	1.220	1.349	1.453	3.588	4.141
R_NEU	2.273	0.279	0.387	0.718	0.868	0.888	1.000	1.064	1.153	1.188	1.359	1.386	2.080	2.465
R_OAS	6.113	0.405	0.486	0.872	0.897	0.921	1.000	1.063	1.140	1.191	1.302	1.377	5.699	6.527
R_REF	0.714	0.538	0.721	0.768	0.861	0.883	1.000	1.048	1.077	1.237	1.459	1.561	0.660	0.768
R_SSA	-0.164	5.379	4.768	4.055	3.388	2.838	1.000	-2.337	-3.512	-4.838	-7.535	-8.314	-0.423	0.095
R_USA	1.395	0.213	0.348	0.753	0.852	0.904	1.000	1.122	1.158	1.181	1.399	1.431	1.266	1.523
W_canada	2.635	0.286	0.416	0.829	0.879	0.926	1.000	1.107	1.149	1.244	1.383	1.484	2.420	2.849
W_china	2.506	0.651	0.664	0.749	0.811	0.877	1.000	1.224	1.280	1.529	2.129	2.369	2.167	2.845
W_europe	0.161	0.230	0.233	0.269	0.287	0.333	1.000	8.988	9.443	10.300	12.242	12.430	-0.113	0.434
W_india	1.237	0.647	0.684	0.749	0.808	0.862	1.000	1.241	1.360	1.542	2.099	2.275	1.069	1.404
W_jpnkor	3.421	0.303	0.364	0.714	0.852	0.905	1.000	1.062	1.142	1.196	1.339	1.353	3.138	3.704
W_laca	1.279	0.503	0.566	0.699	0.814	0.832	1.000	1.220	1.307	1.485	1.843	1.956	1.115	1.442
W_mena	3.864	0.435	0.513	0.876	0.901	0.915	1.000	1.045	1.161	1.220	1.349	1.453	3.588	4.141
W_oceania	2.172	0.432	0.596	0.827	0.878	0.938	1.000	1.140	1.166	1.274	1.481	1.565	1.992	2.351
W_sasia	0.508	0.402	0.450	0.541	0.615	0.703	1.000	1.739	2.123	2.542	3.487	4.471	0.308	0.708
W_seasia	9.292	0.475	0.524	0.881	0.907	0.926	1.000	1.059	1.119	1.199	1.323	1.417	8.686	9.898
W_southafrica	1.723	0.247	0.545	0.711	0.799	0.898	1.000	1.148	1.195	1.354	1.542	1.752	1.546	1.901
W_ssa	-0.633	1.809	1.687	1.431	1.358	1.239	1.000	0.037	-0.505	-0.921	-1.489	-1.748	-0.877	-0.389
W_te	0.714	0.538	0.721	0.768	0.861	0.883	1.000	1.048	1.077	1.237	1.459	1.561	0.660	0.768
W_usa	1.395	0.213	0.348	0.753	0.852	0.904	1.000	1.122	1.158	1.181	1.399	1.431	1.266	1.523

Note: The first letter of the region name indicates the Model: I = FAIR/IMAGE, R=REMIND, W=WITCH. Coloured rows highlight the suggested parameters for each IAM

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Table 4: Damage function parameters for IAMs: FAIR/IMAGE, REMIND and WITCH – SLR with incremental adaptation– Logistic Robust Regression

Region	b1	b2	b3	a (q=0.025)	a (q=0.05)	a (q=0.16)	a (q=0.25)	a (q=0.33)	a (q=0.5)	a (q=0.67)	a (q=0.75)	a (q=0.84)	a (q=0.95)	a (q=0.975)
World	0.729	3.267	12.256	0.456	0.587	0.829	0.883	0.910	0.997	1.099	1.123	1.191	1.338	1.515
I_CAN	0.910	12.503	17.036	0.395	0.585	0.829	0.908	0.936	0.997	1.066	1.143	1.212	1.572	1.602
I_CEU	670.183	4463.381	2.810	0.198	0.209	0.296	0.361	0.440	0.871	2.284	2.682	2.927	3.792	4.447
I_CHN	0.734	2.737	34.617	0.575	0.658	0.960	0.974	0.982	1.000	1.020	1.034	1.070	1.104	1.162
I_EastAsia	1.541	8.691	11.967	0.437	0.627	0.788	0.866	0.920	1.002	1.084	1.142	1.203	1.513	1.558
I_FSU	0.583	0.844	5.892	0.468	0.657	0.827	0.883	0.919	1.003	1.091	1.121	1.194	1.341	1.466
I_INDIA	0.317	5.904	39.169	0.539	0.614	0.915	0.932	0.964	0.999	1.044	1.051	1.081	1.156	1.182
I_JAP	1.277	13.607	15.241	0.376	0.577	0.822	0.893	0.953	1.000	1.093	1.123	1.229	1.602	1.653
I_Laca	0.326	10.651	28.969	0.328	0.505	0.769	0.829	0.916	0.999	1.147	1.186	1.212	1.378	1.525
I_MiddleEast	1.326	4.167	11.238	0.481	0.537	0.846	0.909	0.944	1.000	1.069	1.124	1.209	1.406	1.465
I_NAF	2.673	4.603	11.712	0.478	0.503	0.891	0.923	0.952	0.999	1.036	1.113	1.135	1.400	1.470
I_OCE	0.749	5.830	15.599	0.440	0.531	0.847	0.914	0.925	1.013	1.091	1.102	1.174	1.403	1.536
I_RSAF	0.519	8.293	19.800	0.249	0.464	0.808	0.852	0.876	1.005	1.090	1.124	1.188	1.411	1.599
I_RSAS	0.126	6134383.256	366.646	0.507	0.579	0.672	0.782	0.842	1.017	1.249	1.340	1.400	1.518	1.553
I_SEAS	3.719	5.751	12.522	0.511	0.556	0.873	0.924	0.953	1.000	1.044	1.096	1.130	1.446	1.482
I_SSA	-0.265	314323.058	57.952	3.442	1.702	1.158	1.106	1.037	1.019	0.897	0.857	0.727	0.407	0.019
I_USA	0.470	19.150	18.811	0.334	0.540	0.795	0.885	0.908	0.999	1.079	1.133	1.234	1.573	1.784
I_WEU	0.479	109.330	16.381	0.031	0.031	0.041	0.046	0.055	0.755	1.818	2.139	2.841	4.583	5.393
R_CAZ	0.807	9.624	17.062	0.429	0.473	0.830	0.903	0.932	1.004	1.079	1.110	1.180	1.496	1.541
R_CHA	0.734	2.737	34.617	0.575	0.658	0.960	0.974	0.982	1.000	1.020	1.034	1.070	1.104	1.162
R_EUR	0.406	130.226	17.481	-0.293	-0.266	-0.153	-0.114	-0.098	0.882	1.950	2.281	3.104	5.285	6.088
R_IND	0.317	5.904	39.169	0.539	0.614	0.915	0.932	0.964	0.999	1.044	1.051	1.081	1.156	1.182
R_JON	1.277	13.607	15.241	0.376	0.577	0.822	0.893	0.953	1.000	1.093	1.123	1.229	1.602	1.653
R_LAM	0.326	10.651	28.969	0.328	0.505	0.769	0.829	0.916	0.999	1.147	1.186	1.212	1.378	1.525
R_MEA	1.597	4.906	11.665	0.495	0.512	0.864	0.911	0.943	0.999	1.063	1.135	1.171	1.417	1.502
R_NEU	0.936	11.103	13.493	0.402	0.586	0.795	0.873	0.920	1.006	1.104	1.141	1.253	1.553	1.632
R_OAS	2.358	7.590	13.668	0.481	0.541	0.851	0.923	0.947	1.001	1.030	1.087	1.137	1.446	1.514
R_REF	0.583	0.844	5.892	0.468	0.657	0.827	0.883	0.919	1.003	1.091	1.121	1.194	1.341	1.466
R_SSA	0.730	-0.999	0.000	5.187	4.598	3.910	3.267	2.737	0.964	-2.253	-3.386	-4.665	-7.265	-8.016
R_USA	0.470	19.150	18.811	0.334	0.540	0.795	0.885	0.908	0.999	1.079	1.133	1.234	1.573	1.784
W_canada	0.910	12.503	17.036	0.395	0.585	0.829	0.908	0.936	0.997	1.066	1.143	1.212	1.572	1.602
W_china	0.734	2.737	34.617	0.575	0.658	0.960	0.974	0.982	1.000	1.020	1.034	1.070	1.104	1.162
W_europe	0.601	87.171	13.950	0.043	0.048	0.059	0.064	0.104	0.731	1.910	2.243	2.973	4.630	5.346
W_india	0.317	5.904	39.169	0.539	0.614	0.915	0.932	0.964	0.999	1.044	1.051	1.081	1.156	1.182
W_jpnkor	1.367	11.580	13.973	0.400	0.602	0.808	0.897	0.941	1.001	1.093	1.134	1.239	1.581	1.605
W_laca	0.326	10.651	28.969	0.328	0.505	0.769	0.829	0.916	0.999	1.147	1.186	1.212	1.378	1.525
W_mena	1.597	4.906	11.665	0.495	0.512	0.864	0.911	0.943	0.999	1.063	1.135	1.171	1.417	1.502
W_oceania	0.749	5.830	15.599	0.440	0.531	0.847	0.914	0.925	1.013	1.091	1.102	1.174	1.403	1.536
W_sasia	0.126	6134383.253	366.646	0.507	0.579	0.672	0.782	0.842	1.017	1.249	1.340	1.400	1.518	1.553
W_seasia	3.719	5.751	12.522	0.511	0.556	0.873	0.924	0.953	1.000	1.044	1.096	1.130	1.446	1.482
W_southafrica	0.519	8.293	19.800	0.249	0.464	0.808	0.852	0.876	1.005	1.090	1.124	1.188	1.411	1.599
W_ssa	-0.265	314321.450	57.952	3.442	1.702	1.158	1.106	1.037	1.019	0.897	0.857	0.727	0.407	0.019
W_te	0.583	0.844	5.892	0.468	0.657	0.827	0.883	0.919	1.003	1.091	1.121	1.194	1.341	1.466
W_usa	0.470	19.150	18.811	0.334	0.540	0.795	0.885	0.908	0.999	1.079	1.133	1.234	1.573	1.784

Note: The first letter of the region name indicates the Model: I = FAIR/IMAGE, R=REMIND, W=WITCH.

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Table 5: Damage function parameters for IAMs: FAIR/IMAGE, REMIND and WITCH – SLR with constant adaptation– Linear Quantile Regression

Region	b1	a (q=0.025)	a (q=0.05)	a (q=0.16)	a (q=0.25)	a (q=0.33)	a (q=0.5)	a (q=0.67)	a (q=0.75)	a (q=0.84)	a (q=0.95)	a (q=0.975)	b1_low	b1_high
World	7.227	0.298	0.412	0.751	0.841	0.902	1	1.122	1.203	1.348	1.597	1.774	7.029	7.426
I_CAN	10.460	0.135	0.215	0.456	0.628	0.765	1	1.162	1.266	1.370	1.678	1.703	9.864	11.055
I_CEU	2.115	0.048	0.127	0.279	0.367	0.423	1	2.505	2.899	3.286	4.296	4.654	1.913	2.318
I_CHN	11.220	0.669	0.702	0.756	0.793	0.821	1	1.130	1.218	1.376	1.602	1.804	10.993	11.446
I_EastAsia	21.084	0.131	0.194	0.452	0.591	0.743	1	1.185	1.274	1.422	1.658	1.848	19.545	22.622
I_FSU	2.185	0.297	0.386	0.583	0.686	0.804	1	1.196	1.289	1.470	1.849	1.976	2.124	2.245
I_INDIA	3.336	0.283	0.350	0.435	0.527	0.644	1	1.344	1.478	1.599	1.781	1.941	3.144	3.528
I_JAP	34.374	0.077	0.114	0.335	0.489	0.660	1	1.222	1.344	1.475	1.732	1.930	31.265	37.483
I_Laca	4.594	0.242	0.470	0.719	0.800	0.886	1	1.145	1.207	1.289	1.631	1.893	4.473	4.716
I_MiddleEast	11.122	0.246	0.366	0.617	0.737	0.825	1	1.207	1.295	1.394	1.555	1.691	10.598	11.647
I_NAF	12.657	0.371	0.566	0.743	0.849	0.917	1	1.083	1.115	1.169	1.295	1.339	12.419	12.894
I_OCE	7.590	0.323	0.417	0.739	0.808	0.882	1	1.172	1.294	1.467	1.925	2.108	7.349	7.831
I_RSAF	5.821	0.152	0.287	0.643	0.777	0.849	1	1.144	1.228	1.365	1.656	1.851	5.625	6.018
I_RSAS	2.223	-0.534	-0.403	0.042	0.196	0.410	1	1.491	1.783	2.115	2.520	2.704	2.014	2.432
I_SEAS	15.759	0.493	0.565	0.713	0.810	0.885	1	1.098	1.135	1.196	1.411	1.585	15.455	16.064
I_SSA	-1.563	2.711	2.536	1.950	1.656	1.451	0.999998	0.117	-0.540	-0.994	-1.419	-1.557	-1.826	-1.300
I_USA	7.486	0.106	0.176	0.492	0.682	0.827	1	1.156	1.230	1.339	1.564	1.646	7.098	7.873
I_WEU	1.136	-0.092	-0.063	0.068	0.206	0.350	1	4.308	5.528	6.511	7.768	8.258	0.981	1.290
R_CAZ	8.976	0.185	0.290	0.583	0.741	0.836	1	1.190	1.281	1.443	1.773	1.866	8.561	9.391
R_CHA	11.220	0.669	0.702	0.756	0.793	0.821	1	1.130	1.218	1.376	1.602	1.804	10.993	11.446
R_EUR	0.886	-0.752	-0.569	-0.166	-0.068	-0.008	1	5.538	6.873	8.193	9.633	10.559	0.713	1.059
R_IND	3.336	0.283	0.350	0.435	0.527	0.644	1	1.344	1.478	1.599	1.781	1.941	3.144	3.528
R_JON	34.374	0.077	0.114	0.335	0.489	0.660	1	1.222	1.344	1.475	1.732	1.930	31.265	37.483
R_LAM	4.594	0.242	0.470	0.719	0.800	0.886	1	1.145	1.207	1.289	1.631	1.893	4.473	4.716
R_MEA	11.318	0.272	0.404	0.672	0.794	0.858	1	1.183	1.249	1.337	1.486	1.581	10.911	11.726
R_NEU	8.282	0.183	0.261	0.526	0.694	0.804	1	1.170	1.253	1.364	1.558	1.652	7.847	8.716
R_OAS	13.882	0.378	0.504	0.771	0.847	0.902	1	1.118	1.189	1.323	1.561	1.755	13.598	14.165
R_REF	2.185	0.297	0.386	0.583	0.686	0.804	1	1.196	1.289	1.470	1.849	1.976	2.124	2.245
R_SSA	-0.216	15.641	13.748	9.839	7.126	5.768	1	-4.775	-7.152	-9.587	-12.414	-13.679	-0.432	0.000
R_USA	7.486	0.106	0.176	0.492	0.682	0.827	1	1.156	1.230	1.339	1.564	1.646	7.098	7.873
W_canada	10.460	0.135	0.215	0.456	0.628	0.765	1	1.162	1.266	1.370	1.678	1.703	9.864	11.055
W_china	11.220	0.669	0.702	0.756	0.793	0.821	1	1.130	1.218	1.376	1.602	1.804	10.993	11.446
W_europe	1.207	-0.066	-0.025	0.101	0.248	0.362	1	4.131	5.151	6.100	7.217	7.796	1.049	1.365
W_india	3.336	0.283	0.350	0.435	0.527	0.644	1	1.344	1.478	1.599	1.781	1.941	3.144	3.528
W_jpnkor	29.982	0.085	0.135	0.364	0.503	0.662	1	1.205	1.313	1.440	1.663	1.891	27.359	32.605
W_laca	4.594	0.242	0.470	0.719	0.800	0.886	1	1.145	1.207	1.289	1.631	1.893	4.473	4.716
W_mena	11.318	0.272	0.404	0.672	0.794	0.858	1	1.183	1.249	1.337	1.486	1.581	10.911	11.726
W_oceania	7.590	0.323	0.417	0.739	0.808	0.882	1	1.172	1.294	1.467	1.925	2.108	7.349	7.831
W_sasia	2.223	-0.534	-0.403	0.042	0.196	0.410	1	1.491	1.783	2.115	2.520	2.704	2.014	2.432
W_seasia	15.759	0.493	0.565	0.713	0.810	0.885	1	1.098	1.135	1.196	1.411	1.585	15.455	16.064
W_southafrica	5.821	0.152	0.287	0.643	0.777	0.849	1	1.144	1.228	1.365	1.656	1.851	5.625	6.018
W_ssa	-1.563	2.711	2.536	1.950	1.656	1.451	0.999998	0.117	-0.540	-0.994	-1.419	-1.557	-1.826	-1.300
W_te	2.185	0.297	0.386	0.583	0.686	0.804	1	1.196	1.289	1.470	1.849	1.976	2.124	2.245
W_usa	7.486	0.106	0.176	0.492	0.682	0.827	1	1.156	1.230	1.339	1.564	1.646	7.098	7.873

Note: The first letter of the region name indicates the Model: I = FAIR/IMAGE, R=REMIND, W=WITCH. Coloured rows highlight the suggested parameters for each IAM

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Table 6: Damage function parameters for IAMs: FAIR/IMAGE, REMIND and WITCH – SLR with constant adaptation– Quadratic Quantile Regression

Region	b1	b2	a (q=0.025)	a (q=0.05)	a (q=0.16)	a (q=0.25)	a (q=0.33)	a (q=0.5)	a (q=0.67)	a (q=0.75)	a (q=0.84)	a (q=0.95)	a (q=0.975)	b1_low	b2_low	b1_high	b2_high
World	4.349	13.695	0.470	0.569	0.766	0.849	0.903	1	1.100	1.150	1.255	1.505	1.690	4.025	12.527	4.674	14.864
I_CAN	1.844	36.890	0.419	0.553	0.737	0.821	0.898	1	1.149	1.200	1.331	1.577	1.689	1.328	35.030	2.360	38.749
I_CEU	0.302	9.595	-0.010	0.057	0.256	0.357	0.433	1	2.251	2.421	2.881	3.651	4.081	-0.219	7.716	0.824	11.473
I_CHN	9.975	5.050	0.693	0.721	0.750	0.790	0.852	1	1.162	1.229	1.378	1.590	1.759	9.379	2.903	10.571	7.197
I_EastAsia	1.360	83.944	0.516	0.558	0.757	0.871	0.921	1	1.113	1.207	1.342	1.627	1.889	0.616	81.262	2.105	86.626
I_FSU	1.544	3.268	0.343	0.391	0.561	0.661	0.845	1	1.185	1.274	1.384	1.722	1.873	1.406	2.770	1.682	3.765
I_INDIA	5.944	-11.365	0.326	0.374	0.506	0.631	0.745	1	1.166	1.253	1.335	1.625	1.786	5.621	-12.528	6.267	-10.202
I_JAP	-4.141	167.005	0.417	0.452	0.713	0.791	0.850	1	1.120	1.203	1.352	1.685	1.826	-5.404	162.458	-2.879	171.553
I_Laca	4.059	2.698	0.282	0.490	0.694	0.786	0.885	1	1.127	1.209	1.293	1.573	1.774	3.745	1.566	4.374	3.831
I_MiddleEast	4.447	31.155	0.488	0.555	0.726	0.830	0.890	1	1.112	1.174	1.265	1.475	1.613	3.916	29.242	4.978	33.068
I_NAF	13.670	-4.192	0.348	0.539	0.734	0.853	0.904	1	1.067	1.112	1.159	1.272	1.328	13.050	-6.425	14.290	-1.959
I_OCE	3.609	19.502	0.456	0.550	0.768	0.842	0.892	1	1.133	1.209	1.333	1.697	1.966	3.244	18.190	3.973	20.815
I_RSAF	3.664	9.779	0.273	0.417	0.656	0.800	0.880	1	1.161	1.241	1.327	1.605	1.786	3.256	8.310	4.071	11.248
I_RSAS	5.475	-14.333	-0.237	-0.118	0.265	0.519	0.686	1	1.237	1.357	1.460	1.713	1.827	5.123	-15.601	5.827	-13.065
I_SEAS	18.910	-15.961	0.456	0.568	0.766	0.836	0.889	1	1.098	1.143	1.224	1.465	1.583	18.078	-18.957	19.742	-12.964
I_SSA	2.077	-14.217	2.315	2.139	1.682	1.509	1.310	1	0.816	0.710	0.615	0.496	0.463	1.762	-15.354	2.392	-13.081
I_USA	2.542	20.882	0.292	0.434	0.710	0.825	0.883	1	1.142	1.217	1.340	1.570	1.730	2.058	19.135	3.027	22.629
I_WEU	-0.387	10.525	-0.044	-0.035	0.061	0.158	0.198	1	2.445	2.742	3.471	4.893	5.469	-0.881	8.748	0.106	12.302
R_CAZ	2.767	28.731	0.466	0.548	0.737	0.827	0.884	1	1.115	1.199	1.306	1.571	1.726	2.329	27.155	3.204	30.307
R_CHA	9.975	5.050	0.693	0.721	0.750	0.790	0.852	1	1.162	1.229	1.378	1.590	1.759	9.379	2.903	10.571	7.197
R_EUR	-0.298	7.704	-0.371	-0.316	-0.185	-0.051	-0.006	1	3.356	3.766	4.648	6.751	7.506	-0.820	5.823	0.224	9.585
R_IND	5.944	-11.365	0.326	0.374	0.506	0.631	0.745	1	1.166	1.253	1.335	1.625	1.786	5.621	-12.528	6.267	-10.202
R_JON	-4.141	167.005	0.417	0.452	0.713	0.791	0.850	1	1.120	1.203	1.352	1.685	1.826	-5.404	162.458	-2.879	171.553
R_LAM	4.059	2.698	0.282	0.490	0.694	0.786	0.885	1	1.127	1.209	1.293	1.573	1.774	3.745	1.566	4.374	3.831
R_MEA	6.294	24.230	0.449	0.542	0.731	0.824	0.885	1	1.097	1.159	1.227	1.421	1.520	5.704	22.105	6.884	26.355
R_NEU	2.720	24.063	0.413	0.527	0.736	0.819	0.869	1	1.120	1.200	1.315	1.532	1.679	2.289	22.513	3.150	25.614
R_OAS	12.346	8.528	0.423	0.526	0.746	0.828	0.882	1	1.106	1.172	1.261	1.491	1.716	11.629	5.943	13.064	11.113
R_REF	1.544	3.268	0.343	0.391	0.561	0.661	0.845	1	1.185	1.274	1.384	1.722	1.873	1.406	2.770	1.682	3.765
R_SSA	2.697	-12.047	0.847	0.896	0.924	0.971	0.979	1	1.069	1.092	1.125	1.191	1.212	2.430	-13.007	2.963	-11.087
R_USA	2.542	20.882	0.292	0.434	0.710	0.825	0.883	1	1.142	1.217	1.340	1.570	1.730	2.058	19.135	3.027	22.629
W_canada	1.844	36.890	0.419	0.553	0.737	0.821	0.898	1	1.149	1.200	1.331	1.577	1.689	1.328	35.030	2.360	38.749
W_china	9.975	5.050	0.693	0.721	0.750	0.790	0.852	1	1.162	1.229	1.378	1.590	1.759	9.379	2.903	10.571	7.197
W_europe	-0.425	11.473	-0.036	-0.026	0.096	0.163	0.210	1	2.278	2.551	3.146	4.554	5.016	-0.932	9.648	0.081	13.297
W_india	5.944	-11.365	0.326	0.374	0.506	0.631	0.745	1	1.166	1.253	1.335	1.625	1.786	5.621	-12.528	6.267	-10.202
W_jpnkor	-2.063	135.546	0.450	0.482	0.749	0.822	0.882	1	1.128	1.217	1.356	1.675	1.837	-3.149	131.636	-0.978	139.456
W_laca	4.059	2.698	0.282	0.490	0.694	0.786	0.885	1	1.127	1.209	1.293	1.573	1.774	3.745	1.566	4.374	3.831
W_mena	6.294	24.230	0.449	0.542	0.731	0.824	0.885	1	1.097	1.159	1.227	1.421	1.520	5.704	22.105	6.884	26.355
W_oceania	3.609	19.502	0.456	0.550	0.768	0.842	0.892	1	1.133	1.209	1.333	1.697	1.966	3.244	18.190	3.973	20.815
W_sasia	5.475	-14.333	-0.237	-0.118	0.265	0.519	0.686	1	1.237	1.357	1.460	1.713	1.827	5.123	-15.601	5.827	-13.065
W_seasia	18.910	-15.961	0.456	0.568	0.766	0.836	0.889	1	1.098	1.143	1.224	1.465	1.583	18.078	-18.957	19.742	-12.964
W_southafrica	3.664	9.779	0.273	0.417	0.656	0.800	0.880	1	1.161	1.241	1.327	1.605	1.786	3.256	8.310	4.071	11.248
W_ssa	2.077	-14.217	2.315	2.139	1.682	1.509	1.310	1	0.816	0.710	0.615	0.496	0.463	1.762	-15.354	2.392	-13.081
W_te	1.544	3.268	0.343	0.391	0.561	0.661	0.845	1	1.185	1.274	1.384	1.722	1.873	1.406	2.770	1.682	3.765
W_usa	2.542	20.882	0.292	0.434	0.710	0.825	0.883	1	1.142	1.217	1.340	1.570	1.730	2.058	19.135	3.027	22.629

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Note: The first letter of the region name indicates the Model: I = FAIR/IMAGE, R=REMIND, W=WITCH. Coloured rows highlight the suggested parameters for each IAM

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

5.2. Annex 5.II: Call impacts SLR Adaptation

Table 7: Damage function parameters for IAMs: FAIR/IMAGE, REMIND and WITCH – All impacts (SLR with incremental adaptation) – Quadratic Regression

Region	b1	b2	b1.l	b2.l	b1.h	b2.h	b1 q0.025	b2 q0.025	b1 q0.05	b2 q0.05	b1 q0.16	b2 q0.16	b1 q0.25	b2 q0.25	b1 q0.33	b2 q0.33	b1 q0.5	b2 q0.5	b1 q0.67	b2 q0.67	b1 q0.75	b2 q0.75	b1 q0.84	b2 q0.84	b1 q0.95	b2 q0.95	b1 q0.975	b2 q0.975
I_CAN	0.797	0.620	0.639	0.530	0.956	0.709	0.232	0.182	0.286	0.202	0.469	0.278	0.552	0.362	0.607	0.413	0.797	0.620	0.913	0.723	1.013	0.831	1.284	1.128	1.449	1.281	1.536	1.352
I_CEU	0.382	0.634	0.266	0.575	0.499	0.693	0.062	0.086	0.105	0.169	0.199	0.338	0.258	0.445	0.296	0.506	0.382	0.634	0.592	0.800	0.643	0.889	0.734	1.006	0.976	1.411	1.067	1.533
I_CHN	1.687	-0.034	1.516	-0.123	1.857	0.056	-0.808	0.076	-0.372	0.054	0.749	0.001	1.079	-0.013	1.337	-0.022	1.687	-0.034	2.147	-0.046	2.390	-0.055	2.633	-0.054	3.102	-0.047	3.348	-0.047
I_EastAsia	1.412	0.653	1.226	0.549	1.598	0.757	0.465	0.221	0.615	0.289	0.947	0.426	1.104	0.492	1.211	0.553	1.412	0.653	1.641	0.781	1.778	0.845	2.034	0.992	2.368	1.168	2.441	1.211
I_FSU	0.880	0.263	0.740	0.174	1.019	0.351	0.088	0.019	0.147	0.034	0.356	0.100	0.525	0.152	0.615	0.180	0.880	0.263	1.131	0.342	1.318	0.401	1.487	0.452	1.850	0.563	1.953	0.594
I_INDIA	2.475	1.678	1.991	1.372	2.958	1.985	-0.316	-0.284	-0.112	-0.141	0.889	0.568	1.218	0.798	1.561	1.038	2.475	1.678	2.910	1.968	3.224	2.182	3.697	2.503	4.641	3.127	5.005	3.372
I_JAP	0.483	0.871	0.360	0.809	0.606	0.932	0.143	0.223	0.164	0.279	0.329	0.494	0.406	0.597	0.432	0.689	0.483	0.871	0.533	1.069	0.566	1.161	0.614	1.428	0.713	1.886	0.730	2.006
I_Laca	0.853	0.658	0.670	0.548	1.036	0.768	-1.766	-1.684	-1.425	-1.379	-0.011	-0.097	0.280	0.155	0.486	0.343	0.853	0.658	1.036	0.798	1.172	0.913	1.490	1.183	1.786	1.409	1.881	1.483
I_MiddleEast	1.368	0.127	1.191	0.026	1.545	0.228	-0.008	0.006	0.203	0.025	0.753	0.074	0.952	0.091	1.066	0.101	1.368	0.127	1.781	0.162	2.061	0.186	2.404	0.216	2.916	0.261	3.038	0.271
I_NAF	1.323	1.617	1.012	1.442	1.634	1.791	-0.035	-1.087	0.131	-0.725	0.841	0.501	0.943	0.721	1.043	0.973	1.323	1.617	1.518	2.051	1.760	2.509	2.004	3.112	2.376	3.839	2.522	4.008
I_OCE	0.618	0.948	0.467	0.861	0.768	1.035	-0.036	-0.380	0.058	-0.245	0.311	0.263	0.433	0.547	0.498	0.678	0.618	0.948	0.734	1.160	0.779	1.259	0.910	1.530	1.087	1.855	1.144	1.946
I_RSAF	0.570	1.505	0.423	1.420	0.717	1.590	0.230	0.741	0.311	0.823	0.396	1.030	0.452	1.186	0.497	1.289	0.570	1.505	0.652	1.716	0.683	1.806	0.754	1.964	0.925	2.509	1.027	2.753
I_RSAS	2.844	0.898	2.490	0.679	3.198	1.117	0.145	0.041	0.377	0.115	1.386	0.437	1.744	0.551	2.112	0.667	2.844	0.898	3.414	1.071	3.645	1.141	4.022	1.256	4.907	1.527	5.256	1.627
I_SEAS	3.317	1.064	2.887	0.821	3.747	1.306	-0.630	-0.433	0.046	-0.163	1.854	0.482	2.123	0.588	2.471	0.730	3.317	1.064	3.926	1.302	4.297	1.439	5.060	1.736	5.785	2.001	6.181	2.137
I_SSA	2.232	1.610	1.961	1.448	2.502	1.772	0.943	0.743	1.098	0.846	1.554	1.154	1.762	1.297	1.927	1.407	2.232	1.610	2.543	1.785	2.747	1.904	2.987	2.053	3.343	2.277	3.495	2.372
I_USA	0.643	0.468	0.546	0.413	0.739	0.523	0.211	0.170	0.280	0.216	0.453	0.323	0.503	0.357	0.539	0.384	0.643	0.468	0.753	0.555	0.808	0.603	0.899	0.686	1.062	0.809	1.105	0.846
I_WEU	0.249	0.431	0.157	0.389	0.341	0.474	0.048	0.085	0.075	0.135	0.141	0.256	0.173	0.315	0.189	0.344	0.249	0.431	0.474	0.571	0.505	0.626	0.576	0.716	0.806	1.079	0.861	1.175
R_CAZ	0.730	0.669	0.583	0.585	0.878	0.754	0.082	-0.017	0.190	0.084	0.464	0.347	0.525	0.419	0.579	0.484	0.730	0.669	0.903	0.883	0.992	0.990	1.155	1.203	1.357	1.430	1.436	1.501
R_CHA	1.687	-0.034	1.516	-0.123	1.857	0.056	-0.808	0.076	-0.372	0.054	0.749	0.001	1.079	-0.013	1.337	-0.022	1.687	-0.034	2.147	-0.046	2.390	-0.055	2.633	-0.054	3.102	-0.047	3.348	-0.047
R_EUR	0.253	0.470	0.158	0.426	0.348	0.513	0.032	0.088	0.061	0.144	0.130	0.278	0.164	0.344	0.185	0.384	0.253	0.470	0.470	0.614	0.513	0.682	0.574	0.770	0.806	1.161	0.856	1.253
R_IND	2.475	1.678	1.991	1.372	2.958	1.985	-0.316	-0.284	-0.112	-0.141	0.889	0.568	1.218	0.798	1.561	1.038	2.475	1.678	2.910	1.968	3.224	2.182	3.697	2.503	4.641	3.127	5.005	3.372
R_JON	0.483	0.871	0.360	0.809	0.606	0.932	0.143	0.223	0.164	0.279	0.329	0.494	0.406	0.597	0.432	0.689	0.483	0.871	0.533	1.069	0.566	1.161	0.614	1.428	0.713	1.886	0.730	2.006
R_LAM	0.853	0.658	0.670	0.548	1.036	0.768	-1.766	-1.684	-1.425	-1.379	-0.011	-0.097	0.280	0.155	0.486	0.343	0.853	0.658	1.036	0.798	1.172	0.913	1.490	1.183	1.786	1.409	1.881	1.483
R_MEA	1.250	0.484	1.057	0.376	1.442	0.593	-0.095	-0.141	0.106	-0.046	0.710	0.212	0.868	0.294	1.010	0.370	1.250	0.484	1.570	0.651	1.834	0.773	2.147	0.933	2.587	1.149	2.747	1.216
R_NEU	0.491	0.095	0.415	0.059	0.566	0.132	-0.092	-0.040	0.013	-0.015	0.219	0.030	0.312	0.050	0.371	0.066	0.491	0.095	0.675	0.146	0.915	0.212	1.107	0.266	1.441	0.356	1.600	0.401
R_OAS	2.142	1.243	1.811	1.052	2.474	1.434	-0.025	-0.235	0.350	0.032	1.305	0.618	1.499	0.765	1.685	0.907	2.142	1.243	2.526	1.527	2.741	1.664	3.124	1.954	3.633	2.316	3.819	2.431
R_REF	0.880	0.263	0.740	0.174	1.019	0.351	0.088	0.019	0.147	0.034	0.356	0.100	0.525	0.152	0.615	0.180	0.880	0.263	1.131	0.342	1.318	0.401	1.487	0.452	1.850	0.563	1.953	0.594
R_SSA	1.622	1.824	1.375	1.679	1.870	1.970	0.676	0.859	0.786	0.970	1.119	1.325	1.266	1.475	1.391	1.603	1.622	1.824	1.867	2.030	2.001	2.156	2.194	2.344	2.496	2.626	2.614	2.742
R_USA	0.643	0.468	0.546	0.413	0.739	0.523	0.211	0.170	0.280	0.216	0.453	0.323	0.503	0.357	0.539	0.384	0.643	0.468	0.753	0.555	0.808	0.603	0.899	0.686	1.062	0.809	1.105	0.846
W_canada	0.797	0.620	0.639	0.530	0.956	0.709	0.232	0.182	0.286	0.202	0.469	0.278	0.552	0.362	0.607	0.413	0.797	0.620	0.913	0.723	1.013	0.831	1.284	1.128	1.449	1.281	1.536	1.352
W_china	1.687	-0.034	1.516	-0.123	1.857	0.056	-0.808	0.076	-0.372	0.054	0.749	0.001	1.079	-0.013	1.337	-0.022	1.687	-0.034	2.147	-0.046	2.390	-0.055	2.633	-0.054	3.102	-0.047	3.348	-0.047
W_europe	0.272	0.438	0.178	0.394	0.366	0.482	0.054	0.086	0.084	0.137	0.155	0.258	0.191	0.320	0.212	0.355	0.272	0.438	0.501	0.580	0.541	0.635	0.605	0.719	0.856	1.090	0.912	1.181
W_india	2.475	1.678	1.991	1.372	2.958	1.985	-0.316	-0.284	-0.112	-0.141	0.889	0.568	1.218	0.798	1.561	1.038	2.475	1.678	2.910	1.968	3.224	2.182	3.697	2.503	4.641	3.127	5.005	3.372
W_jpnkor	0.769	0.794	0.628	0.720	0.910	0.868	0.240	0.255	0.282	0.294	0.513	0.490	0.626	0.615	0.675	0.674	0.769	0.794	0.886	0.990	0.952	1.064	1.081	1.292	1.294	1.626	1.338	1.706
W_laca	0.853	0.658	0.670	0.548	1.036	0.768	-1.766	-1.684	-1.425	-1.379	-0.011	-0.097	0.280	0.155	0.486	0.343	0.853	0.658	1.036	0.798	1.172	0.913	1.490	1.183	1.786	1.409	1.881	1.483
W_mena	1.250	0.484	1.057	0.376	1.442	0.593	-0.095	-0.141	0.106	-0.046	0.710	0.212	0.868	0.294	1.010	0.370	1.250	0.484	1.570	0.651	1.834	0.773	2.147	0.933	2.587	1.149	2.747	1.216
W_oceania	0.618	0.948	0.467	0.861	0.768	1.035	-0.036	-0.380	0.058	-0.245	0.311	0.263	0.433	0.547	0.498	0.678	0.618	0.948	0.734	1.160	0.779	1.259	0.910	1.530	1.087	1.855	1.144	1.946
W_sasia	2.844	0.898	2.490	0.679	3.198	1.117	0.145	0.041	0.377	0.115	1.386	0.437	1.744	0.551	2.112	0.667	2.844	0.898	3.414	1.071	3.645	1.141	4.022	1.256	4.907	1.527	5.256	1.627
W_seasia	3.317	1.064	2.887	0.821	3.747	1.306	-0.630	-0.433	0.046	-0.163	1.854	0.482	2.123	0.588	2.471	0.730	3.317	1.064	3.926	1.302	4.297	1.439	5.060	1.736	5.785	2.001	6.181	2.137
W_southafrica	0.570	1.505	0.423	1.420	0.717	1.590	0.230	0.741	0.311	0.823	0.396	1.030	0.452	1.186	0.497	1.289	0.570	1.505	0.652	1.716	0.683	1.806	0.754	1.964	0.925	2.509	1.027	2.753
W_ssa	2.232	1.610	1.961	1.448	2.502	1.772	0.943	0.743	1.098	0.846	1.554	1.154	1.762	1.297	1.927	1.407	2.232	1.610	2.543	1.785	2.747	1.904	2.987	2.053	3.343	2.277	3.495	2.372
W_te	0.880	0.263	0.740	0.174	1.019	0.351	0.088	0.019	0.147	0.034	0.356	0.100	0.525	0.152	0.615	0.180	0.880	0.263	1.131	0.342	1.318	0.401	1.487	0.452	1.850	0.563	1.953	0.594
W_usa	0.643	0.468	0.546	0.413	0.739	0.523	0.211	0.170	0.280	0.216	0.453	0.323	0.503	0.357	0.539	0.384	0.643	0.468	0.753	0.555	0.808	0.603	0.899	0.686	1.062	0.809	1.105	0.846
World	0.673	0.890	0.530	0.806	0.816	0.974	0.055	-0.092	0.175	0.069	0.403	0.451	0.475	0.563	0.535	0.661	0.673	0.890	0.797	1.092	0.859	1.193	0.982	1.386	1.179	1.684	1.268	1.792

*This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No **776479.***

Note: The first letter of the region name indicates the Model: I = FAIR/IMAGE, R=REMIND, W=WITCH.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement No ***776479.***