ACCREU

Assessing Climate Change Risk in Europe

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Changes with respect to the DoA

(with justification if applicable)

The key focus of Task 3.4 is to provide the data and functions for the macroeconomic computable general equilibrium (CGE) and integrated assessment models (IAM) in WP4. This is based on analysis of WP2 sector impact assessment results, as well as insights from the literature. The deliverable has met the anticipated DoA. It has also produced European specific costs and benefits for policy dissemination in WP5 policy brief, and global adaptation costs for a case study linked to the Adaptation Gap report and for the UNFCCC negotiations. There were some issues with the task due the data from WP2, which was delayed and revised (the results from all of the models were updated several times following Task 3.4 review). This allowed more specific and usable data, but meant that the processing and functional analysis of WP2 data had to be repeated three times. This took additional resources that had not been anticipated, limiting some of the additional review and analysis that could have been undertaken for the inventory. The Task has provided valuable new insights on aggregate functions. It was found that the objectives for adaptation (the decision paradigm) have a strong impact on the costs and benefits, and this makes it difficult to provide consistent composite, functions. The task went beyond the DoA in producing dissemination material for WP5 with European results for the policy brief, as well as global results to feed into global assessment reports.

1. **Dissemination and uptake**

(who will/could use this deliverable, within the project or outside the project)

The key user of this deliverable are the teams in WP4. However, this information is also relevant for other teams outside the project looking to develop adaptation functions for CGE and IAM, especially the ACCREU sister projects (CROSSEU and SPARCCLE). Results from the D3.4 have been used in the policy brief for WP5 and has led to dissemination of European results on costs of inaction and costs and benefits of adaptation from the project. The global adaptation costs have also been disseminated and used to inform three major global assessment reports (with a very large number of downloads and media citations) on the costs of adaptation, as well as providing inputs to the UNFCCC negotiations.

2. **Short Summary of results (<250 words)**

Task 3.4 has processed the results data from the sector models in WP2, updating them to a common price year and comparable units, with resolution at the level of every individual country of the world. This includes the data on economic costs, as well as adaptation costs and benefits. This data set was uploaded for the direct use by the CGE models in WP4. The task has also used this WP2 data to derive functional relationships (global) for economic costs of climate change, against temperature, as well as functions of the costs and benefits of adaptation. The task also reviewed the academic and grey literature to complement this information and investigate possible evidence for the functional forms, including on limits of adaptation. The data has been further analysed and summarised to provide the information for the WP5 policy brief on European results, and also a case study on the global adaptation costs for developing countries.

3. **Evidence of accomplishment**

(report, manuscript, web-link, other)

The analysis has fed into the WP4 activities, which by running the data will provide evidence of accomplishment. The data from the task have been fed into the policy brief for WP5 on European results, which was published at the start of the next reporting period. A further accomplishment is the task produced costs of adaptation for developing countries that have fed into two global assessment report (the adaptation gap report 2024 and the adaptation gap report 2025 and Independent High Level Expert Group on Climate Finance report). The ACCREU project is directly accredited in both reports. The ACCREU results have, in turn, informed the global UNFCCC negations, with the study results on global adaptation costs cited in the Baku to Belem Roadmap to 1.3 Tr . Work is underway to develop an academic paper on the results.

Summary

The aim of deliverable 3.4 is to gather data on adaptation costs and effectiveness that will inform the macroeconomic computable general equilibrium (CGE) and integrated assessment models (IAM) in WP4. The Task has processed the results data from the sector models in WP2, updating them to a common price year and units. This data set has been uploaded for the direct use by the CGE models in WP4.

The Task then used this WP2 data to derive functional relationships (global) for impacts, as well as the costs and benefits of adaptation. The task also reviewed the literature to complement this information and investigate possible evidence for the functional forms, including on limits of adaptation. This task proved more difficult than first anticipated, because of the different forms of adaptation in the WP2 sector models, and because of the variation in adaptation decision approach and objectives. This means it is not easy to provide simple functional forms that assess avoided damage as a function of cost. Nonetheless, functions for sea level rise are provided (which are used directly by a number of WP4 IAMs), as well as functions for other key WP2 results (river flooding, agriculture and labour productivity) which can be used to derive an indicative composite function.

The data from D3.4 has fed into dissemination activities. The data from 3.4 has been used for the policy brief for WP5 on European results, which as published at the start of the next reporting period. The adaptation cost data has also been used to provide inputs to major international assessment studies on adaptation finance needs (the UNEP adaptation finance gap report and the IHLEG report). These have achieved very high levels of dissemination outreach, as identified through download statistics and citations of the reports. The ACCREU estimates were cited in the UNFCCC Baku to Belem Roadmap to 1.3 Tr.

1. Introduction

1.1 Work Package Description

Work package 3.4 aims to gather information on the costs, effectiveness, and benefits of adaptation by combining model-based estimates from WP2 with insights from a literature review. This information is compiled in an inventory. The objectives, work package description and deliverable, as set out in the grant agreement, are shown below.

Work Package Objectives (grant agreement)

3) To gather data on adaptation costs and effectiveness that will inform the CGE and IAM models that will be used in the distributional, fiscal, and financial analyses of WP4

Work package description

Task 3.4, Assessing adaptation costs and effectiveness for the integrated analysis with CGE/IA models [M4-26] (Lead: PWA, Participants: Fondazione CMCC, IIASA, UNIGRAZ, Stichting VU, Ecologic, PIK, UU, GCFsee D3.4 and Milestone 3.3) is functional to conduct the integrated analysis of mitigation adaptation and residual damages with the macroeconomic and IAM models in WP4, Task 4.4, that will complement the adaptation assessment conducted at the case study level in Task 3.2. It will deliver a comprehensive database on the costs, effectiveness, and benefits of adaptation strategies across all sectors for all world's countries by combining model-based estimates from WP2 with insights from a systematic literature review. The analysis will rely upon both academic and grey literature including information from Nationally Determined Contributions and reports such the "adaptation finance gap report". It will gather evidence by sector/risk, and consider how costs and effectiveness vary across scenarios, highlighting possible limits to adaptation.

Work package deliverable

Deliverable D3.4 – Economics of adaptation inventory

Deliverable Number	D3.4	**Lead Beneficiary**	14. PWA
Deliverable Name	Economics of adaptation inventory		
Type	R — Document, report	**Dissemination Level**	PU - Public
Due Date (month)	26	**Work Package No**	WP3

1.2 Deliverable Outline and Information Sources

This deliverable sets out the analysis undertaken on the WP2 data, including post-processing steps, and then provides discussion on the functional relationships for WP4. The deliverable also includes a review of other potential sources of adaptation costs and benefits.

2. Framing Adaptation

2.1 Introduction and Challenges

In simple terms (Stern, 2006: UNEP 2015), the costs and benefits of adaptation can be assessed by estimating the future economic impacts of climate change (the costs of inaction), then assessing the reduction in these impacts (the benefit of adaptation) and the associated cost (the cost of adaptation).

However, adaptation is rarely completely effective (e.g. see Rexter and Matthews, 2021) and this means there is a trade-off around how much adaptation to undertake, and the residual damage costs after adaptation (see figure 1 below). The modest effectiveness also means it will be more costly (and less cost-effective) to reduce climate impacts down towards zero. Progressively increasing the quantity of adaptation implemented will lead to greater reductions in climate impacts, and thus greater adaptation benefits, as well as lower residual damage, but it will also lead to higher costs, potentially disproportionately so. In theory, it could be possible to address this by identifying the optimal economic level of adaptation, which balances marginal costs and benefits, as well as residual damage.

In practice, however, current disaster risk reduction objectives are often not set on the basis of the economic optimal level, because of this issue of residual risk. In several sectors (notably coastal and river floods), targets are often set on levels of acceptable risk, e.g., to protect against a 1 in 100 year event (or larger) because of the unacceptable risks of loss of life.[1] This reflects a broader recognition that the discourse around the economics of adaptation has evolved from a focus on cost-benefit analysis and identification of best or optimal adaptations to the development of multi-metric evaluations including the risk and uncertainty dimensions in order to provide support to decision makers (see IPCC 3rd Assessment Chapter on the Economics of Adaptation, Chambwera et al., 2014).

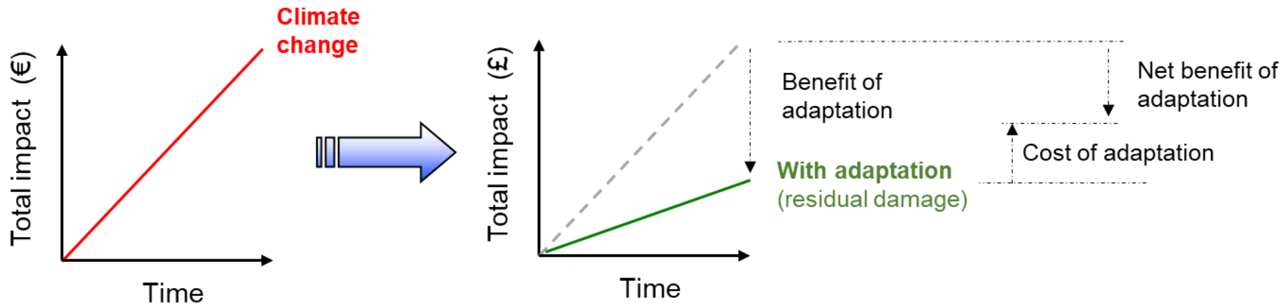

***Figure 1** Schematic of the Costs of Climate Change, and the Costs and Benefits of Adaptation.*

In practice, deriving adaptation costs and benefits – as in the schematic above – is extremely challenging. A list of the reasons for this is set out in Box 1, based on the review by UNEP (2023).

[1] As an example, while many countries use a 1 in 100-year level of acceptable risk for flood protection, the UK uses economic efficiency for its flood protection investment and invests when the benefit to cost ratio exceeds 1 (LTIS, 2019), except for the Thames barrier, which was designed to a 1 in 1000 year event. However, countries with higher risk profiles often include higher risk protection levels. Due to the low lying areas of the Netherlands, with areas below sea level protected by large dikes, and given historical impacts (notably the 1953 storm), protection levels were set at a 1:1,250 up to 1:10,000.year event (though the government has since moved to a more detailed approach, initially with dynamic optimisation, and now with a life protection level, e.g., see link).

Box 1. The challenges on estimating adaptation costs and benefits

There are several challenges in appraising, modelling, designing, and implementing adaptation (UNEP, 2023).

- **Adaptation costs and benefits vary.** Adaptation is a response to site and context specific climate risks, reflecting local hazard, vulnerability, and exposure. This leads to large ranges in costs and benefits, even for the same action, in different locations and contexts.
- **Adaptation is not a one-off decision.** It is an ongoing response to dynamically changing risks over time. Adaptation can be a reactive response to changes that are already being experienced (e.g., observed trends of temperature), or a pro-active, anticipatory action to prepare for future climate change (e.g. future sea level rise, Burton, 2009). Ideally, a combination of reactive and proactive adaptation is needed but these actions have different profiles of costs and benefits, and these change dynamically over time. Reactive adaptation generates benefits immediately, which can be compared to costs, in a standard discounted present value analysis. Future risks can be addressed with proactive adaptation, but this generates benefits that are primarily in the future, which may be difficult to justify when compared to upfront costs (in present value terms) (OECD, 2015).
- **Future climate change involves deep uncertainty.** The analysis of future climate risks is complicated by deep uncertainty, where often the sign of the change is unknown (Wilby and Desai, 2010: Hallegatte et al., 2012), and which cannot be assessed with probabilities. This uncertainty arises from different future warming levels (i.e., whether the Paris Goals will be met), from the range of projections from different climate models (e.g. hotter, drier or wetter projections) and from the uncertainty around specific impacts from changes in multiple variables (e.g., impact on crop yields) as captured by models. This uncertainty is not a reason for inaction, but it does make the planning and economics of adaptation more challenging. To address this, adaptation can be designed with an adaptive management or adaptation pathway framework (IPCC, 2022) - an iterative approach that seeks to encourage robust options and to minimize regrets, with learning and feedback to change actions over time.
- **Adaptation is not just a set of technical options implemented in a linear sequence, it requires a focus on process and portfolios of actions.** Climate change will lead to both gradual shifts (slow onset change) and changes in the intensity and frequency of extreme events. To address these risks requires capacity building, institutional strengthening and awareness raising (soft options) as well as technical, structural, or engineered actions (hard options) (IPCC, 2022), and for this reason adaptation is often seen as a (continual) process, which requires combinations (portfolios) of actions rather than single technical solutions. While it is more difficult to quantify the economic benefits of soft measures, they often lead to higher efficiency and effectiveness of adaptation delivery.
- **It is difficult to set quantitative targets and there are no common metrics for adaptation.** This reflects the fact it is challenging to set and measure adaptation objectives. There is no single agreed quantitative goal for adaptation and no common metrics (as for mitigation). Indeed, the Global Goal on Adaptation identifies 100 separate adaptation indicators (UNFCCC, 2025). Further, in line with Figure 1, costs of adaptation vary with the objective set, and whether this is based on economic efficiency, acceptable risk levels, or reducing impacts to current levels, noting that different actors have very different views on these approaches. It is also stressed that different countries and sectors set current objectives using all of these approaches, inconsistently across and between economies, in the current policy space.
- **Adaptation coverage and boundaries vary**. Adaptation costs vary with the coverage of sectors and the risks as well as the boundaries e.g. whether to include costs to address existing natural climate variability and extremes, and whether general development is included (e.g. activities to increase household incomes).

At a more detailed level, there are a large number of methodological issues and assumptions that also determine adaptation costs and benefits. These issues also make it difficult to produce a database of adaptation costs and benefits, hence the focus in previous projects has been on useful information, such as an inventory (see ECONADAPT, 2015).

The challenges in adaptation also mean that there are different ways to assess adaptation analytically, and this is often reported as two distinct literatures based on a 'science-first' and 'policy-first' approach (Ranger et al., 2010), shown in Figure 2.

The 'science-first approach' is a scenario and model centered approach which draws on the impact assessment literature. This starts with the global emission scenarios and climate model projections, and then undertakes a step-by-step analysis, where the output of one step is used as the input for the next. The climate model outputs are used to run impact assessments to assess physical impacts, for example using crop models to assess agriculture yield loss or hydrological models for flood damages. The outputs of these models can then be quantified in monetary terms and put into a macro-economic model. This approach is typically used for medium and long- term assessment of the costs of climate change (2050s and 2080s). This framework can be extended to model adaptation (see Figure 2). In this case, the impact analysis can assess the costs of adaptation (e.g., agricultural irrigation or flood dyke costs) and assess the benefits these have in reducing future climate change, as well as residual impacts after adaptation. These approaches provide key headline information, and are extremely beneficial in providing the context for adaptation, but they have a number of disadvantages. They assess each scenario individually using an if-then approach (e.g., optimized dyke projections for a RCP4.5 median sea-level rise scenario for 2050) which assumes perfect foresight, and thus largely exclude uncertainty considerations. They are also focused on future impacts and adaptation decisions, e.g. in 2050, rather than providing information to inform real-world policy decisions today. They also focus on hard, technical options, which can be integrated within the modelling framework.

However, while this science-first approach provides useful outputs, it does not support near-term decision making under uncertainty. In response to this, an alternative approach has emerged, termed, the 'policy-first approach'. This frames the analysis from the policy question and decisions around adaptation, and priorities current or near-term adaptation decisions. It is a much greater focus on decision making under uncertainty including the use of extended cost-benefit analysis and techniques such as real options analysis, robust decision making, portfolio analysis and others (see Watkiss et al., 2016). However, while this provides more real-world applicability, this approach also has disadvantages. It is costly and time-consuming to undertake, and requires considerable data and expertise.

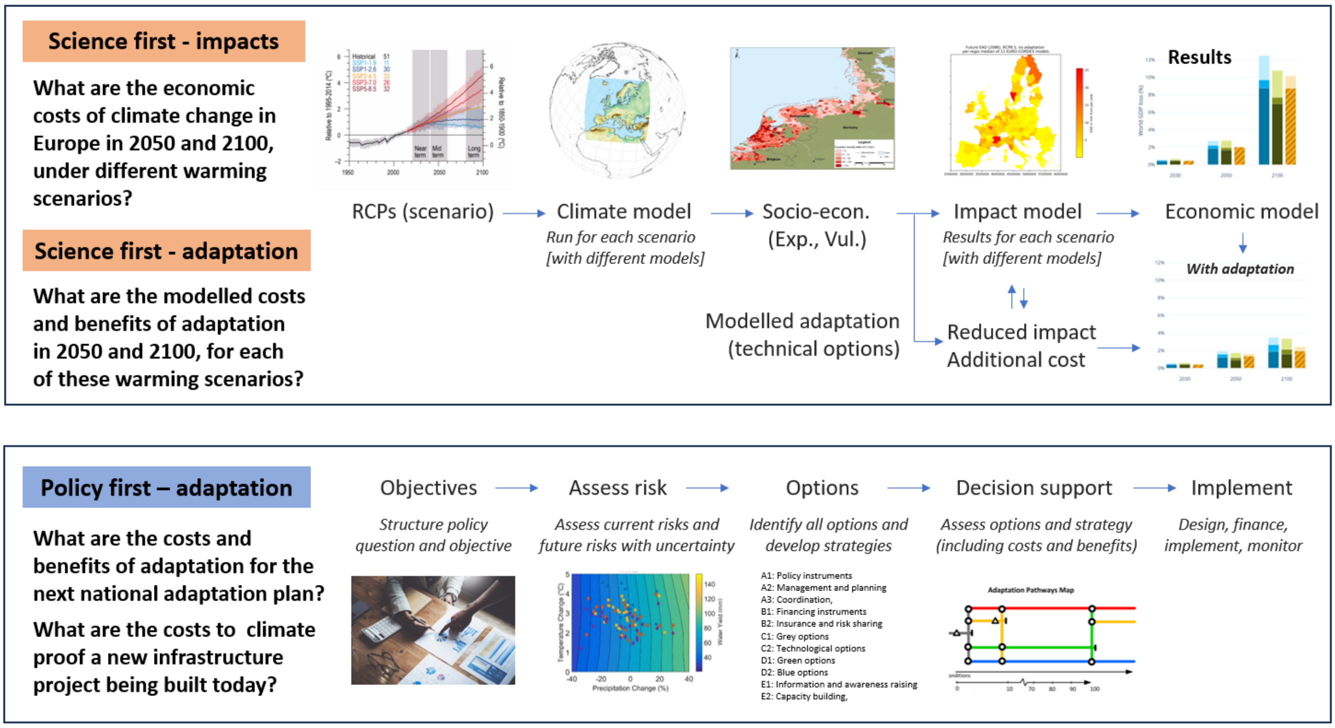

Figure 2 The Science-First and Policy First Approaches for Adaptation Analysis.

The type of adaptation framing used in any study depends on the objectives and context of the work, noting that it is also possible to blend the approaches above.

For the analysis of adaptation in WP4, and thus D3.4, the focus is on a modelling framework from WP2, which is a science-first approach. This is the focus of the main analytical work in this task. However, a review of literature, which includes policy first studies is included, especially as this provides additional information on the effectiveness of adaptation as well as potential limits of adaptation. We note that for the analysis of adaptation in WP3, which is more focused on national to sub-national adaptation decisions, the policy-first approach is most relevant.

2.2 Providing functions for the IAMs and CGEs in ACCREU

Linking back to Figure 1, most of the earlier literature on the global economic costs of climate change was produced using a small number of integrated assessment models (IAMs). There are now other modelling approaches used in addition to these IAMs, including structural models (such as computable general equilibrium modelling (CGE)) and econometric (statistical) studies (O'Neill *et al.* 2022). While this has led to a greater number of studies, it has also significantly increased the range of published estimates, such that the wide range of estimates and lack of comparability prevent identification of a robust range of estimates with confidence (O'Neill *et al.* 2022).

However, there has been much less progress in modelling global adaptation costs in these frameworks. Adaptation remains poorly represented in current global modelling frameworks and models (van Maanen *et al.* 2023) and the synthesis in AR6 (New *et al.* 2022) found a limited number of studies (limited to Chapagain *et al.* 2022: UNEP, 2023: Markandya and González-Eguino 2019. While there are also more CGE studies that look at adaptation (for a recent review, see Wei and Aaheim 2023), most of these are focused on autonomous adaptation at the global level, with most planned adaptation studies at the sectoral or regional level.

Following discussion with the WP4 teams, it was agreed there were **two functional forms** that would be of interest for the IAMs.

The first would be to produce an improved set of functions from WP2 data that are specific to each impact category, and can be used to assess adaptation in the ACCREU WP4 modelling suite, including for the CGEs and the IAMs. These can be described as damage functions which have baseline economic costs (without adaptation) and with adaptation. An example is shown below from the COACCH project (Van der Wijst et al, 2021). This developed a function for modelling the economic costs for climate change based on the COACCH modelling analysis, but included adaptation for coastal based on the DIVA coastal model.

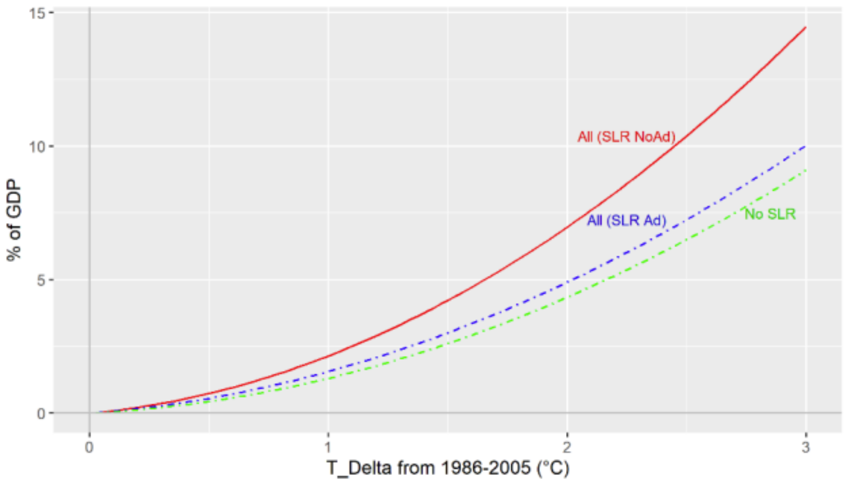

Figure 3. Aggregated global Climate Change Damage Functions (CCDFs): Including SLR without adaptation (red line), SLR with adaptation (blue dashed line) and all climate change impacts, but SLR (green dashed line). Source Van der Wijst et al, 2021.

The second function is to allow IAMs to trade off impacts, mitigation, and adaptation in a cost-benefit framework. This requires a function that links the adaptation benefit to adaptation cost (avoided damage versus adaptation costs), noting this can be expressed either in $, % of GDP or % avoided damage. This is similar to the concepts developed for the DICE model (AD-DICE) (de Bruin et al., 2009: de Bruin and Ayuba 2020). The functional form for adaptation in these studies is highly stylistic, but broadly reflects the view that adaptation effectiveness will reduce with growing impacts. As an example, de Bruin et al., (2009) use a function (AD-DICE) where the adaptation costs of the first 15% of gross damage reduction are extremely low, after which they rise. They assume an optimal level of adaptation varies from 0.13 to 0.34, with an average of 0.27, i.e., 27 percent of gross damages are reduced due to adaptation. This is shown below in Figure 4. This function is applied to different regions, which give very different results because of the interplay of positive and negative impacts. Task 3.4 aims to improve this functional form by using the WP2 sectoral models to provide more detailed information on the curves for each sectoral impact. Note in the figures below, we present adaptation costs on the x axis, hence the shape of curves are different.

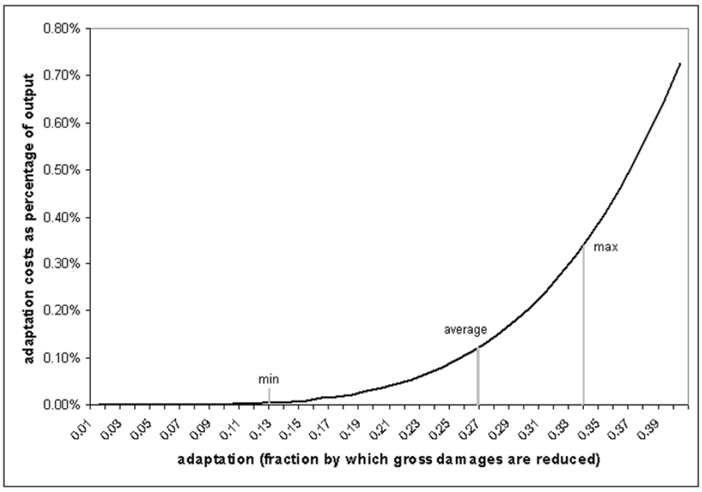

Figure 4 The adaptation cost curve implicit in the DICE2007 model (range 0.15-0.4). Source De Bruin et al., 2009.

The starting point for Task 3.4 analysis are the outputs from WP2. The ACCREU WP2 task has a set sector impact models, which can provide potential functions forms, set out in Figure 5. The framework is shown below. In theory, if a model includes adaptation, it should be possible to produce a function.

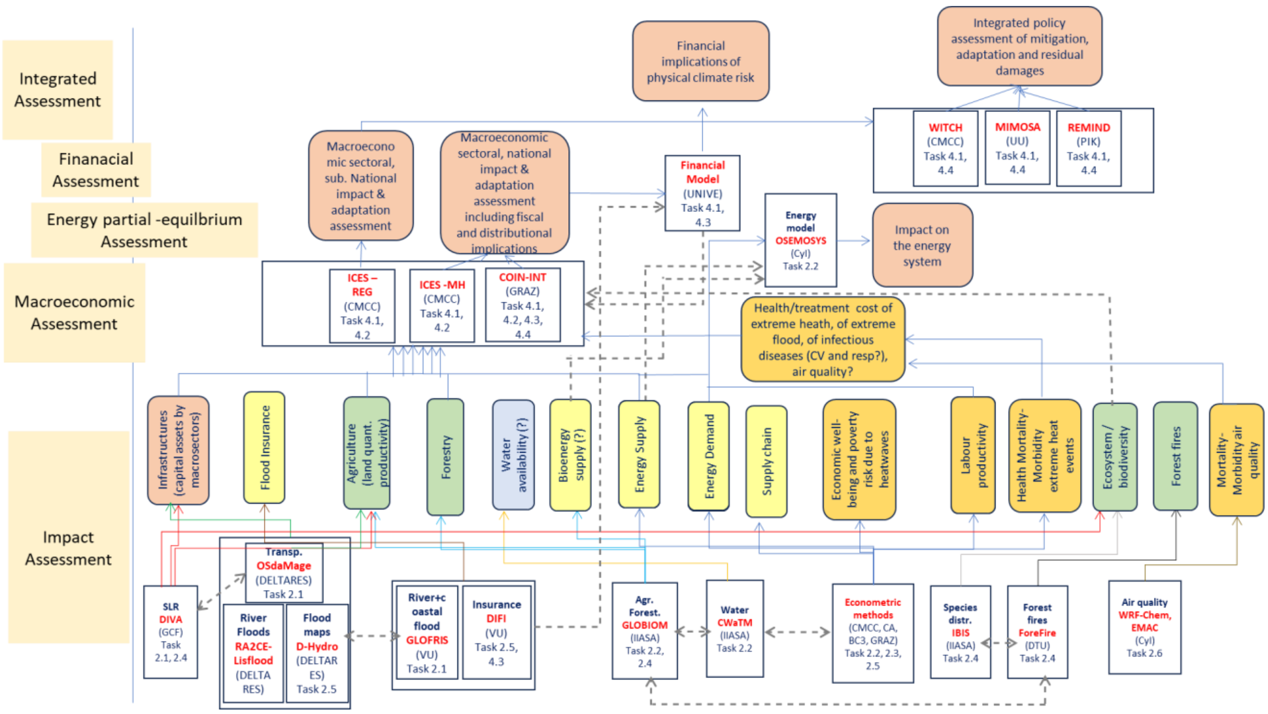

Figure 3. ACCREU modelling framework. Source ACCREU

To look at the potential for adaptation functions, a stocktake of the WP2 outputs was made, based on Deliverables 2.1, 2.2 and 2.3, see table below, Table 1. Additional data sets for wildfires and ecosystems services are available in Deliverable 2.4 were considered, but do not provide adaptation costs and benefits, and therefore were not included. The data from WP2 is provided for the ACCRUE core scenarios, RCP2.6, RCP4.5, RCP7.0, for one SSP only, SSP2. In line with the ACCREU protocol, each team defined a low, medium and high adaptation (see right hand column). However, all of the models have very different structures and teams made different assumptions on adaptation levels.

For example, it emerged that some teams in WP2 had set adaptation levels based on different objectives (see earlier discussion from Figure 1 on the decision paradigm). Adaptation can be set using different goals or objectives, e.g., it may be set based on economic efficiency or acceptable levels of risk. This led to some subsequent issues where sector teams had used low, medium and high adaptation levels, which in fact involved different objective approaches, e.g., they compared acceptable risk standards as medium and optimal as high, while other teams chose one decision characteristic and looked at low medium and high adaptation levels within one decision paradigm. This is a valuable message for future research on looking at different objectives, and different levels for each of these.

Table 1. Analysis of data sets from WP 2.

Sector	Model	RCPs and SSPs	Time periods	CMIP	SSP data	Output	Adaptation
Coastal	DIVA	RCP2.5, 4.5, 7.0	10 yr increments	CMIP6 (AR6) SLR	SSP2 data 2024	EAD (PPP) Annual Adaptation $	Low medium and high
Coastal	GLOFRIS coastal	RCP2.5, 4.5 8.5	2010, 2030, 2050, 2080	CMIP5	SSP2 2018	EAD (PPP) Adapt costs $	Low medium and high
River floods	GLOFRIS river	RCP2.5, 4.5 8.5	2010, 2030, 2050, 2080	CMIP5	SSP2 2018	EAD (PPP) Adapt costs $	Low medium and high
Labour	CMCC Labour	RCP2.6, 4.5, 7.0	2030, 2050, 2070	CMIP6	SSP2 2024	Hours worked and productivity (effective labour units), earnings	L, M, H AC (indoor) Autonomous (outdoor)
Energy	CMCC Energy	RCP2.6, 4.5, 6.0	2030, 2050 and 2100	CMIP6	SSP2 2024	Final energy demand / $ (AC) ownership	Low, ref, high adaptation
Agriculture	EPIC	RCP 2.6, 4.5, and 7.0.	10 year increments	CMIP6	SSP2 2024	Yields	
	GLOBIOM	2.5, 4.5 7.0 8.5	10 year increments	CMIP6	SSP2 2024	Yield, Prices, Consumer expenditure Investment Irrigation	Low central high adaptation EU only
Health (EU only)	BC3 heat	2.6, 4.5, 7.0,	2030, 2050, 2080	CMIP6 (world bank portal)	SSP2	Mortality and $ VSL/VOLY Morbidity and treatment/labour productivity cost	EU only

Finally, it is noted that every individual CGE and IAM has a different structure, and therefore a different set of functions are needed for each model. This includes different spatial aggregation levels (e.g., overall world, aggregate IAM regional areas, and for Europe, individual countries), as well as different sectoral composition. For example, several IAMs include sea level rise separately, so this has to be split out from the wider damage function. The decision was therefore made to work at a high level of disaggregation in data analysis, at individual country level for all countries of the world, to allow WP4 teams to use data at the appropriate level, but with the main results here presented for the global analysis only.

2.2 Literature review

Complementing the WP2 results, a literature review was undertaken. To do this, a search protocol was produced, as set out in Annex 1 of this deliverable, based on review protocol methods following Page et al., 2021.

A wide literature on adaptation exists – the most comprehensive of which is that undertaken by Berrang-Ford et al. (2021) and more broadly in the Global Adaptation Mapping Initiative (GAMI[2]). The systematic review by Berrang-Ford and her co-authors (2021) assessed 1,682 articles.

However, the literature on adaptation costs, and especially the economic costs and benefits, is much more limited, and indeed, Berrang-Ford identify one of their eight suggested priorities for adaptation research is the need to assess effectiveness of adaptation responses.

There are a number of framing papers on the economics of adaptation in the literature (e.g., Chambwera et al., 2014; Fankhauser, 2017; UNEP, 2023: Josephson et al., 2024; Carleton et al, 2024). There are also a small number of papers that provide informal meta-analyses of economic dimensions of adaptation. These include reviews of adaptation cost-benefit ratios based on literature review (Watkiss, 2015: Mechler, 2016, ECONADAPT, 2017: GCA, 2018; Markanday, et al., 2019; GCA, 2021; Watkiss et al., 2021) and narrative review (Josephson et al., 2024).

Complementing these, there is a recent systematic review of the effectiveness of adaptation (Rexter and Sharma, 2024), which captures 324 studies, and provides analysis based on standardized quantitative estimates from 80 of the reviewed papers, with a meta-regression analysis of the effectiveness of adaptation. There is also a further study of 320 adaptation and resilience investments (Brandon et al., 2025) of economic appraisals, primarily from multilateral development banks and international climate funds with benefit-cost ratios, economic internal rates of return, and net present values for each investment.

It is stressed that the studies in these reviews include a mix of science first and policy first methods (see Figure 2) and that this means they are often not directly comparable. Further, a large proportion of the estimates reported are based on ex ante appraisal values, not ex post data. Indeed, a recent ex post/evaluation umbrella review in low- and middle-income countries - a review of systematic reviews (Greene et al., 2025) - identified only around nine systematic review studies that included cost or economic information (from an identified initial list of 3,348 documents).

There are also grey literature studies that cite BCRs or return, including for the private sector (Swiss Re Institute, 2023: WEF, 2024: US Chamber of Commerce, 2024; JP Morgan, 2025; SystemIQ, 2025), citing very returns, though these are considered less robust.

In order to properly assess potential costs and benefits, there is therefore a need to dive down to sectoral literature. This includes the analysis of actions that are not explicitly labelled as adaptation, but which are routinely included in lists of adaptation (e.g., weather and climate services, soil and water agricultural management, flood protection). This literature is reported by hazard/sector in the following chapter.

There are also some reviews of adaptation costs in developing countries (Chapagain et al., 2020), especially drawing on costs submitted in national adaptation plans and nationally determined contributions, and a systematic review of adaptation cots (Boero, 2024), as well as again, detailed sectoral/hazard adaptation costs for activities that include actions that are commonly considered as adaptation (for an example, see Aerts, 2018).

[2] https://globaladaptation.github.io/index.html

3. WP2 Sector Results and Functions

This section presents the results of the analysis and functions from the WP2 models for WP4.

3.1 Adjustment and alignment of values

Each WP2 model (see ACCREU Deliverable 2.1, 2.2, 2.3) has a slightly different set up.

Most of the models assess and report values in United States dollars (referred to here as US$). However, these values are often not directly comparable. For example, some models provide adaptation costs in US$2005, some in US$2012, etc. while some report purchasing power parity (PPP) values. There are conventions on how to produce comparable values[3] and adjust for different currencies or values in different countries.[4] However, the exact approach used varies with the objective of the study. For the WP4 CGE models, the analysis is centred on the year $2017 MER values, because this aligns to the GTAP data. The data from D3.4 feeds into the European policy brief, and this is most relevant if results are presented in Euro 2023. An additional output of D3.4 is to produce updated global adaptation costs to feed into the UNEP Adaptation Gap Report 2025 analysis. This requires analysis in US$2023 in order to allow direct comparison with international public adaptation finance flows collated by the OECD Network on Environment and Development Co-operation of the Development Assistance Committee (DAC)[5].

When moving the original WP2 model outputs to these three inventories, price level adjustments were made based on the World Bank's GDP deflator series. GDP deflators were considered more representative of the types of expenditure needed for adaptation than consumer price indices (CPI), though it is noted that GDP deflators exclude imports, which might be important for some sectors. There was a further choice on whether to use country level series, the global series or the US series: the values here used the individual country series (World Bank, 2025).

All values are reported using market exchange rates rather than PPP values.[6] As highlighted above, the CGE models explicitly use MER. For the Adaptation Finance Gap Update, the relevant cost of providing adaptation finance to a developing country is that using market exchange rates, so it would not be relevant to make a PPP adjustment.[7] When expressing adaptation costs/finance needs as a percentage of GDP, it is important to be consistent. It would therefore not be appropriate to adjust either the GDP or the adaptation cost for PPP without adjusting the other. We therefore report both the adaptation cost and GDP using market exchange rates.

Cost and financial flows are presented initially as annual costs, with no discounting applied. This makes it easier to compare the likely resource needs for adaptation in different time periods. We stress that in analytical contexts, such as in economic project appraisal, it would be appropriate to discount costs arising in future years. It should be noted that the modelled adaptation costs for the 2050s are also undiscounted for the same reasons.

Finally, when considering the residual damages after adaptation, there is an issue of comparing values across countries, especially as the negative impacts from climate change are generally considered to disproportionately arise in developing countries (Tol 2018). The challenge concerns how to compare the welfare losses from climate impacts (before and after adaptation) across those with disparate incomes and

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[3] Values or prices can be expressed either in nominal (current) or real terms. Nominal terms are the values expected to transpire at the point that relevant transactions take place, hence they are sometimes referred to as 'money of the day' prices. Real prices attempt to strip out the effects of inflation. This can be useful when comparing the relative size of resource flows associated with a time series of costs or values. However, there are different ways to adjust for inflation, either using consumer price indices or GDP deflators, and there are choices on whether these are applied at the country level or using global values.

[4] When converting between values in different local currency units, conversions can be made using either (expected) market exchange rates or PPP-adjusted exchange rates. This is potentially important when expressing values in per capita- or GDP-equivalent terms. The use of PPP exchange rates adjusts for difference in price levels between economies, therefore effectively providing a measure of what a local currency can buy in another economy. Some adaptation modelling studies express results with a PPP adjustment.

[5] https://www.oecd.org/en/networks/dac-network-on-environment-and-development-co-operation-.html

[6] Where source data was provided in PPP terms, the values were first converted to US$ nominal for the price year in which they were presented using the World Bank's county-level series for the ratio of PPP conversion factor to market exchange rate. Values were then inflated to 2017/2023 US$ using the GDP deflator series.

[7] However, we note that converting to PPP might provide an indication of the relative value for money that international finance flows could produce (for some types of domestic action).

consumption levels: in simple terms, a dollar (of lost production, for example) to a poor person is not the same as a dollar to a rich person. In theory, it is possible to use some form of distributional or equity weighting when comparing or aggregating welfare losses to explicitly address these differences. However, this is challenging, and the values here do not make any adjustments for equity or distributional effects. Nevertheless, these issues are important and further work on this is a priority.

3.2 Coastal

Introduction

In addition to containing high population densities and significant economic activity, coastal zones provide important ecosystem services. Sea level rise and changes in storm surges have the potential to increase risks to coastal areas, which could in turn lead to increased flooding, loss of land, coastal erosion, salt water intrusion and impacts on coastal wetlands and the services they provide (Glavovic et al. 2022).

Adaptation to these coastal risks includes different strategies, including protect, accommodate or retreat, but also with the potential to use ecosystem-based adaptation, or to advance (IPCC 2019). Most adaptation cost studies have focused on protection to address flood risks (e.g. using dikes) and measures to reduce erosion (e.g. beach nourishment). However, even with coastal protection, a residual risk remains.

Modelling of the global costs of sea level rise, and of the costs (and benefits) of coastal adaptation, are the most covered sector in the literature, with multiple global models and many estimates in the literature (see UNEP, 2023). The ACCREU analysis uses the Dynamic Interactive Vulnerability Assessment (DIVA) model (Hinkel et al. 2013, Hinkel et al. 2014), the results of which have been widely published in academic literature (Lincke and Hinkel et al., 2018; Lincke and Hinkel 2021).

Full details of the analysis and the recent updates to the model are set out in Deliverable 2.1 (Impacts on infrastructure and built environment). The analysis has considered future climate and socio-economic change, using the ACCREU scenarios, which includes CMIP6 data. It also includes a higher resolution spatial assessment, which also improves analysis of adaptation planning. The model also now includes novel adaptation options, and can investigate coastal protection, migration, nature-based solutions (wetlands), and zoning restrictions across a range of different scenarios.

For the coastal impact simulations with DIVA the latest AR6 SLR scenarios were used (Fox-Kemper et al., 2021). This uses the 50th percentile of SSP126, SSP245 and SSP370 and as a high-end scenario the 95th percentile of SSP370.

Adjusting costs in the coastal flooding sector for inflation

DIVA's raw data is provided in 2011 USD PPP. The data is decennial from 2030 to 2100 (but note the models adjusts values to provide a baseline in the year 2020). Investment, maintenance and migration costs are treated separately.

DIVA include migration. Migration is used as an adaptation measure when the flood risks become very high (a 1 in 1 year return period) but can be switched on or off in the analysis.

There are three RCPs - 2.6, 4.5 & 7.0. All are combined with SSP2.

Adjusting these values to a different price year requires three inputs (all sourced from World Bank, 2025).

- Historical inflation data (GDP deflators).
- Historical FX data (USD/LCU).
- Historical PPP conversion factors.

The three price year options provided as outputs of this analysis are:

1. 2023 USD nominal – using country level inflation data
2. 2017 USD nominal – using country level inflation data
3. 2017 USD nominal – using USA inflation data

Converting the raw data to country level data in nominal 2017 and 2023 USD requires the following steps.

1. *Exchange 2011 USD PPP to 2011 USD nominal -*

Country level data in 2011 USD PPP is converted into 2011 USD nominal using country level World Bank PPP conversion factors for the year 2011. A PPP conversion factor is the price level ratio of the PPP exchange rate (LCU/USD) to the market exchange rate (LCU/USD).

2. *2011 USD nominal inflated to 2017/2023 USD –*
    i. 2023 USD (country inflation):
        a. 2011 USD nominal are converted to 2011 LCU using 2011 LCU/USD market exchange rates
        b. 2011 LCU are inflated to 2023 LCU using country level GDP deflators
        c. 2023 LCU are converted to 2023 USD using 2023 LCU/USD market exchange rates
    ii. 2017 USD (country inflation): As above (i) but inflated to 2017 instead of 2023.
    iii. 2017 USD (US inflation): 2011 USD nominal inflated to 2017 USD using US GDP deflator.

Impacts and Adaptation

The description of DIVA and its approach to impacts and adaptation is set out in D2.1. DIVA provides analysis first with flood risk estimated as an expected annual damage (EAD), as this provides a more average statistic for flood risk management than the absolute damage that occurs for a certain exceedance probability.

DIVA assesses all adaptation options at each time step (10 year intervals). Adaptation, such as dike heights, are thus implemented incrementally with changing flooding hazards. There were three adaptation scenarios considered in ACCREU:

- Low adaptation scenario: No additional coastal protection compared to present is built. Protection (dike) height is kept constant at the level at which the models are initialised. Dikes that are overtopped permanently do not provide any protection anymore. Migration in DIVA is allowed, such that people and assets migrate from floodplains that become uninhabitable (when they fall in the 1-in-1-year floodplain).
- Medium. Protection levels constant. Coastal planners pursue a business-as-usual protection strategy in which protection levels are kept constant. Dikes rise with sea-level rise in this scenario, but will not be optimal.
- High protection (high). Coastal planners in this scenario are most proactive, employing cost-benefit analysis to assess optimal protection levels. Overall coastal impacts, the sum of residual damages and adaptation cost, are minimised with respect to coastal protection. For some floodplains dike height may be higher in the reference scenario, however at suboptimal levels. Migration in DIVA is still allowed (and migration costs are included in the cost-benefit calculation).

As highlighted earlier, these involve different adaptation objectives (decision paradigms), rather than different adaptation levels of a single goal. This did lead to wide variations in results when comparing subsequently, and required several iterations to provide information.

Review of the literature to provide additional evidence

In order to complement the WP2 DIVA results an additional literature review was undertaken.

There are review studies on adaptation costs for flood protection, that look at a wide range of different measures (see Aerts, 2018), and compile evidence from current schemes and engineering studies. There is a also a relatively large evidence base on the economic costs and benefits of flood protection, based on real-world applications, although this tends to include both coastal flooding and riverine flooding, with some (albeit less) information on surface water flooding. Most of this is ex ante, but there is some ex post data. Note also note that most literature that is forward looking (e.g., to 2050) is based on the policy first approach, though there are some studies of science first approach. The latter includes a more complicated literature on decision making under uncertainty for coastal areas, which includes policy first studies, notably in Europe with the application of dynamic adaptation pathways (discussed below) and adaptation pathways.

Mechler (2016) undertook a review of the literature and identified 21 studies and an average benefit to cost ratio of 4.6:1 for coastal and river floods. The study identifies a large range, which is influenced by the site and context specificity of flood hazards, and existing protection levels, but also the benefits included (intangibles such as fatalities, but also indirect effects), as well as with discount rate. The paper also notes that the real-world BCRs are often lower when actual effectiveness is assessed, and also realistic maintenance regimes. These data included some ex post studies though most were ex ante appraisals.

Table 2. Summary results of average B/C ratios across studies (Source Mechler, 2016).

Hazard	**Review**	**Review**
	Simple average (number of studies)	**Range of estimates**
Flood (riverine and coastal)	4.6 (21)	0.1–30
Wind (tropical and extratropical)	2.6 (7)	0.05–50
Drought	2.2 (1)	1.3–2.2
Landslide and avalanche	1.5 (2)	0.1–3.7

The ECONADAPT project (2015) constructed a database of DRM investments for floods in Europe, containing 110 observations on investments/projects from 32 studies and databases, covering 16 European countries (figure 6).. This found that, on average, flood protection investments have high Benefit-to-Cost Ratios (BCR). The mean BCR of the investments was 5.9 while the median BCR was 3.0. The analysis considered different investments. DRM investments that enhance preparedness to disasters showed the highest economic returns, while also investment that prevents floods from occurring and investments that mitigate the damage of floods show high BCRs. Preparedness had the highest mean BCR (10.8), followed by flood damage mitigation (BCR = 8.5), hard flood control (4.1) and soft flood control (1.6). Again this highlights that BCRs of adaptation measures are highly site- and context-specific and there is future uncertainty about the scale of climate change, noting also again that studies use different discount rates. Note importantly that some data points show a BCR below 1. It is also noted that in real world studies (e.g., see UK, LTIS, 2019) that many possible schemes have BCRs below 1 (typically for rural schemes with low economic returns), but these are simply not funded. This is critical when reporting on the potential benefits of flood protection – schemes that are approved have BCRs that almost always are above 1 and have high BCRs, but this does not mean all flood protection provides BCRs>1, because low return schemes are filtered out.

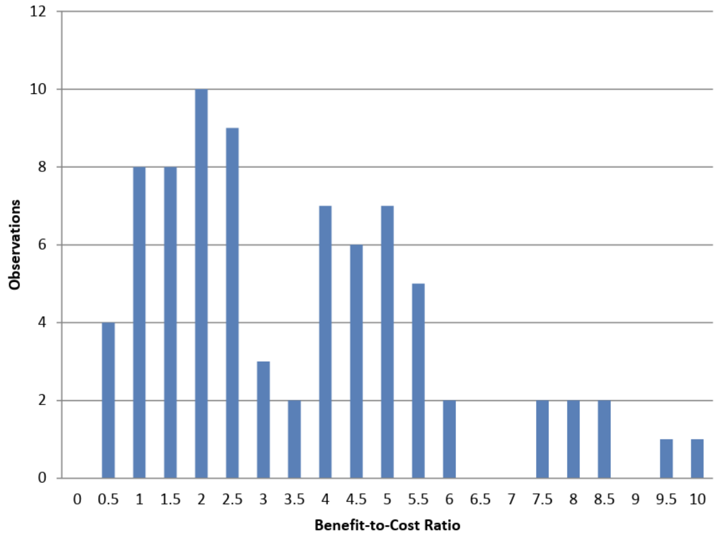


Figure 4. Frequency distribution of BCRs of DRM investments in Europe. Source Econadapt (2015).

Recent reviews for Europe (World Bank, 2021: 2024) report similar findings, though exact BCRs vary, including for different adaptation measures, reporting median BCR for flood prevention and preparedness at 2.6, with the majority of BCRs found to be greater than 1.5.

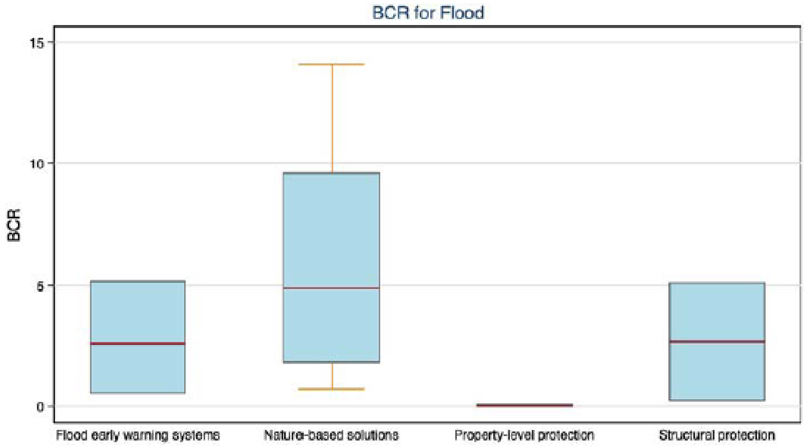


Figure 5. Findings of BCR for floods. Source World Bank 2021.

Markanday et al., (2019) also undertake a review of various adaptation measures and identify positive BCRs for floods, though this involves a wide range of studies.

Table 3. Benefit-cost ratios, ranks, standard deviation and variance of measures disaggregated by hazard type Source Markanday et al., 2019

Measure/Hazard	BCR (mean)	Rank	σ	S^2	No. of studies*
Drought					
Rainwater harvesting	1.37	2	1.22	1.5	4 (66)
Wastewater reuse and recycling	1.98	1	2.75	7.6	8 (49)
Pluvial flooding					
Rainwater harvesting	1.37	5	1.22	1.5	4 (66)
SuDS	1.80	4	1.53	2.3	7 (37)
Community preparedness	30.49	1	5.89	34.7	1 (4)
Property level measures	7.81	2	16.11	259.7	3 (14)
Green measures	2.25	3	8.83	78.0	20 (95)
Fluvial flooding					
Hard and soft defences	1.47	2	0.61	0.4	1 (4)
Green measures	1.42	3	0.29	0.1	1 (3)
Hard defences	0.50	4	0.23	0.1	1 (6)
Early warning systems	4.31	1	5.46	29.8	2 (5)
Heat waves					
Green measures	2.25	–	8.83	78.0	20 (95)
Sea-level rise					
Hard defences	40.45	3	108.11	11687.5	10 (98)
Hard and soft defences	82.91	2	163.28	26658.8	5 (19)
Resettlement	1.82	5	2.33	5.4	2 (11)
Soft defences	110.98	1	189.07	35746.03	4 (25)
Property level measures	8.21	4	16.70	278.84	2 (13)

Note: *Values in parentheses represent the count used for statistical summaries. This is due to, for example, the testing of multiple climate scenarios, implementation scales, discount rates, etc and thus study range.

This data provides useful but often contradictory information. Specific results on effectiveness and economic returns vary widely, with the type of approach (ex-ante vs ex post, science vs policy first, with location).

There are large ranges around green measures, which are identified as highly cost beneficial by some studies but not by others, and also are reported as having low effectiveness. For example, some studies on mangrove restoration report high BCRs (e.g. IISD, 2025), while others identify values just above 1 (e.g., Karanja and Saito, 2018). This is influenced by what is included (health and environmental benefits valued), but also by assumptions, for example, NBS often have high benefits for low levels of risk, but cannot address major impacts, and thus the boundaries of effectiveness strongly influence results. This leads to the combination of green and grey measures, which are often cited are more preferable portfolios (e.g., Aerts et a.., 2013).

As above, studies that are based on science first ex ante modelling, e.g., for SLR, tend to give high BCRs, but this is because they assume perfect foresight. This can be seen in numerous coastal flooding assessments including from the DIVA model team as well as other coastal models (e.g. Narain, Margulis and Essam 2011; Hinkel et al. 2014; Diaz 2016; Nicholls et al. 2019; Lincke and Hinkel 2019; Tamura et al. 2019, Tiggeloven et al. 2020; Lincke and Hinkel 2021; Brown et al. 2021: Wong et al. 2025). There are also an equivalent set of studies for river flooding (Ward, 2017: Tiggeloven et al. 2020).

A key question here is whether this literature can be used to provide additional information on the likely shape of adaptation functions, and the possible limits of adaptation. Several ex ante studies do provide some information on this. However, again, these often mix up the adaptation decision objective with the level of adaptation.

Ward et al (2017), with the GLOFRIS model for **river** flood risk, assess different objectives. They compare the objective/scenario of constant absolute risk, comparing this to constant relative risk and the optimal. The `optimize' objective prescribes protection standards that maximize Net Present Value (NPV). The `constant absolute risk' objective keeps future EAD constant in absolute terms at current levels, assuming no change in societal preferences towards absolute risk. The `constant relative risk' objective keeps future EAD as a percentage of Gross Domestic Product (GDP) constant, reflecting a desire to keep flood risk constant as a share of the economy. The latter leads to highest costs, and lower BCRs, which sometimes drop below 1.

Table 4. Globally aggregated results for the optimize, constant absolute risk and constant relative risk adaptation objectives in GLOFRIS

Adaptation objectives	Scenario			
	RCP2.6/SSP1	RCP4.5/SSP2	RCP6.0/SSP3	RCP8.5/SSP5
Objective: optimize				
Benefits (US$ billion per year)	316	254	105	799
Costs (US$ billion per year)	47	44	27	78
Benefit:Cost ratio	6.7	5.7	3.9	10.2
NPV (US$ billion per year)	269	210	78	721
Objective: constant absolute risk				
Benefits (US$ billion per year)	339	276	125	827
Costs (US$ billion per year)	170	177	155	219
Benefit:Cost ratio	2.0	1.6	0.8	3.8
NPV (US$ billion per year)	169	99	−30	608
Objective: constant relative risk				
Benefits (US$ billion per year)	275	225	100	721
Costs (US$ billion per year)	73	80	76	108
Benefit:Cost ratio	3.8	2.8	1.3	6.7
NPV (US$ billion per year)	202	145	24	613

The table shows the average results across the five Global Climate Models, under the following assumptions: middle-estimate investment costs; maintenance costs of 1% per year; and a discount rate of 5% per year. We assumed that the construction of dykes begins in 2020 and is completed by 2050, and that by 2050 dykes are designed to the standard required for the climate at the end of the twenty-first century (2060-2099). Annual costs are based on the period 2020-2100.

Source Ward et al., 2017.

This indicates that an average function (across all objectives) would unlikely to be linear. However, if an economic objective only is considered, there does seem to be rising BCRs with high warming scenarios.

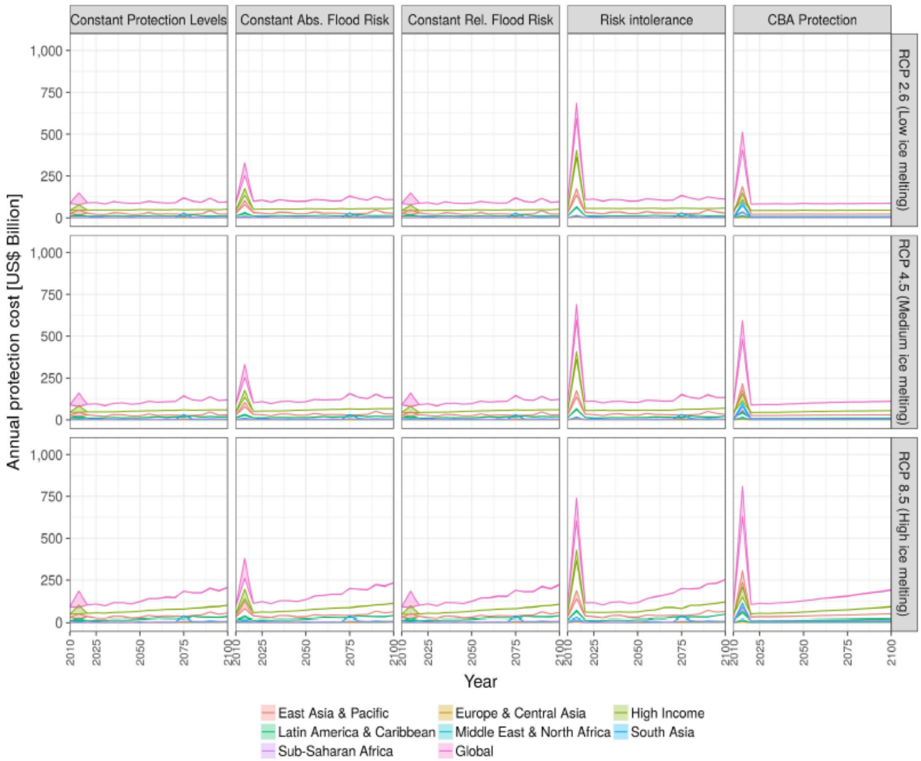
A similar analysis by Tiggeloven et al. 2020 for **coastal** adaptation, also with GLOFRIS, reports similar general findings, though BCRs are much higher. Higher costs and benefits are found for the RCP8.5–SSP5 scenario compared to the RCP4.5–SSP2 scenario, as a result of the larger EAD (and therefore avoided EAD) under this scenario.

Table 5. Global overview of benefit–cost analysis for the different adaptation objectives (benefits, costs, and NPV are in USD billion 2005). Source Tiggeloven et al. 2020

		Benefits	Costs	BCR	NPV
Protection constant	RCP4.5–SSP2	9705	144	67	9561
	RCP8.5–SSP5	18 729	176	106	18 552
Absolute-risk constant	RCP4.5–SSP2	11 550	307	38	11 243
	RCP8.5–SSP5	23 020	399	58	22 620
Relative-risk constant	RCP4.5–SSP2	11 027	186	59	10 840
	RCP8.5–SSP5	22 101	224	99	21 878
Optimize	RCP4.5–SSP2	11 550	152	76	11 398
	RCP8.5–SSP5	23 031	208	111	22 823

For coastal, Nicholls et al. 2019 also consider different objectives, looking at five alternative objectives. Constant protection levels (no additional adaptation), constant absolute risks (maintain current flood risk in monetary terms), constant relative risk (raising protection levels), risk intolerance (keep relative average annual losses below 0.01% percent of GDP), and optimal (cost benefit analysis). The highest costs are found with the Risk Intolerant strategy. The CBA optimal strategy costs are also high (though influenced by the initial model action in 2015) but it has lower residual damages and thus lowest overall costs.

Figure 6. Annual protection costs (for dike and barrier protection) for different regions and the total global costs over time for SSP2, high adaptation unit cost. Source Nicholls et al., 2019



There are some emerging discussions on the limits of adaptation for flood protection (Aerts et al., 2024), reproduced in the table below.

There are clearly soft limits to adaptation, notably for the financing and funding of large protection projects.

There can also be hard limits where conventional protection is not possible and managed retreat or other more transformative solutions are sought. DIVA includes this by switching between adaptation strategies from flood protection to migration when flood risks become very high (when the return period becomes 1, and thus every year flooding is experienced). This happens especially in the scenarios of constant protection levels and even in constant standards.

Table 6. Summary of adaptation constraints that may lead to flood adaptation limits. Source Aerts et al 2024a

Constraints	Current	Reference	Remarks
Flood protection, forecasting and control			
Maximum levee height	~16 m	Ponseti and Lopez-Pujol[39]	Highest levees along Yangtze River (China)
Protection standards	From 2 years in Africa to 10,000 years in Europe	FLOPROS; Scussolini et al.[33]	Optimal design standards vary between 5 and 1,000 years (Ward et al.[14])
Flood forecasting	~1/3 of the countries do not have early warning	(WMO[54])	UN initiative to provide early warning for all
Flood control by reservoirs	35,000 global reservoirs	Boulange et al.[43]	+#3,700 new reservoirs planned: would reduce 12–20% people exposed in future 1/100 flood zone
Adaptation to lower exposure and vulnerability			
Future flood zone delineation	<1/100 years	Aerts[103]	Building codes applied to max. 1/100 flood zones
Maximum wet/dry flood proofing height for buildings	~+1 m	Endendijk et al.[53]	Based on empirically derived different depth–damage curves
Flood insurance/governmental compensation			
Coverage	>25%	Tesselaar et al.[4]	Below 25% the flood insurance is economically not attractive
Affordability	High premiums drive households below poverty line	Tesselaar et al.[4]	Poverty line set at 60% of national median income
Ratio losses/premium income	<60%	Born and Viscusi[62]	Ratio of losses incurred divided by premiums earned
Government debt ratings	% loss/GDP	Moody's[63]	Higher flood losses as percentage of GDP lead to lower public debt ratings
Socio-economic constraints related to adaptation decisions			
Discount rate	3–7%	Ward et al.[14]	Discount rates >4% do not factor in future trends
Equity	Equity criteria only applied in some countries[77]	Kind et al.[22]; Thaler and Hartmann[77]	Adaptation investments prioritize wealthy communities
Behaviour	Risk perception and aversion, attitude	Bubeck et al.[72]	Factors influencing the uptake of adaptation measures
Socio-vulnerability and local adaptive capacity			
Social vulnerability	Age, income, education level and so on	Rufat et al.[8]	Factors influencing flood vulnerability and impacts
Maximum percentage of flood-proofed buildings in flood zones	17–47%	Table 1 (this study)	Dependent on: percentage of old buildings, policy incentives, behavioural factors and social vulnerability

Source Aerts et al., 2024

Hinkel et al (2019) report there are effectively no technical limits to adaptation this century for coastal protection. They do, however, suggest finance barriers, as well as potential social conflict barriers, before technical limits are reached.

However, there are likely to be some limits or non-linearities in practice before this, and the unit costs of avoiding a unit of damage are likely to increase. Technically, high structures are possible (see Hinkel et al., 2018), and already in place in some locations (notably the Netherlands) although there will be limits to building such high structures in many places due to land availability or space constraints. But it would also seem logical that larger structures would have higher relative costs, e.g., larger dike structures will require larger foundations and widths to support weight, however, the models tend to work with constant unit costs.

There are some national studies that provide additional real-world information that indicate some non-linearities or limits of adaptation. As an example, future flood and coastal investment needs in England are set out in Long-Term Investment Scenarios (LTIS) (EA, 2019). This sets out optimum FCERM investment in a range of 'what if' scenarios, with investment undertaken where benefits are greater than the costs (as measured by positive net present values). Across the overall LTIS (2014) investment profile the overall BCR ratio is ~ 5:1. The study sets out that the long-term optimal level of investment (depending on policy choices) could range from £1.0 billion to £1.2 billion in 2019 prices for England. However, they identify there would be much higher investment costs in a high warming high sea level scenario (high ++) (of £1.6Bn to £2bn). This higher investment costs is because it is possible to refurbish embankments and walls with an increase in height of around 0.6 metres, but above this height they may need full re-engineering. Higher levels of climate change also cause assets to deteriorate faster - particularly on the coast (EA, 2019) and this will increase costs. Again the LTIS scenarios investigated this and found in a high++ scenario, long-term asset maintenance and replacement costs could increase by factors of up to 3 and 5 (affecting for some locations whether to upgrade or retreat).

This leads to some challenges, because while there are apparent real-world limits of adaptation, in a modelling domain that is focused on technical approaches, these are less pronounced. In a techno-economic modelling framework, as for the WP2 models, then adaptation is likely to be considered extremely economically beneficial, and as there are low technical limits, there will be no limits to adaptation. This, as shown subsequently, is what happens in the models.

Global Results and functions from DIVA

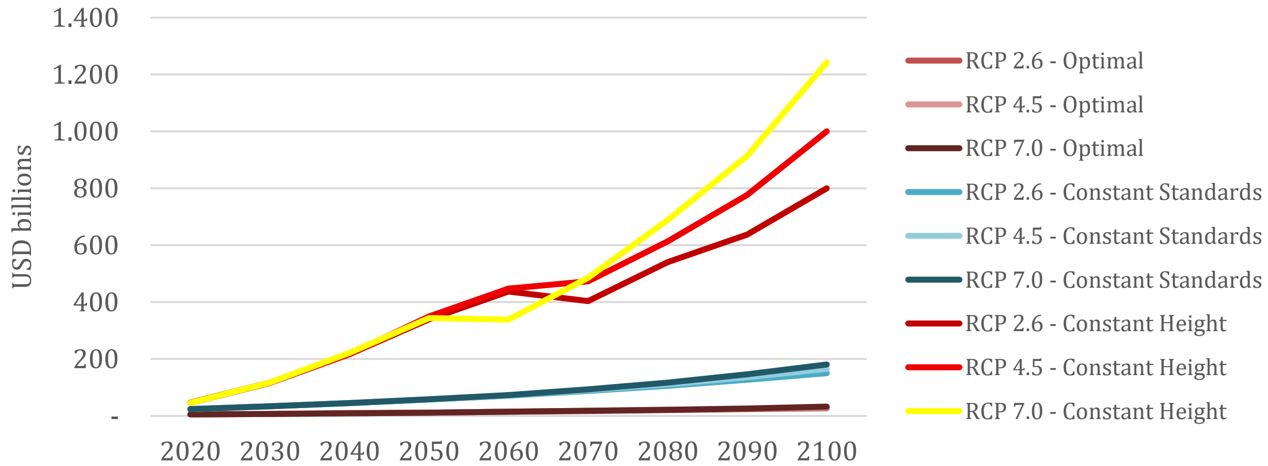
The WP2 results from the DIVA model were collated, with values expressed in US$2017 and US$2023, the former to align to the CGE models, and the latter for the adaptation gap analysis. The values are derived for each individual country, and then aggregated up globally. This includes the EAD values, and the adaptation cost values, as well as EAD after adaptation. Adaptation costs were split between capital and maintenance costs, as this split is needed for the CGE models.

The data was then use to investigate potential functions. As highlighted above, several of the IAMs model SLR separately, and so a separate function is useful.

To start with, the analysis looked at the functional relationships between annual EAD and SLR, based on the WP2 data. As shown in the Figure below, EAD increases fairly linearly with SLR with no adaptation (constant height). There is relatively low variation in the scenarios until after mid-century, when there is an acceleration under the RCP7.0 scenario.

With constant dike protection levels, the EAD fall significant, and there is much less difference between RCPs. Finally, with the optimal level of adaptation, EAD falls to extremely low levels. The level of EAD reduction is extremely high. There is relatively low variation between RCPs for the constant and optimal protection standards scenarios. However, the difference to baseline EAD is extreme. EAD in 2100 is 30-38 times greater with constant dyke height relative to optimal protection standards and 5-7 times greater than with constant protection standards, depending on the RCP.

Figure 7 - EAD by scenario and RCP



This can be used to derive EAD with SLR. This is shown below for the three adaptation scenarios.

Figure 8 - EAD by decade (2020 - 2100) by RCP for the Constant Dyke Height scenario.

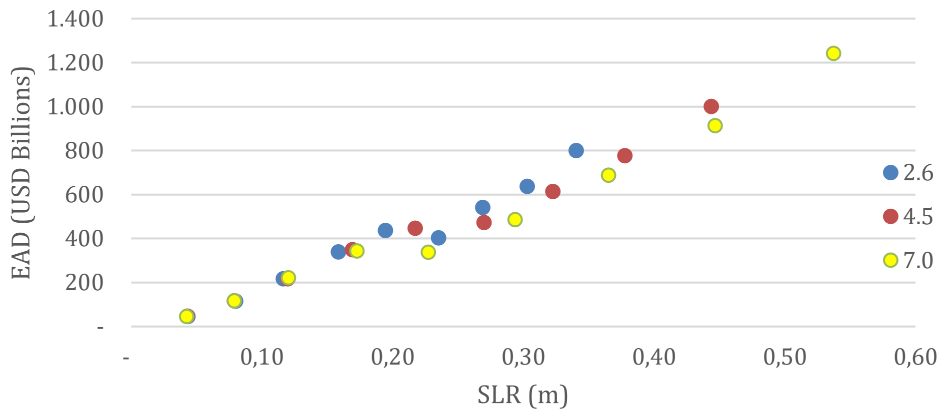


Figure 9 - EAD by decade (2020 - 2100) by RCP for the Constant Protection Standards scenario.

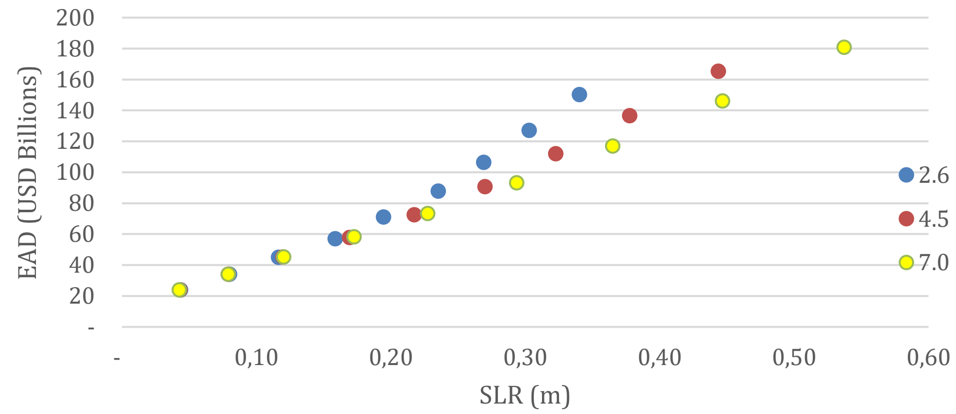
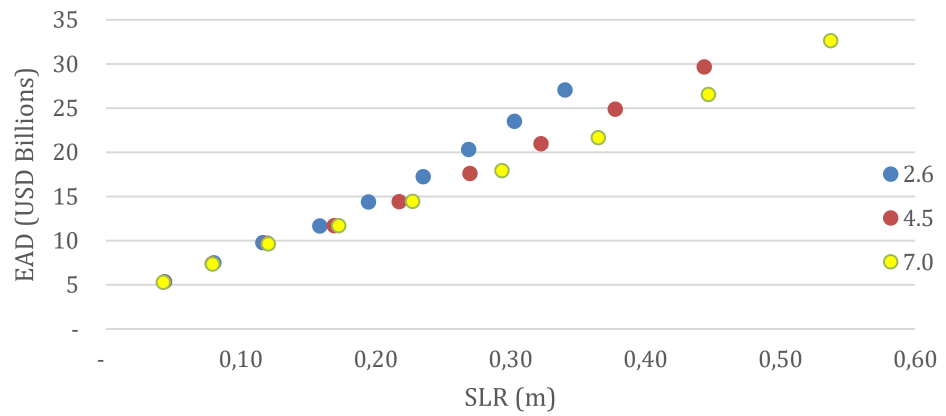


Figure 10 - EAD by decade (2020 - 2100) by RCP for the Optimal Protection Standards scenario.



The issues come when looking at the adaptation costs. One might expect a trend to arise where rising adaptation costs translate into rising adaptation benefits. However, several factors complicate this. First, in DIVA, there are adjustment costs in the starting period (2020) – that adjust to the under-adapted current state (and adaptation deficit). These involve very high costs in a short-period. There would likely be limits to this adaptation in reality (e.g., financing constraints on whether this finance is available and how the investment would be funded). These spikes in 2020 can be seen in the constant protection and optimal scenarios below. Second, there are non-linearities in the data, because of the inclusion of migration costs, which are included when flooding happens with a 1 in 1 year probably. For example, the baseline (constant dyke height) leads to the highest levels of EAD and costs are influenced by extreme migration away from coastal areas.

For the two adaptation scenario, there are almost no variations in adaptation costs over time. The constant protection and optimal scenarios have very similar levels of costs, as shown in the figures below, despite the large reduction in EAD. The optimal scenario, despite having the largest benefits, has the lowest costs. This is because it does not seek to protect everywhere, and thus assumes that in many cases where it is not economically justified, SLR will be allowed to rise.

Figure 11 - Adaptation costs by RCP in the Constant Dyke Height scenario broken down by investment, maintenance and migration costs

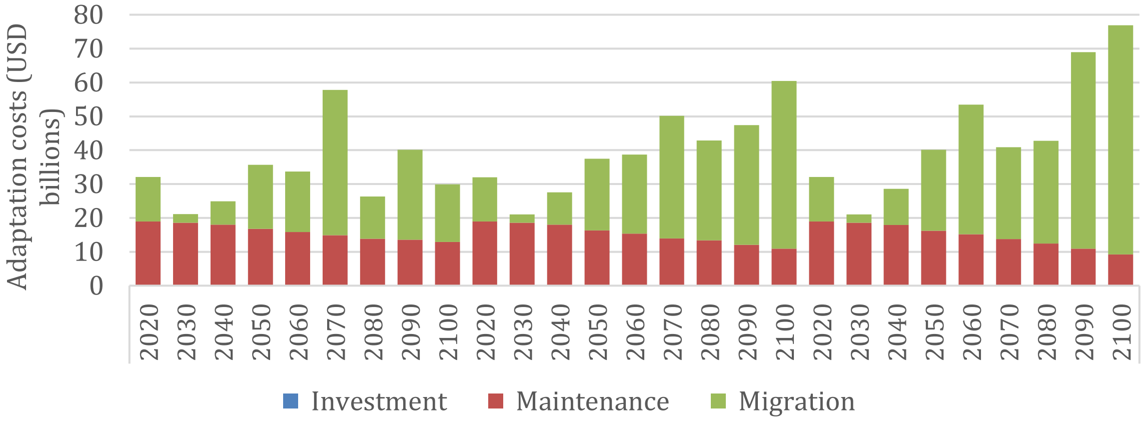


Figure 12 - Adaptation costs by RCP in the Constant Protection Standards scenario broken down by investment, maintenance and migration costs

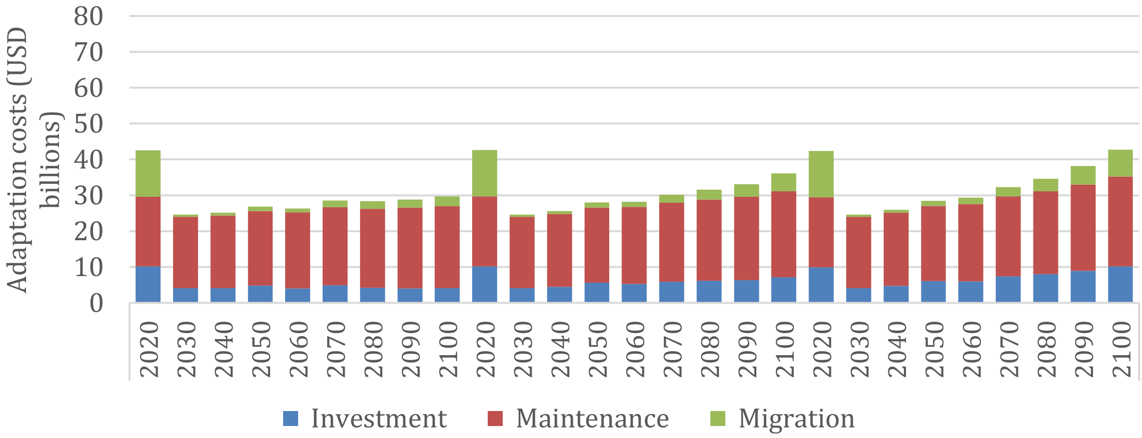
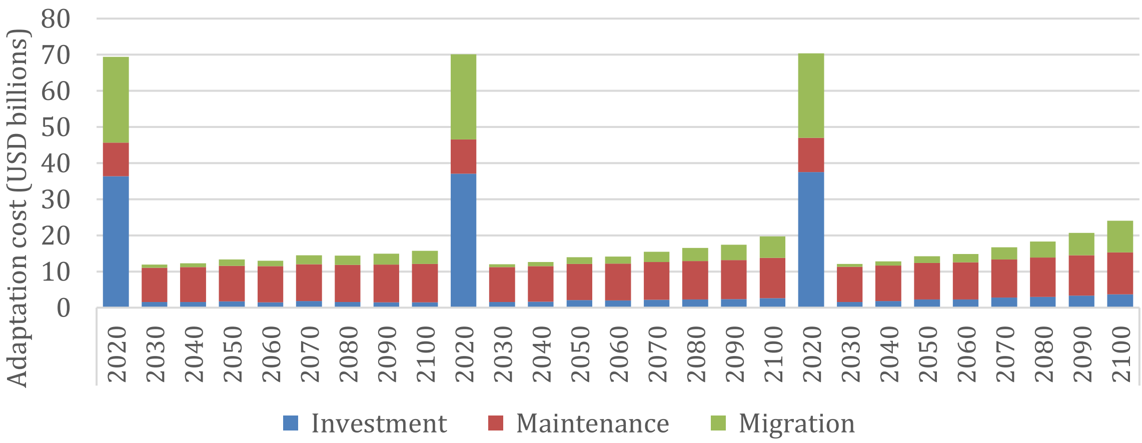


Figure 13 - Adaptation costs by RCP in the Optimal Protection Standards scenario broken down by investment, maintenance and migration costs



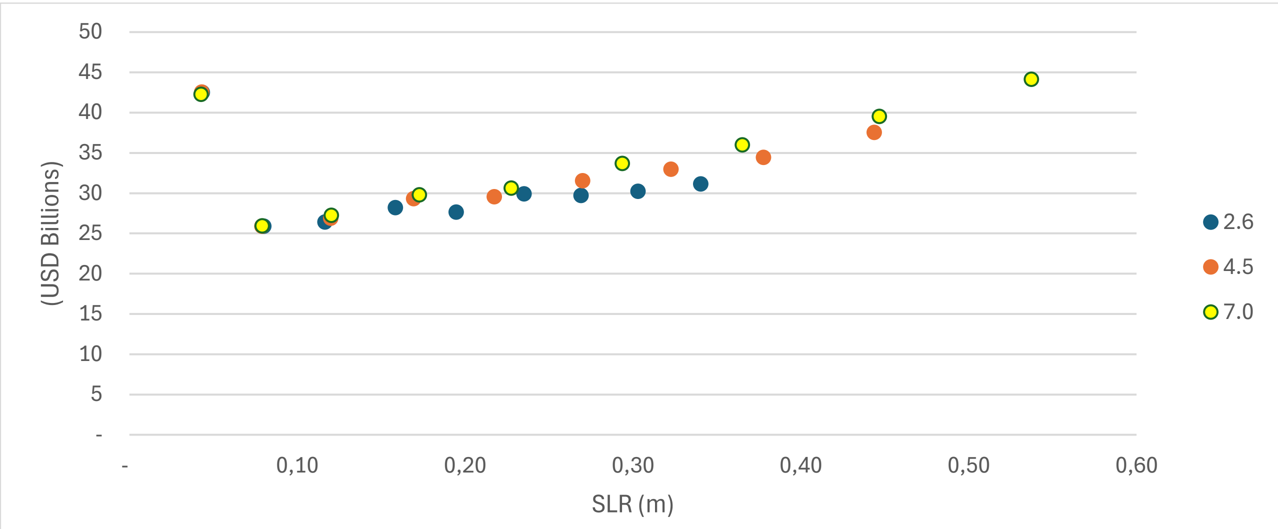
The migration costs are the dominant driver of adaptation costs in the constant dyke height (no adaptation) scenario. With absolute dyke protection remaining constant, the only available adaptation measure to at risk communities is migration and in many locations that is associated with large costs. Costs trend upwards towards the end of the century and costs in more extreme RCP scenarios are higher than in milder RCPs.

After 2020, maintaining constant protection standards is associated with a very moderate increase in annual spending over time. Across RCPs, all three components of adaptation spending trend slightly upwards over the period. The increase in costs over time is slightly greater in more extreme RCP scenarios than in milder RCPs. The spike in costs in 2020 is driven by the DIVA model set up with 2020 being the initialisation year.

Post 2020, for optimal protection, there is a similar pattern. All cost types gradually increase over time and costs are slightly higher in more extreme RCPs. The difference is that total costs are approximately half those seen with constant protection standards, due to the optimal allocation of spending. As highlighted previously, in 2020 there is again a spike in the adaptation costs for all three RCPs. This is again driven by the model initialisation period which leads to an instant update of the coastal dyke protection map. In this period, economically inefficient dykes are abandoned and where migration is more cost effective than dyke protection, migration is assumed to take place. This would involve a level of global upheaval which is difficult to envisage in reality, but it demonstrates the economic gains which could be achieved by an extreme rethinking of coastal flood protection strategies.

Comparing costs across strategies, the highest average annual costs are observed in the constant dyke height scenario, followed by constant protection standards. Optimal standards are shown to be the least costly, even after accounting for the 2020 spike. This is driven by a reduced need for migration and an optimised investment schedule which allows for a long period during which the benefits of that investment can be experienced.

Figure 14 - Adaptation costs with rising SLR in the Constant Protection Standards scenario (includes migration).



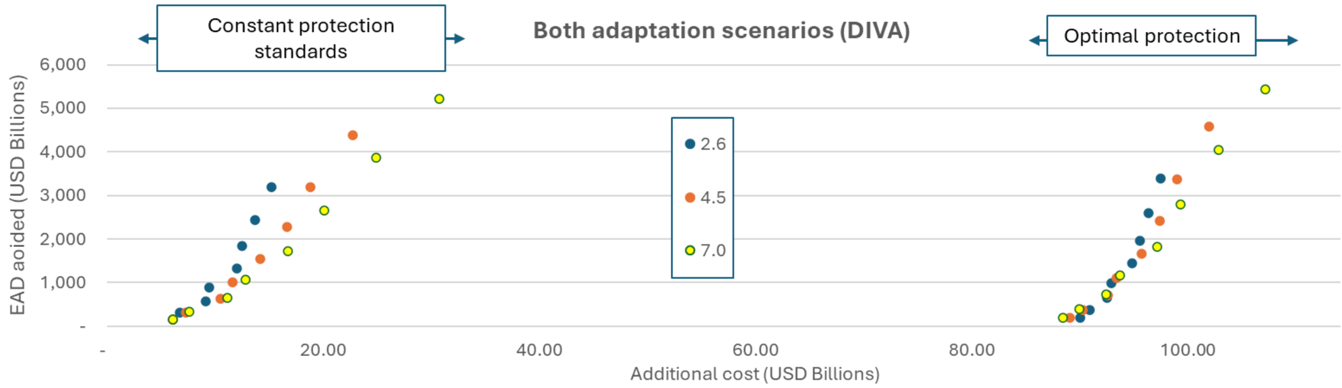
Moving to the function, the relationship which we are trying to model is the following:

$$EAD\_avoided = f(AC)$$

Where AC is the additional adaptation cost relative to the no adaptation scenario. This can be expressed in $ terms or % GDP reduction or the % of total expected damages avoided due to climate change in absence of adaptation. The latter may provide a more intuitive interpretation, particularly when considering limits to adaptation.

The problem is that the functions for damage avoided (benefits) against adaptation costs, are very spatially distinct for each adaptation decision paradigm. This can be seen in the initial set of data from DIVA showed two distinct sets of damage functions, as shown below when plotted together, plotting all data on a single graph.

Figure 15 – Initial plots of DIVA data, economic benefits (Avoided EAD) against Costs, for the two adaptation scenarios. Note these data were subsequently revised, but the figure is provided to illustrate the two distinct sets of data.



This also leads to a question of the fit for different hypothetical functions for the DIVA data, when working with one decision paradigm. An initial analysis was made, shown below.

Hypothetical functions

Function	**Fit (R^2_{adj} – approximate)**
Linear	>0.90
Quadratic	>0.90
Ln	>0.85
Logistic (S-shape)	>0.95

Based on the literature review, it is possible a negative exponential saturation function might be more realistic of the real-world, because it provides a consistent representation of flood protection: rapid initial reductions in risk, diminishing marginal effectiveness, and an upper limit to the achievable reduction in damages.

$$EAD\_avoided = L(1 - e^{-\beta AC})$$

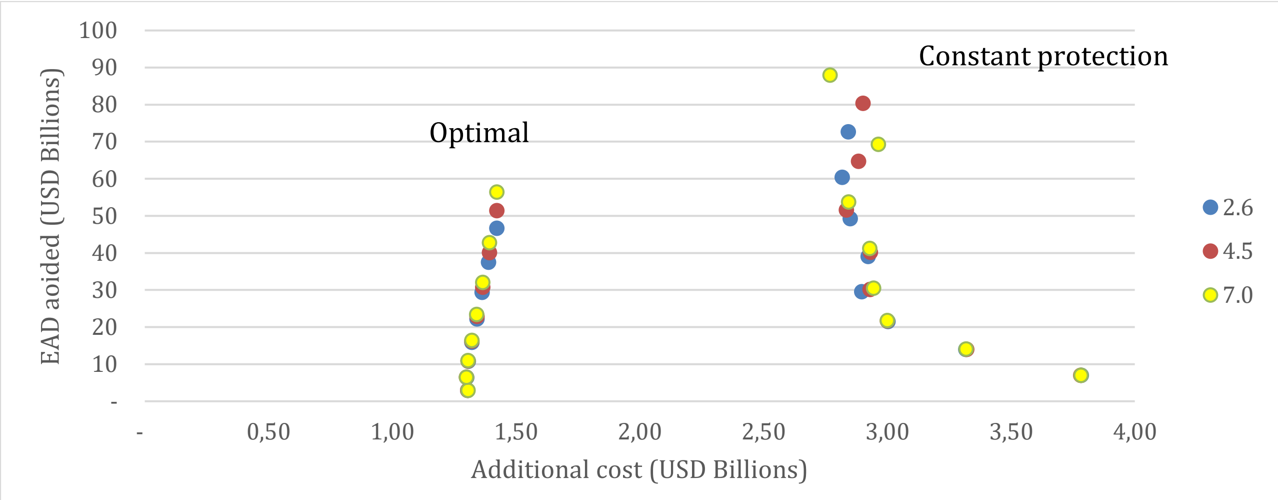
Where L is the limit to adaptation and β is the curvature parameter, estimated by the regression.

The choice of function depends on the shape of the data provided, and whether or not to let the model estimate the parameter L or to impose a limit to adaptation from the literature. This choice will depend on whether real world data exhibits diminishing returns to adaptation spending and, if so, if the exhibited limit is consistent with the literature. As reported by the literature review earlier, while there appear to be few technical limits to adaptation for SLR this century, there is some indication of rising marginal costs, and there are definitely limits, though these might be fiscal.

The updated run with the DIVA data updated the figures, and did lead to a change between the optimal and constant scenarios, such that optimal scenario involved the lowest costs. This also generated some issues, as the update led to the constant dyke height scenario having highest average annual adaptation costs of the three scenarios, although this was because of the migration costs.

This created a new set of functions, that were harder to interpret, as below.

Figure 16 – Revised plots of DIVA data, economic benefits (Avoided EAD) against Costs, for the two adaptation scenarios.



To try and resolve this, additional runs were undertaken, focusing on one decision paradigm only. Two additional scenarios were run in the DIVA model to allow for a comparison of costs and damages between scenarios where only the intensity of adaptation differs:

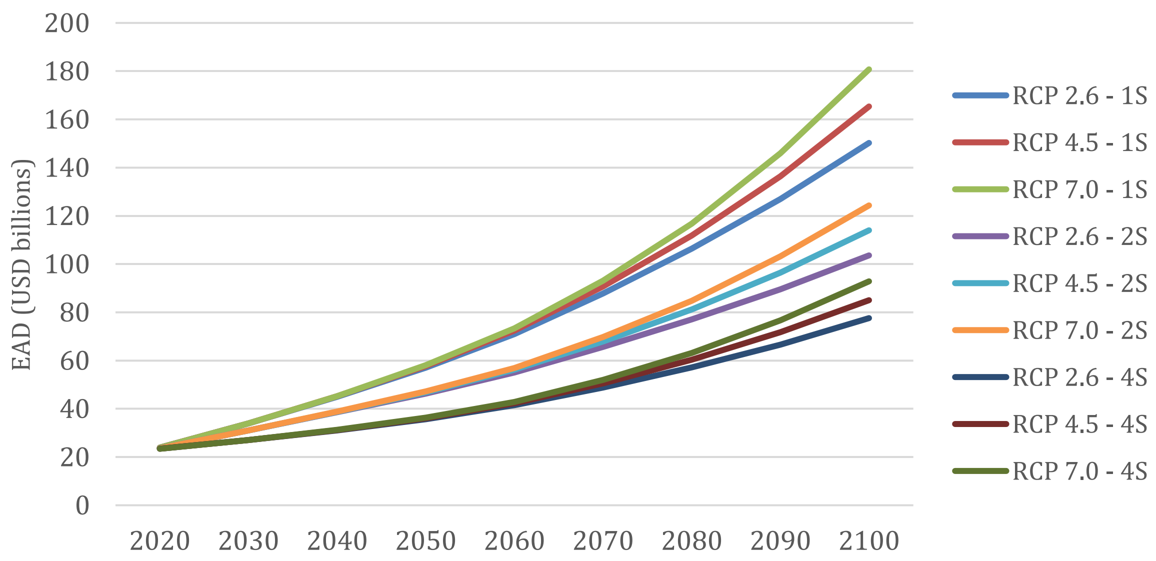
- Doubling constant protection standards
- Quadrupling constant protection standards

This leads to the following data set

- 1S = Constant protection standards
- 2S = Doubling of constant protection standards
- 4S = Quadrupling of constant protection standards
- OP = Optimal protection standards
- CH = Constant dyke height

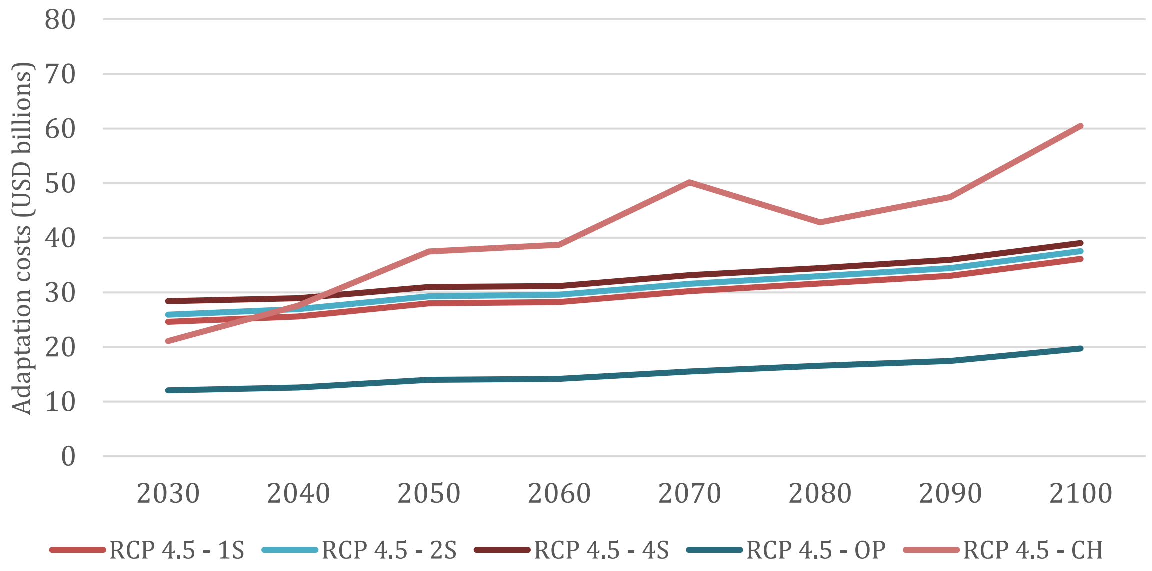
Residual damages are reduced significantly in the 2S and 4S scenarios relative to the 1S baseline (see Figure). Average annual damages between 2030 and 2100 are reduced by 25-26% in the 2S scenario and by 43-44% in the 4S scenario, depending on the RCP.

Figure 17 - EAD by scenario by RCP for 1S, 2S and 4S.



The doubling and quadrupling of constant protection standards leads to a moderate increase in adaptation costs over time. Average annual costs between 2030 and 2100 are 5% higher in the doubling scenario and 10% higher in the quadrupling scenario. For clarity, the figure only displays the costs for RCP 4.5 but the costs in the other two RCP scenarios follow the same pattern.

Figure 18 - Adaptation costs by scenario for RCP 4.5.



A set of functions were derived for this new data. This looked at different options. Unless otherwise specified, the analysis below refers to annual data (i.e. costs in 2030 vs damages in 2030). 2020 was excluded due it being an initialisation year in the model. This was run for three scenarios.

The other decision that led to more intuitive functions was to transfer migration costs from the adaptation to the impact side of the equation. The updated runs and results are described below.

<u>Constant (1x, 2x & 4x) compared to the constant height baseline where migration costs are treated as a damage.</u>

Treating migration costs as damages allows the analysis to use constant dyke height (CH) as a baseline for the three constant protection (CP) variations, as it means the costs are always higher with constant protection than constant height. The results are plotted below, using two versions of the same chart but with different colour codes. These look at additional adapt costs and additional damage avoided in the three constant protection scenarios relative to the constant dyke height scenario.

By treating migration costs as a damage, total costs in the constant dyke height scenario are greatly reduced.

The first figure shows that the pattern of damage avoided vs additional cost is pretty consistent between scenarios. The second plot below shows the same data but broken down by RCP. It shows the pattern is also quite consistent between RCPs. As expected, the data points for RCP 2.6 are slightly more bunched towards the beginning of the curve with RCP 7.0 more bunched towards the higher cost, higher damage quadrant.

Figure 19 - EAD avoided vs additional adaptation costs by adaptation scenario (CH baseline)

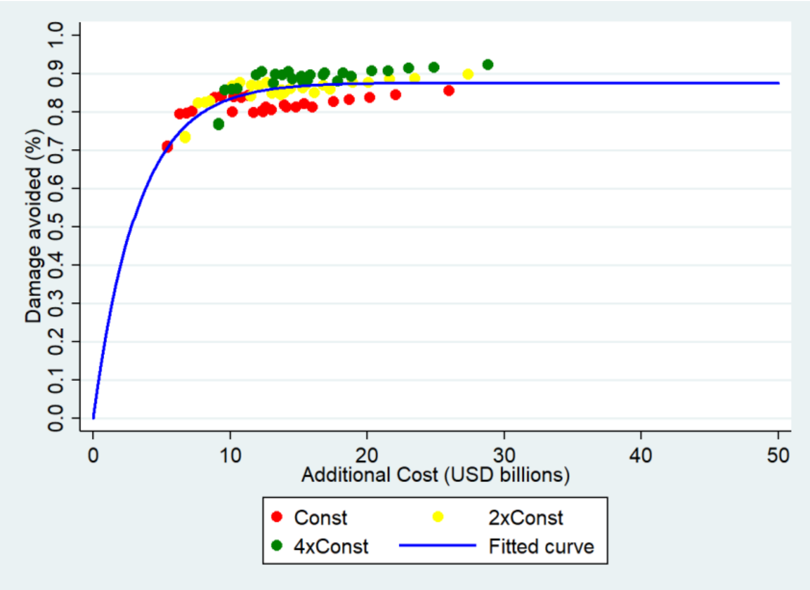
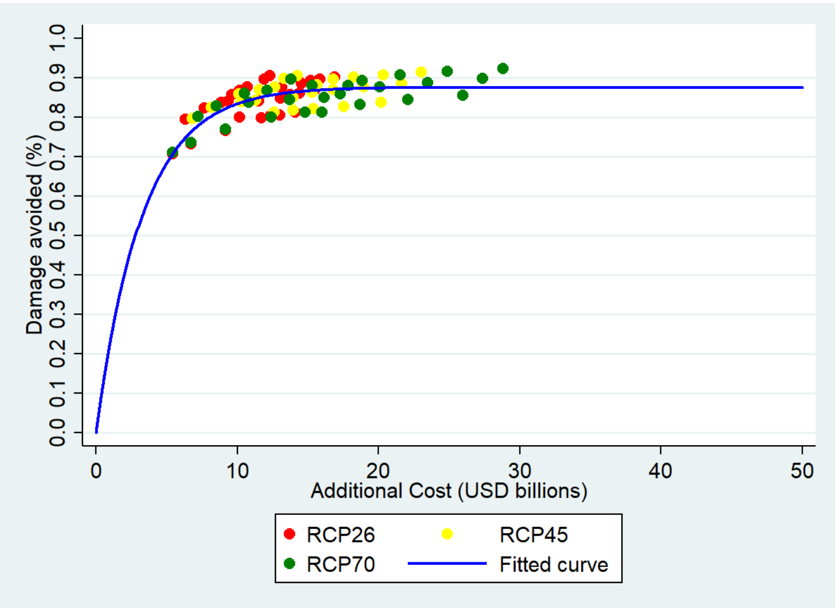


Figure 20 - EAD avoided vs additional adaptation costs by RCP (CH baseline)



Constant (2x & 4x) compared to the 1X constant protection baseline where migration costs are treated as a damage[8].

An alternative analysis was tried, using CH as a baseline for the CP scenarios. The Figure shows the damage avoided and additional costs in 2x and 4x constant standards relative to the 1x constant standards scenario. There is very little variation in annual costs which leads to the two straight lines – one for each scenario. The average annual cost vs damage is essentially two data points – one per scenario - because there is very little variation between RCPs.

[8] The results are almost identical whether migration is defined as cost or damage as there is ~0 different in migration costs/damages between 1x, 2x and 4x constant standards.

Figure 21 - EAD avoided vs additional adaptation costs by adaptation scenario (CS baseline)

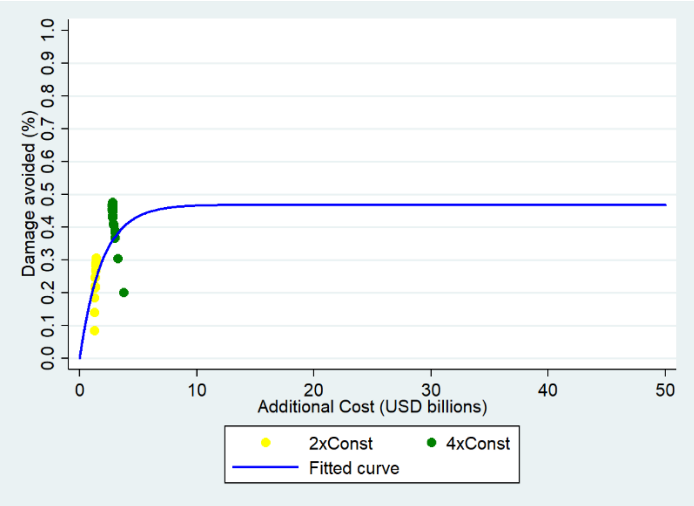
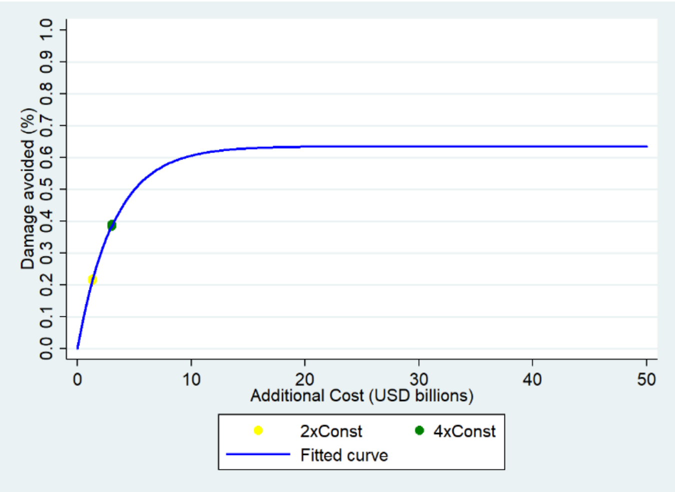


Figure 22 – AVERAGE EAD avoided vs additional adaptation costs by adaptation scenario (CS baseline)



A third function was tested using CP as a baseline for the 2x and 4x CP scenarios does not work well. This is true with migration as a cost or damage. There is no variation in costs over time or between RCPs so there are insufficient data points, one per scenario.

This led to the decision to work with the data from Figure 19 and 20 for the damage function for the IAMs.

It is noted that the DIVA model does have very high effectiveness, in terms of the reduction in EAD with adaptation. EAD is reduced by an order of magnitude under the constant scenario. The benefits (annual reduction in EAD) to annual costs are also very high. The BCR varies with time period and run, but are usually >10:1, sometime significantly so. This is in line with other modelling studies (e.g., Tiggeloven et al. 2020) but this is much higher than the real-world adaptation data, for example, the extension data set of current schemes collated by ECONDAPT (2017).

3.3 River Floods

Introduction

Floods are one of the most important weather-related loss events and have significant economic impacts. In addition to affecting hydrological cycles, climate change has the potential to increase the magnitude and/or frequency of intense precipitation events and flood events, although there will be differences in how these changes take place between regions (Caretta et al. 2022). Although there is a wide range of adaptation options for addressing these flood risks, the modelling literature mainly focuses on flood protection structures.

Modelling of the costs of (river) floods and of the costs and benefits of flood protection are well established in the literature. Most studies use hydrological models that link flood hazard (flood events) and exposure, then use probability-loss (depth) damage functions to capture the impacts of events of different return periods. These are then integrated into a probabilistic expected annual damage (EAD). These models can also consider adaptation protection levels, and thus estimate the benefits of adaptation (in reducing risks) and the costs of protection. Most of the focus has been on flooding of property (residential and non-residential) though with some consideration of other receptors.

The ACCREU analysis uses the GLObal Flood Risk IMAGE Scenarios (GLOFRIS) model (Ward et al. 2017: Tiggeloven et al., 2020), one of the leading global flood risk models for river (fluvial) flooding. This produces flood costs (expected annual damage), as well as adaptation investment and residual damage (expected annual damage [EAD]) after adaptation). Full details of the analysis and the recent updates to the model are set out in Deliverable 2.1 (Impacts on infrastructure and built environment).

New developments of GLOFRIS in ACCREU are the improved spatial resolution from a NUTS2 level to a NUTS3 level, the estimation of coastal flood risk in addition to riverine flood risk, EAD estimates for the commercial and industrial sector alongside residential EAD, and the inclusion of more adaptation scenarios (constant dike heights, constant protection standards, optimal protection standards, exposure reduction via zoning restrictions, and the conservation of saltmarshes (coastal only)).

Adjusting adaptation costs in the riverine flooding sector for inflation

This note sets out how a set of adaptation cost estimates for the riverine flooding sector has been adjusted to reflect the time value of money. The estimates covered are outputs from the GLObal Flood Risk IMAGE Scenarios (GLOFRIS) model regarding investment and maintenance adaptation costs.

Data description:

- GLOFRIS's raw data is provided in 2005 USD PPP.
- Investment costs and maintenance costs are treated separately.
  - Investment costs are provided as a present value (PV) of investment costs over the investment period 2020-2050 using a 5% discount rate.
  - Maintenance costs are provided as a present value (PV) of maintenance costs over the lifetime period 2020-2100 using a 5% discount rate.
- There are four RCPs - 2.6, 4.5, 6.0 & 8.5. All are combined with SSP2.
- There are two adaptation scenarios: constant protection and optimal protection.

Adjusting values

Adjusting these values to the relevant price years followed the approach as with DIVA above, but as the model has some differences in adaptation costs, some additional assumptions are required.

i. Investment costs:

   a. In the raw data, total costs = investment costs + maintenance costs. Therefore, Investment costs = total costs – maintenance costs.

   b. The PV of investment costs is converted into an annuity using the formula for the PV of an annuity (link), the investment time period of 30 years (2020-2050) and the discount rate of 5%.

ii. Maintenance costs:

   a. Maintenance costs are directly provided in the raw data.

b. The PV of maintenance costs is converted into an annuity using the formula for the PV of an annuity (link), the maintenance time period of 80 years (2020-2100) and the discount rate of 5%.

Impacts and Adaptation in GLOFRIS

The approach for impacts in GLOFRIS is similar to DIVA and focused on EAD (expected annual damage). This is set out in D2.1. However, GLOFRIS has a different functional form for adaptation. This is detailed in D2.1. In summary, instead of incremental increases over time, the adaptation investments are pre-set, meaning that the model is initialised with one predetermined future objective for the future and one predetermined adaptation option that is then implemented at the beginning of the model run. For adaptation measures in GLOFRIS, it is assumed that goal is set for the 2080s, the investment on adaptation starts in 2020 and that the construction is finished in 2050, using a discount rate of 5%, operation and maintenance costs of 1% and an investment lifespan until 2100 (Tiggeloven, 2020). This means that the model also assumes perfect foresight, i.e., it knows what will happen in 2080 and then models the investment to address this specific goal.

The output from the model is produced as investment and maintenance costs over a defined period (2020–2050). This requires post processing of the data to produce in a format similar to those used in other sectors.

GLOFRIS comes with 5 pre-set adaptation options: constant dike heights, constant protection standards, optimal protection standards, foreshore vegetation, and zoning restrictions. Four are used in ACCREU

- constant dyke height (no adaptation)
- constant protection standards
- optimal protection standards
- constant EAD

Constant dike heights means that the protection standards used remain constant over time. This leads to an increase in risk over time, as a dike that protects against flooding with a certain return period will get overtopped more often if the flood hazard increases.

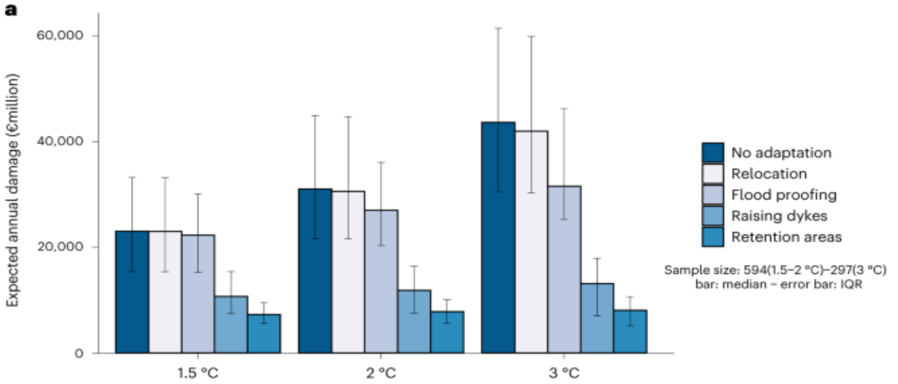
Constant protection standards mitigates this problem by letting the dikes grow in tandem with the hazard. This means that a dike that protects against a certain return period in 2010 is increased if the water-level associated with this return period increases in the future. For example, keeping up protection against 1/100-year flood events requires higher dikes if future 1/100-year events are associated with a higher water level.

Optimal protection standards take the costs and benefits of protection standards into account, the protection standards are chosen such that the Net Present Value (NPV) is maximised (Ward et al., 2017) over the period 2020-2080. To determine optimal protection standards, benefits are assessed up to 2080, while the investment and associated costs occur over the period 2020-2050. Over the period 2020-2050, costs and benefits accrue over 5-year timesteps. Total benefits are, then, reduced flood risk over the period 2020-2080, while total costs are investment costs made over the period 2020-2050. Costs and benefits are discounted at a rate of 5% to obtain the NPV.

Review of the literature to provide additional evidence

The main body of evidence on costs and benefits, and limits of adaptation, was presented in the earlier coastal section. This includes the BCR reviews as well as the global assessments.

In the European context, the LISFLOOD model has been used (Dottori et al. 2023). This compares presents an assessment of the costs and benefits across Europe of four key flood adaptation options: raising dykes, detention areas, flood proofing and relocation. First, flood hazard and risk were projected up to the end of the century for different global warming levels (GWL, 1.5, 2 and 3 °C) assuming present flood protection based on a large ensemble of climate projections and long-term socioeconomic projections for the European Union (EU). The results are presented below. These derive quite modest BCRs.



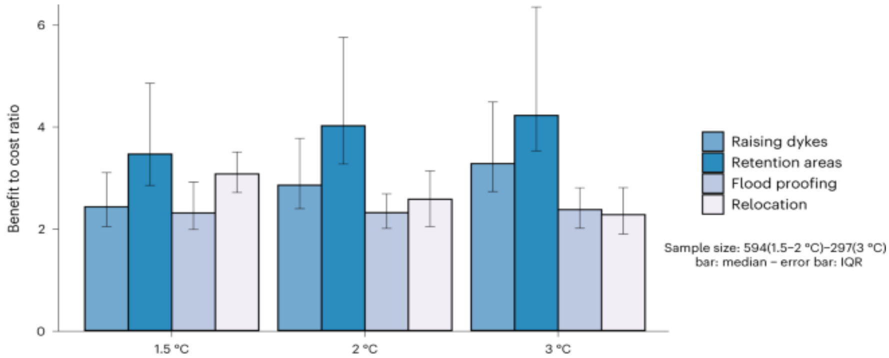


Figure 23. *Future undiscounted economic damages (top) for the year 2100, calculated under a no-adaptation scenario and optimizing each of the four adaptation strategies. (bottom), The benefit-to-cost ratio calculated from total discounted benefits and costs over the period 2020–2100.*

The adaptation scenarios are based on the application of a single type of measure. However, they suggest that 'hybrid' strategies, with different measures working together and optimized at the level of river basins may be the best strategies to maximize local benefits and minimize drawbacks of each measure. The authors suggest, for instance, that it is advisable to use dykes to protect against frequent low-magnitude events and detention systems to mitigate extreme flood peaks.

There are some studies on more specific local options. There is now a reasonable evidence base on the costs and benefits of property resilience and resistance measures for households (Wood Plc 2019). This found that a number of flood resilience and resistance measures could be considered no-regret adaptation measures (i.e., a benefit to cost ratio of greater than one in cases where there is a greater than 1% chance of Annual Exceedance Probability, AEP). In general, this literature reports that all measures are more expensive if retrofitted rather than installed in new builds. For resistance measures, the difference between costs of retrofitting vs. incorporating into new builds are more modest. However, the applicability of each of these measures depends on the type of flooding (recurrence and depth), as this alters the relative cost-effectiveness (and benefit to cost ratio

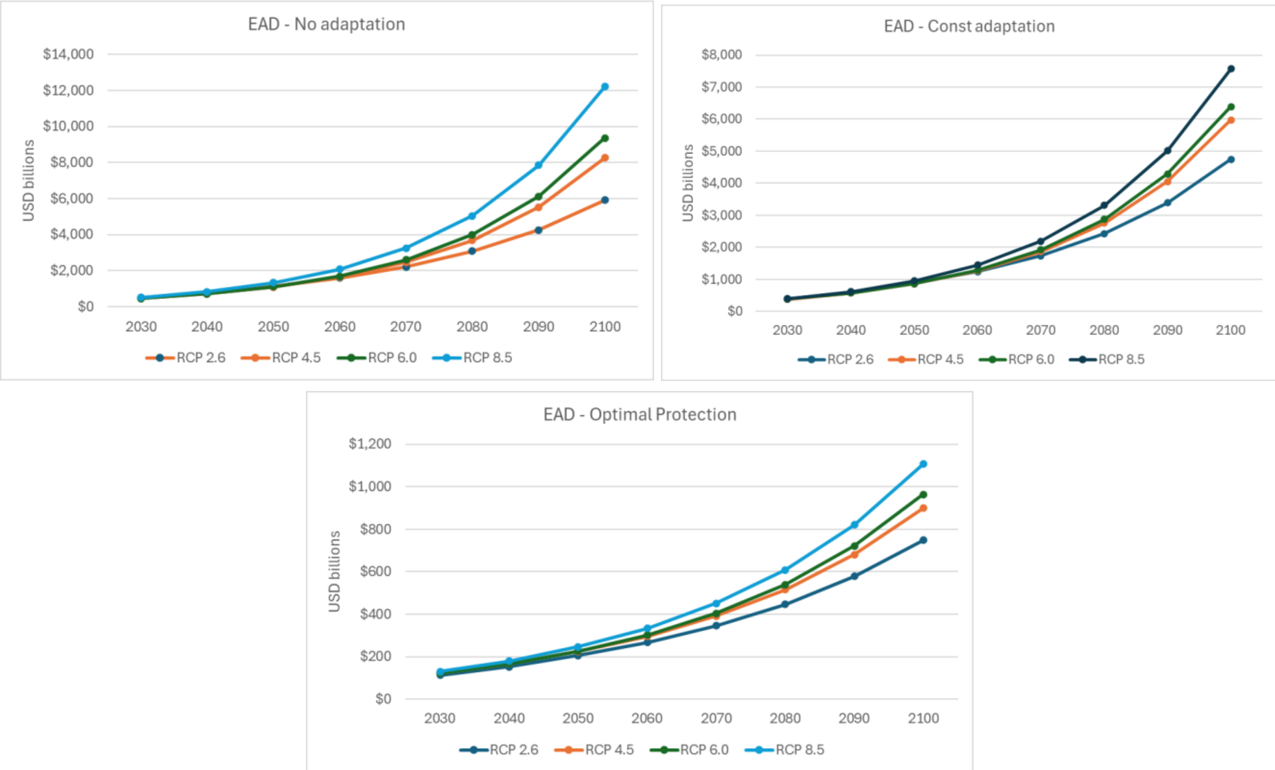
There is also information on the costs and benefits of green infrastructure and its potential for flood management. Measures can have positive BCRs provided that all benefits are valued, including non-market ecosystem service benefits (especially recreational benefits). There are some benefit to cost ratios of green flood resilience, notably sustainable drainage systems in the literature. Ossa-Moreno et al. 2017 assessed five SuDS schemes, with BCRs ranging between 0.9:1 and 1.8:1. It is noted there are also some economic studies of larger nature-based solutions for flood management, for schemes across Europe (ECONADAPT, 2017), and in the UK. These show that these schemes can have positive benefit to cost ratios, especially when all ecosystem services are included, but they also vary according to time periods and discount rates considered. There are also studies that report high BCRs for schemes that combine grey and green schemes (Aerts et al;. 2013: Aerts et al, 2014), reflecting the fact that NBS may be more appropriate for mitigating more frequent, low level flooding, rather than major extremes.

The discussion of limits of adaptation was also presented in the earlier section. It is likely that limits to adaptation for river flooding might be reached earlier than coastal flooding, because of the issues of space, i.e., building large infrastructure projects in urban areas is likely to involve high costs, especially as this may include extended land areas (and land purchase and/or resettlement). Likewise, large urban green schemes are also likely to involve large areas of land, and costs are likely to be very high – while upstream green schemes can reduce downstream impacts – there are still likely to be large downstream investments needed.

Global Functions

The functional form of GLOFRIS allows analysis of the EAD for river floods, and the costs and benefits of adaptation, and thus the two functions. However, there are again some challenges for deriving a function. Looking at the global data, there is an increase in EAD, and this is reduced with the adaptation constant protection and especially with the optimal scenarios. The reductions (effectiveness) are large, but not as large as the DIVA model, so quite high residual damages remain after adaptation.

Figure 24 - EAD (Global) for River Floods (WP2 output)



These data can be converted to damage – temperature functions. This show quite different results by RCP.

Figure 25 - EAD by decade (2020 - 2100) by RCP for the Constant Dyke Height scenario.

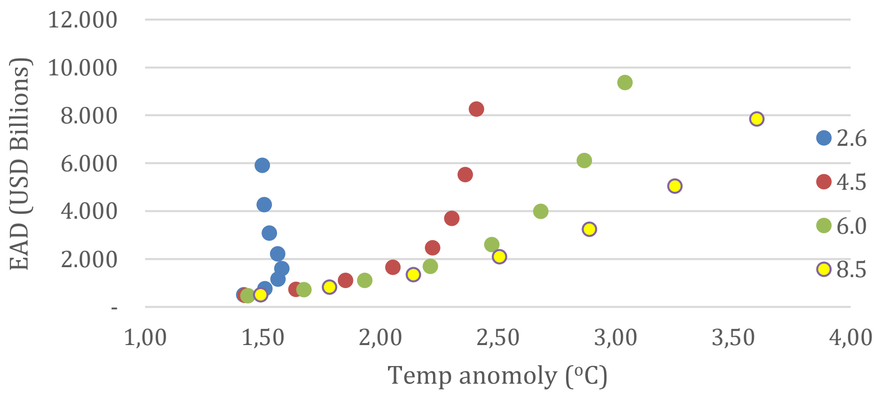


Figure 26 - EAD by decade (2020 - 2100) by RCP for the Constant Protection Standards scenario.

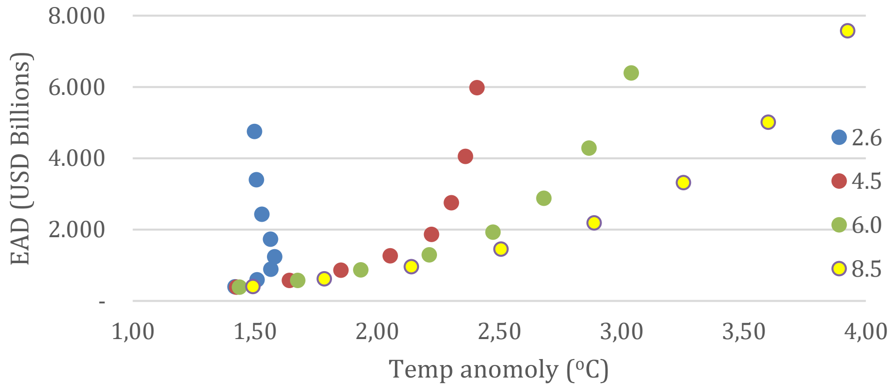
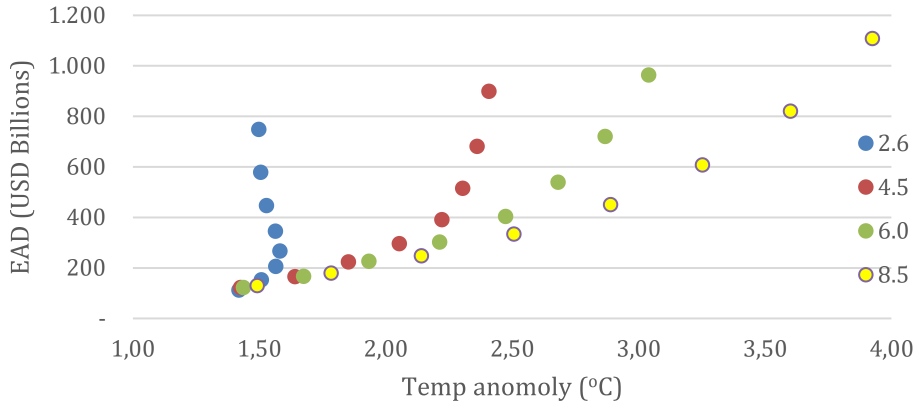
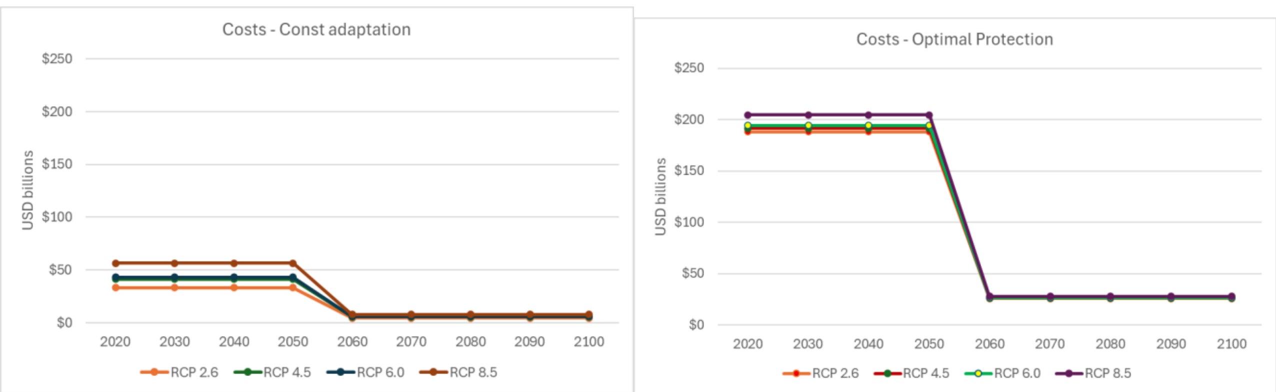


Figure 27 - EAD by decade (2020 - 2100) by RCP for the Optimal Protection Standards scenario.



However, because of the way the GLOFRIS model is set up for adaptation, capital costs are limited to the first 30 years, to hit a predefined level of protection in 2080s. After 2050, maintenance costs only are included. This leads to a sharp drop off in adaptation costs after the initial investment period, shown for the two adaptation scenarios below.

Figure 28. Adaptation Costs (Global) for River Floods



This means that it is not possible to plot benefits (avoided EAD) against costs over the century by decade by RCP (or by global warming levels, for temperature) as for DIVA. Instead, a different approach has been used to look at effectiveness of adaptation, narrowly defined here as the amount of damage avoided per dollar spent on adaptation.

The function is based on GLOFRIS estimates of the adaptation costs and expected annual damages (EAD) associated with riverine flooding between 2020 and 2100, i.e. over the entire period, rather than the decadal analysis as with DIVA above.

As with the DIVA analysis above, in order to isolate the effectiveness of adaptation, this analysis would, ideally, compare scenarios which only differed in the intensity of adaptation measures. In this way, differences in damages avoided between scenarios could be attributed solely to a change in this intensity rather than differences in the adaptation strategy. However, again the GLOFRIS analysis has used different adaptation decision paradigms (constant versus optimal). This also leads to the same issues as with DIVA. For example, the EAD constant scenario will involve high costs but will involve some protection for all areas, while the optimal protection scenario, by design, only allows for investment which makes economic sense and will have a relatively high amount of damage avoided per dollar spent, but will mean higher residual damage in some locations.

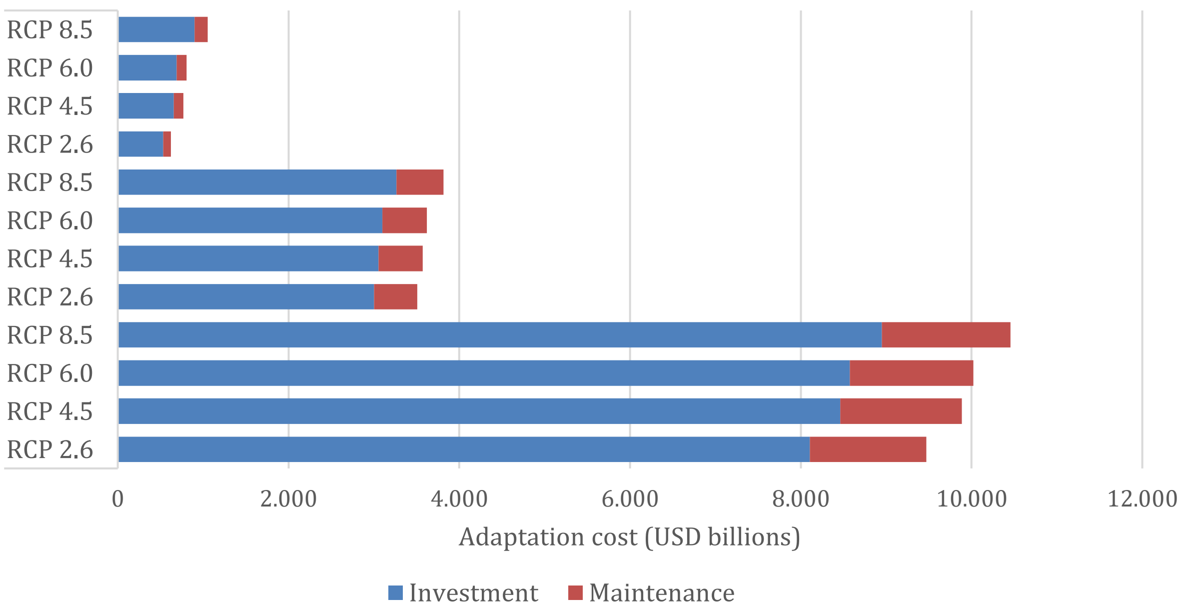
Data

The adaptation cost data provided by the GLOFRIS model is in the format of a present value (PV) of the *additional* investment and maintenance costs between 2020 and 2100 for a given adaptation scenario relative to the no adaptation (constant dyke height) scenario, though capital investments are constrained to the first thirty years. The model also estimates the PV of the damage avoided in each adaptation scenario relative to the no adaptation (constant dyke height) scenario. For this analysis, country level data was aggregated to the global level.

The figure below displays the PVs of the additional global costs of adaptation for each scenario and for each RCP over the period. In all scenarios, higher RCPs are associated with higher adaptation costs and maintenance costs make up approximately 14% of the total PV of additional costs. Interestingly, this is a much lower level of maintenance costs than for DIVA. Additional adaptation costs are lowest in the constant protection standards scenario at between $600-$1,100 billion. Moving from constant protection standards to optimal protection standards would require 4-6 times as much additional adaptation spending as for constant protection standards, depending on the RCP. Maintaining EAD at current levels would require 10-15 times as much additional spending as for constant standards, depending on the RCP.

This also shows that the results from GLOFRIS are different to DIVA. In the analysis above, the optimal solution is associated with the highest costs – whereas in DIVA – it is associated with the lowest costs. It is believed this is due to slight differences in the optimal specification, not least because GLOFRIS optimises over the entire investment period (to the 2080s).

Figure 29 - Present Value (PV) of adaptation costs (2020-2100) by scenario and RCP split into investment and maintenance costs, for baseline (top) constant protection (centre) and optimal (bottom)

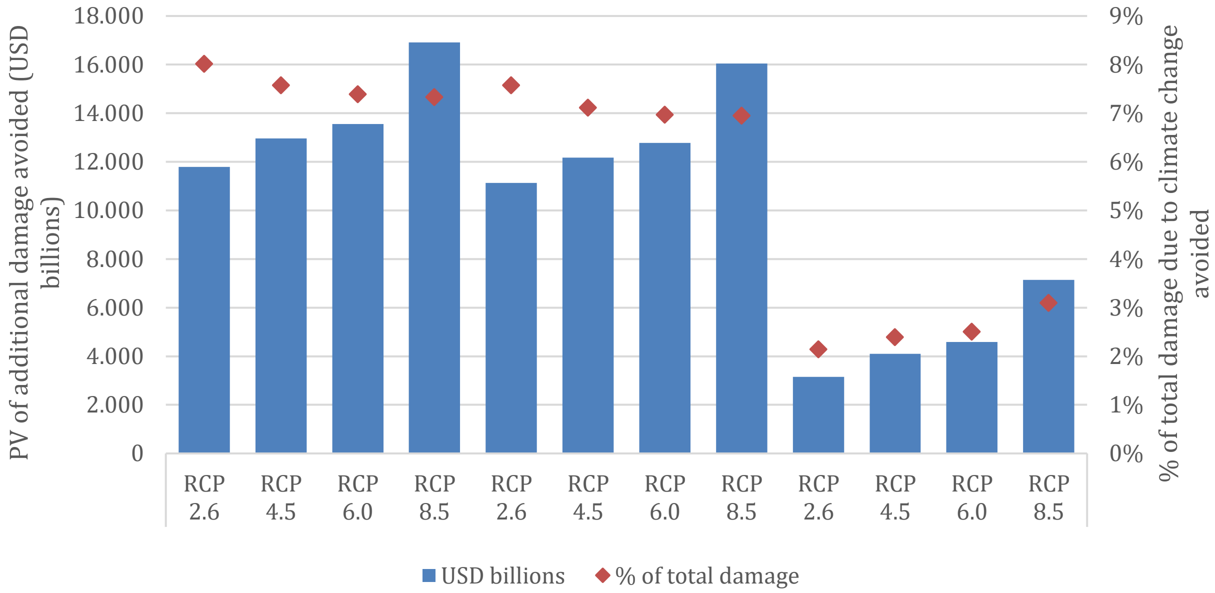


The figure below sets out the PVs of the additional damages avoided for each scenario and for each RCP over the period. Damage avoided is presented in USD and also as a share of the total expected damages due to climate change, in absence of adaptation. Converting damage avoided into a share of total potential damages provides additional information around how the damages avoided relate to the residual damages which will still be experienced, despite adaptation.

Damage avoided is greatest for the constant scenario but only by a very small margin relative to the optimal protection scenario. The protection constant scenario leads to only 27%-45% as much damage being avoided as in the other two scenarios, depending on the RCP.

However, one implication of moving from EAD to total damage, is that the effectiveness of risk reduction changes. When expressed as EAD, GLOFRIS calculates reasonable reductions for the constant but high (order or magnitude) reductions for the optimal scenario (see Figure 24). However, the move to total damage moves to a different metric using the entire probability loss curve, and this reduces the total damage less (see discussion below).

Figure 30 - Present Value (PV) of avoided damages (2020-2100) by scenario and RCP in USD billions and as a percentage of total damages due to climate change with no additional adaptation



Bringing the data displayed above together, it is possible show how the additional adaptation costs relate to damage avoided, in USD and as a percentage of total expected damages due to climate change without adaptation respectively.

In both figures, one can see that the variation between RCPs is less marked than the variation between scenarios. The four data points for constant protection standards are bunched near to the origin, with low costs and low damages avoided. The constant data is bunched to the far right of the chart, with relatively high costs and relatively high damages avoided. Finally, the optimal protection standards data is bunched in between with moderate costs, but still relatively high damages avoided. Again this highlights that the use of different adaptation paradigms/ objectives leads to different damage functions.

Figure 31 – Total damage avoided (USD) vs Additional adaptation costs by RCP for the three adaptation scenarios relative to the constant dyke height scenario. From left to right, the 3 data groupings relate to the constant protection standards, optimal protection standards and constant scenarios respectively.

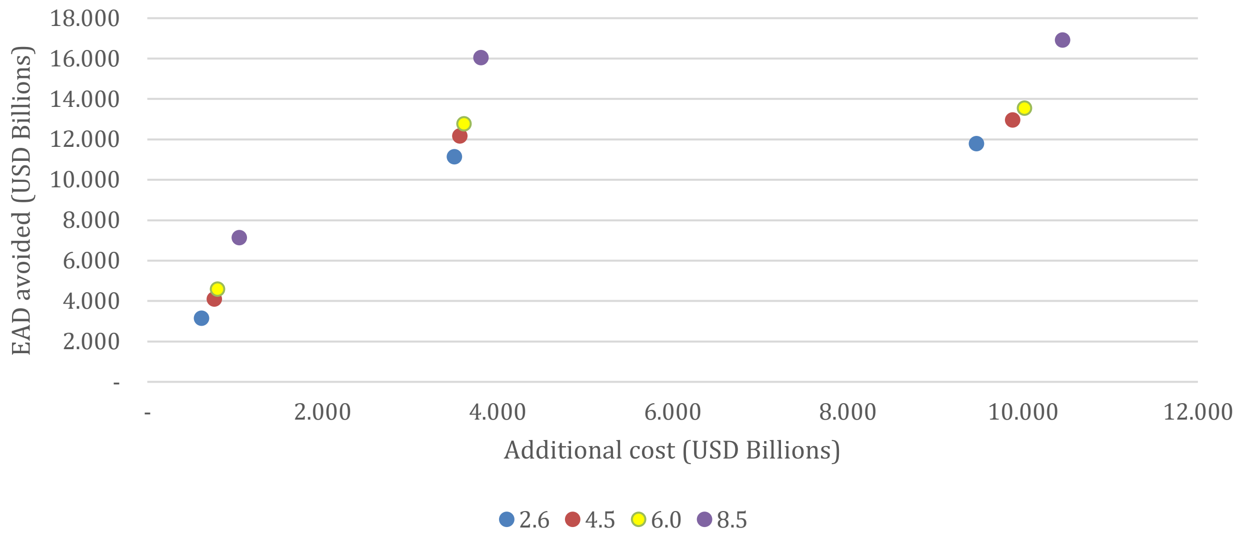
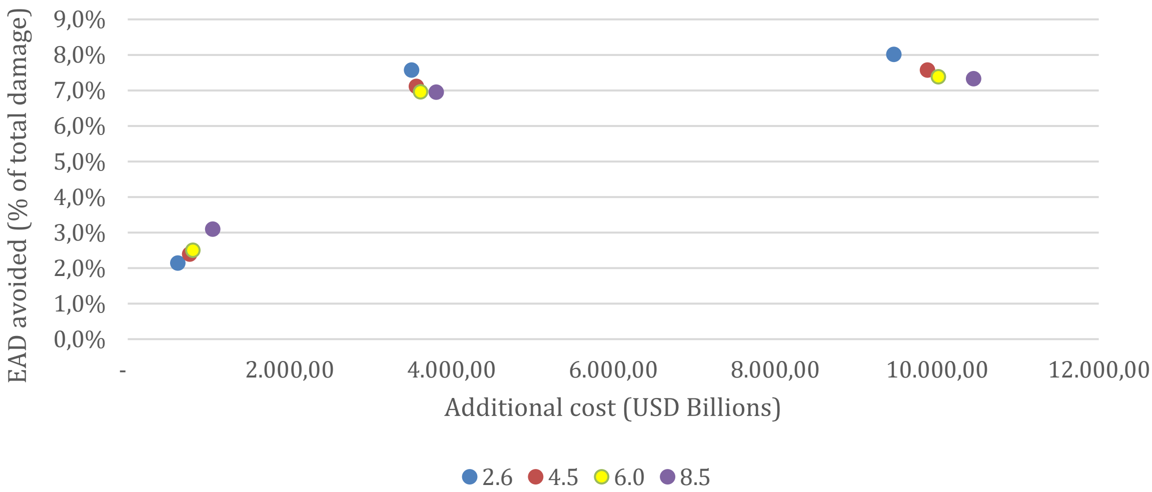


Figure 32 – Total damage avoided (% of total damage) vs Additional adaptation costs by RCP for the three adaptation scenarios relative to the constant dyke height scenario. From left to right, the 3 data groupings relate to the constant protection standards, optimal protection standards and constant scenarios respectively.



The relationship between additional costs and additional damage avoided looks to be consistent when damage is measured in USD or as a share of total potential damage due to climate change without adaptation. While the analysis is based on different adaptation decision paradigms, the figures do suggest that, by either measure, there could be diminishing returns to adaptation with the marginal gains in damage avoided becoming far more expensive once around 8% of the total expected damage is avoided.

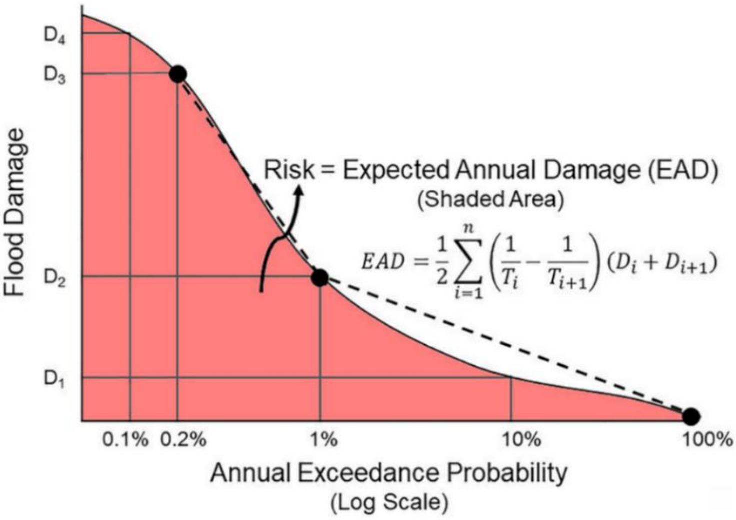
A value of 8% suggests that over 90% of the additional total damage due to climate change will still be residual damage. There are a number of factors which contribute to what, at first, might seem like a low level of protection.

Firstly, and most importantly, the GLOFRIS model includes events which have up to a 1 in 10,000 years probability. As one moves towards these more extreme, but rare, events, the damage associated with such an event becomes extremely large and so, even when adjusting for its low probability of occurrence, it still greatly impacts the total value due to climate change. Given the rarity of these events, it is not cost-efficient to protect against them and so they contribute to the total residual damage. Note that in reality, such events would be expected to be covered by insurance, which is particularly useful for low probability high impact events.

A second factor is the way that the GLOFRIS model treats damages in events which exceed the protection level in place. In these events, the model makes the simplifying assumption that the protection measures provide zero damage avoidance in these scenarios. This is likely to bias the residual damages estimate upwards as the protection infrastructure would still provide an impediment to flooding, even if dykes were topped.

The influence of both these factors on the relationship between residual damage and damage avoided can be explained as in the figure below which shows a stylised relationship between the damage associated with an event (y-axis) against the probability of that event (x-axis). As an illustrative example, if we take a scenario where we protect against flood events with up to a 10% annual exceedance probability (AEP), the only area in Figure 5 which would be avoided is the (approximate) triangle with the coordinates (10%, 0) , (10%, D_1) & (100%,0) – a small portion of the total damage. Even though a 10% AEP event is estimated to have damages at the level D_1, the damage represented by the rectangle (0, 0), (0, D_1), (10%, D_1), (10%, 0) is not protected against because the GLOFRIS model assumes that protection at 10% AEP level provides zero protection during any event with AEP < 10%.

Figure 33 - Stylised diagram of the relationship between total damage, event probability and event scale



Again, moving to the relationship which we are trying to model:

$$Damage\_avoided = f(AC)$$

Where AC is the additional adaptation cost relative to the no adaptation scenario. It was determined that the most appropriate units for damage avoided was as a percentage of total expected damages due to climate change in absence of adaptation. This provides a more intuitive interpretation, particularly when considering limits to adaptation.

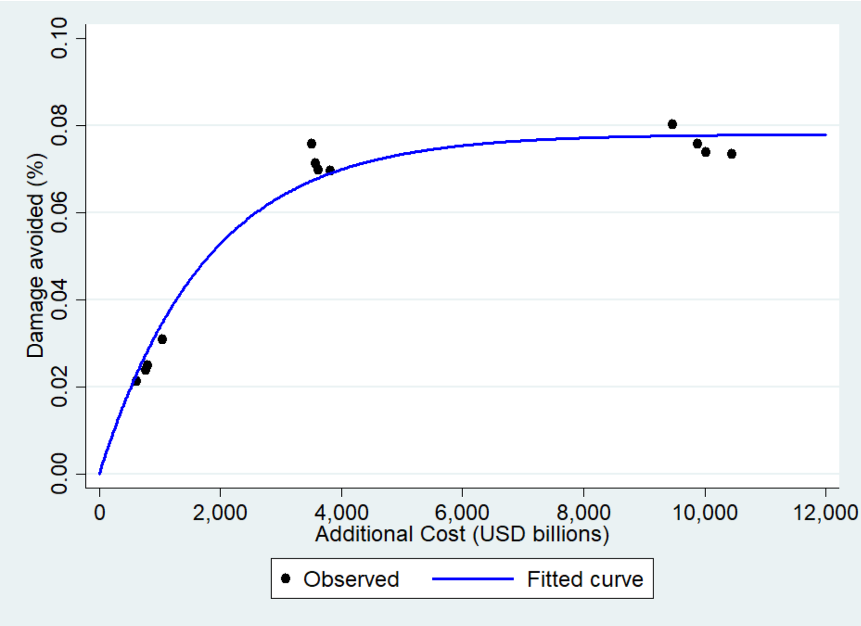
In a context with limited data points, as here, there is a decision to be made as to which functional form would be most appropriate. A negative exponential saturation function was chosen because it provides a consistent representation of flood protection: rapid initial reductions in risk, diminishing marginal effectiveness, and an upper limit to the achievable reduction in damages.

$$damage\_avoided = L(1 - e^{-\beta AC})$$

Where L is the limit to adaptation and β is the curvature parameter, estimated by the regression.

Another choice that was made was to let the model estimate the parameter L. An alternative would be to impose a limit to adaptation from the literature but, given the strong asymptotic shape of the data, this was deemed unnecessary.

Figure 34 - Fitted curve of the function of the effectiveness of adaptation in GLOFRIS



Using non-linear regression analysis, the following function was estimated:

$$DamageD_{avoided} = 0.078(1 - e^{-0.00057AC})$$

The estimation suggests a limit to adaptation (L) of 8% of total damage due to climate change. This seems low, but can represent the large amounts of damage that arise major high impact low probability events.

At face value, the regression results suggest a strong fit to the data. The coefficients both have t-scores over 10 and the adjusted R^2 is 0.995. However, with only 12 observations, it is inherently difficult to assess the adequacy of a nonlinear model as there is insufficient variation to expose misspecification. In small samples, the model can interpolate the data closely regardless of whether the underlying functional form is correct, and the parameter estimates may appear precise even when identification is weak. For these reasons, the statistical results should be interpreted with caution and evaluated alongside the theoretical justification for the chosen functional form rather than relied upon as standalone indicators of model quality.

It is also noted that the analysis of DIVA focused on the EAD metric, and thus this different approach introduces some inconsistencies.

3.5 Agriculture

Introduction

Climate change has the potential to affect the agriculture sector (Bezner Kerr et al. 2022) both negatively (e.g. from changes in temperature, rainfall and extremes affecting suitability and productivity) and positively (e.g. from carbon dioxide [CO2] fertilization and extended seasons in some locations). These will include direct effects from gradual climate change and extreme events, but also indirect effects, such as those caused by changes in prevalence of pests and diseases. In turn, these changes will affect yields and therefore production, consumption, prices, trade and land-use decisions. There is a wide range of potential adaptation options for addressing these risks (Bezner Kerr et al. 2022), ranging from farm-level management and climate-smart agriculture to national policies and strategies. Full details of the analysis and the recent updates to the model are set out in Deliverable 2.2 Impacts on food, energy, and water).

Adjusting adaptation costs in the agriculture sector for inflation

The analysis here uses the output from IIASA's Global Biosphere Management Model (GLOBIOM) (Havlik et al., 2011) regarding investment (expansion, efficiency & upgrade) and maintenance adaptation costs (link). This was set out in D2.2.

Data description:

- GLOBIOM's raw data is provided in 2000 USD nominal.
- The data is decennial from 2030 to 2070.
- Investment costs (expansion, efficiency and upgrade) and maintenance costs are treated separately.
- The data is provided at the country level for 44 countries and at the regional level for a further 115 countries.
- There are three RCPs - 2.6, 4.5 & 7.0. All are combined with SSP2.
- There are two mitigation scenarios. No mitigation (reference) and mitigation where mitigation efforts are in line with the RCP associated with the scenario.
- There are three adaptation scenarios: ref, low adaptation and high adaptation.

Methodology

Adjusting these values to the price years of focus was undertaken using the same approach as previous sections. For this analysis, working with the GLOBIOM outputs, the 115 countries where costs are provided at the regional level, regional costs were distributed between the countries which make up that region on a pro-rata basis in line with the current (2023) GVA in their agriculture sector (constant USD). The data set now has country level data for 159 countries.

Impacts and Adaptation

The use of the GLOBIOM model output to derive functions is much more complicated than for coastal and river flooding above. Traditionally, analysis of climate change impacts on agriculture uses biophysical crop models, and the resulting changes in yield are estimated using market prices. This then allows the consideration of adaptation options and their benefits in reducing these impacts, in a way that is similar to the coastal and river flood analysis.

However, GLOBIOM is an integrated partial equilibrium model, and it takes outputs form detailed crop, forest, vegetation, hydrological, and livestock models, and puts these within an integrated economic land use framework that looks at relative profitability, market prices, trade flows, and land-use decisions.

The analysis includes CO_2 fertilisation which has the effect of significantly reducing future impacts. The analysis. is further complicated because the model includes carbon prices for each scenario, with specific prices to match the RCP scenario. This means the effects seen are a combination of mitigation and adaptation.

The framework can consider adaptation, and in GLOBIOM both autonomous and planned adaptation are represented. Producers *autonomously* adapt to changing climate and market conditions by adjusting their crop choices and management practices based on expected yields, market prices, and trade competitiveness. The *planned* adaptation options include the increase of agricultural research and development to raise crop yields under future possible climate change.

The ACCREU project also assessed the potential for irrigation as an additional adaptation measure to climate change, including its costs and benefits. For Europe, this assessed three alternative scenarios.

- Low adaptation: irrigation expansion is based on historical trends from 2000-2020 and limited to expansion of only 10% in future periods and there is limited support for agricultural R&D and upkeep and maintenance of existing irrigation infrastructure.

- Central (reference): irrigation is limited to 30% expansion in future periods and there is moderate support for improving efficiency of irrigation systems and support for agriculture R&D.

- High adaptation: high expansion is allowed and there is high support for irrigation efficiency improvements and upgrading existing systems and for agricultural R&D.

Table 7 Adaptation options included in GLOBIOM for the Agriculture sector see D2.3 for references

Adaptation options	Short description	Autonomous/ planned	How included in GLBIOM
Ag. R&D	Investments to improving crop resilience and increase crop yields	Planned	**High adaptation:** High levels of R&D (0.8% p.a growth-SSP1 yields) **Reference adaptation:** Medium R&D (0.7% p.a growth-SSP2 yields) **Low adaptation:** Low levels of Agricultural R&D (0.5% p.a growth-SSP3)
Irrigation	Investments to expand sustainable irrigation to ensuring proper growth and adequate water supply when rainfall is insufficient. Investments can include large scale public infrastructure costs to improve water availability, on-farm system expansion costs, system upgrades and rehabilitation to improve water use efficiency, microtanks to provide sustainable water storage,	Planned	**High adaptation:** Reduced water supply costs, 5% increase in the irrigation efficiency per decade, improved local water supply for irrigation **Reference:** 1.5% increase in the water use efficiency per decade (Hanasaki et al., 2013) **Low adaptation:** 3% decrease per decade due to poor maintenance in systems and conveyance losses (Howell, 2005; Hsiao et al., 2007)
International trade	The model employs the spatial equilibrium approach to international trade and assumes homogenous goods (considering initial trade patterns).	Autonomous and planned	Decrease in the trade costs between regions
Change in agricultural management: agricultural land expansion and agricultural land conversion/system transition	Land expands depending on the relative profitability of converting land to different use types and land expansion constraint. Agricultural land will convert to a higher yielding or more intense system (i.e., from rainfed to irrigated or from extensive livestock to intensive/mixed systems livestock) depending on the relative profitability of converting land to different use types	Autonomous	**High adaptation:** Irrigation expansion limited to historical trends from 2000-2020 and allowed to expand beyond the observed historical trends for future years (i.e., 2000-2020) **Reference:** Irrigation expansion limited to historical trends from 2000-2020 then limited to 30% beyond the previous period irrigated area totals in future periods **Low adaptation:** Irrigation expansion limited to historical trends from 2000-2020 and then limited to expand only 10% beyond the previous period irrigated area totals in future periods
Change in agricultural management: crop choice	Cropland will switch to higher yielding crops depending on the relative profitability (taking into account the climate effect on crop productivity)	Autonomous	Crop choice is fully autonomous across all scenarios

Note unlike other sectors, for adaptation, the analysis of low, medium and high adaptation was **only** included for Europe. For the rest of the world, only the central reference scenario was provided. This means it is not possible to derive a global adaptation function, because there is insufficient data points.

The irrigation analysis assumes that the capital investment is provided by the public sector. This also means that they are not included in the producer cost optimization. Farmers are responsible for the operations and maintenance of the systems, which are included in the model as production costs. Additionally, farmers are responsible for paying per unit cost of water used for irrigation. The costs associated with the adaptation costs are divided into expansion costs, as well as enhancement costs (of existing irrigation).

Review of the literature to provide additional evidence

There is a large literature on agricultural adaptation, which includes a large number of different modelling and assessment approaches: for an overview see Watkiss and Hunt (2018).

Looking at specific studies there are a suite of different options. A first set are standard agronomic options such as changing sowing dates, planting new cultivars or varieties, or changing management practices. These are often already implemented as reactive measures - as farmers experience climatic change, they adjust. These deliver high economic benefits, though the effectiveness is highly variable, and differs for crops and regions. Note that in the GLOBIOM model, these actions are assumed to have no costs – but in practice this is not the case – and there are direct costs, labour costs, etc., involved.

A further set of options relate to research and development, which is included in GLOBIOM, but again not costed. There are studies of the potential adaptation costs and benefits of enhanced agricultural R&D, notably (Rosegrant et al. 2023) for the global south (see also Sulser et al., 2021). This reports that increased agriculture R&D spending -– starting at 2 $billion/year in the global south and increasing - would deliver a BCR of 33:1. This is predicated on the yield improvements, and also does not fully consider the costs of implementation e.g., farmer costs to adopt new varieties, advice and extension, etc. (which accounts for the high benefits).

This research can include climate tolerant or climate resilient varieties (seeds). However, in order for these to have impact, there is need to scale-up, with a broader set of interventions, for uptake into seed multiplication and distribution systems. There are economic studies of the benefits of resilient seeds, but these are highly site specific, though general show modest BCRs (e.g. Prasad et al., 2014: Khatri-Chhetri et al., 2017) . However, realisation of benefits requires raising awareness and capacity among farmers and seed multipliers, working with and incentivizing the private sector. (Acevedo et al., 2020)

There is a large evidence base on irrigation. This is included in global, regional and local analysis. In general terms the highest benefits are from rehabilitation and efficiency improvements of existing systems. There is debate, however, as to whether new irrigation should be considered an early low- or high regret option for agriculture, notably when viewed from the perspective of cross-sectoral water demand and up-front capital costs, and especially when introduced in areas of water scarcity. This can be addressed by taking irrigation forward as part of an integrated water resources management (IWRM) framework, considering supply and cross-sectoral demand under climate change, but this shift to allocation efficiency and the need for water charging often reduces the attractiveness of irrigation.

An alternative focus has been on farm level options that more explicitly address current climate risks (from climate variability and extremes) and build resilience for the future, i.e. climate smart agriculture (CSA). These are forms of sustainable agricultural land management (SALM) practices that improve soil water infiltration and holding capacity, as well as nutrient supply and soil biodiversity. They include options such as agroforestry and intercropping, soil and water conservation, reduced or zero tillage, and use of cover crops or crop residues. Actual benefits vary by practice and context, and values are extremely site and context specific (World Bank, 2019). Internationally, there is a body of evidence on the benefit to cost ratios of CSA, which find positive ratios. For example, ex ante analysis of 32 country-level projects (Ferrarase et al 2017) estimated a BCR of 2:1 on average, but with a range from 1:1 to 7:1. There is a large literature of specific interventions in specific regions (e.g., Mogaka et al, 2022: Akinyi et al, 2022; Adimassu et al., 2023: Abegaz et al., 2024), as well as some systematic reviews (Castle et al., 2021; Chen et la., 2022; Guja et al., 2025). Values are highly site-specific, reflected in large BCRs differences for similar interventions in different places, whilst benefits depend on whether non-market benefits are included. Returns are highly risk, context and site specific, and schemes can take time to deliver and involve opportunity costs for farmers thus they require support to scale up adoption. Broader definitions of CSA also exist in climate smart adaptation investment plans, based on appraisal. These report high BCRs (for examples, sett Bangladesh World Bank 2019b and Nepal, World Bank, 2021b), but these show that economic returns are higher than financial returns, due to the role of non-market benefits. These same techniques can be applied in developed country contexts, for example in the UK, CSA options were analysed by SRUC (2013) and Posthumus et al. (2015), reporting generally modest but positive BCRs, but lower financial returns.

Improved weather and climate services for agriculture are early no-regret adaptation options, with demonstrated high economic benefits by reducing current losses and damages to agriculture. These provide improved information and provide economic benefits to users though avoided negative losses or improved agricultural yields. However, to maximize these benefits, investment is needed across the whole information value chain – with enhanced monitoring, modelling, and forecasting, improved communication and reach, and through higher uptake and informed use of the information in decisions (Soares et al., 2018). These services provide high net economic benefits with benefit to cost ratios of 5:1 (ECONADAPT: 2017) though they can be much higher, with targeted seasonal forecasts >10:1 (WISER, 2017).

There is an emerging focus on precision agriculture, as well as digital platforms that indicate potential benefits, either through the improved application of inputs, crop management or irrigation (Wanyama et al., 2024).

The partial and general equilibrium models also include trade. Market-based responses can significantly reduce climate change impacts. However, further work is needed to investigate some of the assumptions that these include, which are thought likely to bias costs downwards. There is also a need to investigate the full implications of some of these shifts, both in terms of the domestic costs or risks of higher trade flows (taking into account of issues such as the effects on rural livelihoods, the wider environmental benefits of agriculture, the greater risks of food price shocks, etc.) and whether countries are willing to increase imports as an adaptation response - especially given that this is likely to lead to high residual damages, domestically.

These can be compared to the earlier reviews. Brandon et al (2024) identify 15 climate smart agriculture schemes, with BCRs from 1.3 to 5.7 (and an average of 3:1) but these are all ex ante appraisal and often include wider non-climate actions (e.g., general access to market or financial inclusion). Rexer and Sharma (2024) suggest that economically efficient measures are likely to include: reallocating farmland to crops less sensitive to local climate change and adjusting other margins of farm investments (Taraz 2017), reallocation to non-farm activities (Blakeslee et al. 2020), climate-resilient agricultural technologies e.g. flood-tolerant rice (Dar et al. 2013) and weather insurance, e.g. index-based rainfall insurance (Bertram-Huemmer 2017). However, as highlighted above, flood tolerant varieties often have low BCRs and are conditional on wide uptake, while index based insurance is likely to require subsidies and also has low potential to address changing trends, because of rising premiums.

Aggregate studies show a very wide range of adaptation costs. There are other estimates of the costs of adaptation in the literature (Baldos, Fuglie and Hertel 2020; Iizumi et al. 2020), some of which report significantly higher costs.

It is quite difficult to take this information and translate into information of relevance for the shape of damage functions here, because of the high site specificity and context, as well as what the potential limits of adaptation could be. There definitely strong biophysical limits for specific crops in specific areas, but which can be overcome with adaptation, noting this will shift over time, i.e., suitability will shift progressively over time. There are also limits to water availability, which are likely to constrain the adaptation option of irrigation. This is likely to lead to rising limits – which is shown in the global analysis with GLOBIOM below.

Global functions

While there are crop productivity losses from the EIPC analysis, which feed into analysis for the CGE models, there are no direct outputs available in monetary terms. Instead the losses caused by climate change which are used as a measure of damage are narrowly defined as the loss in economic surplus in the sector, where the economic surplus is the gross revenue minus costs.

The agricultural adaptation measures with separate cost outputs considered in GLOBIOM exclusively relate to irrigation. They cover the expanding, upgrading and improving the efficiency of irrigation infrastructure (see above). Additional costs of R&D, farm level action, and trade, while these will also involve costs, are not provided as costed outputs from the model.

As highlighted above, while there are three adaptation scenarios for Europe, there are only two global adaptation scenarios :

o Reference adaptation - irrigation expansion is based on historical trends from 2000-2020 and then limited to expand by only 30% in future periods.

o No adaptation.

There are two mitigation scenarios. No mitigation (reference) and mitigation where mitigation efforts (and carbon prices) are in line with the RCP associated with the scenario. The analysis of adaptation costs provides a separate of investment costs (expansion, efficiency and upgrade) and maintenance costs. The data is provided at the country level for 44 countries and at the regional level for a further 115 countries.

The analysis first shows the losses in producer surplus by adaptation scenario and RCP, relative to a no climate change counterfactual. Losses in the no adaptation scenario are far higher than with adaptation. By 2070, losses in the no adaptation scenario are 9 to 30 times larger than with adaptation, depending on the RCP.

Figure 35 - Impact by decade (2020 - 2070) by RCP for the no adaptation scenario.

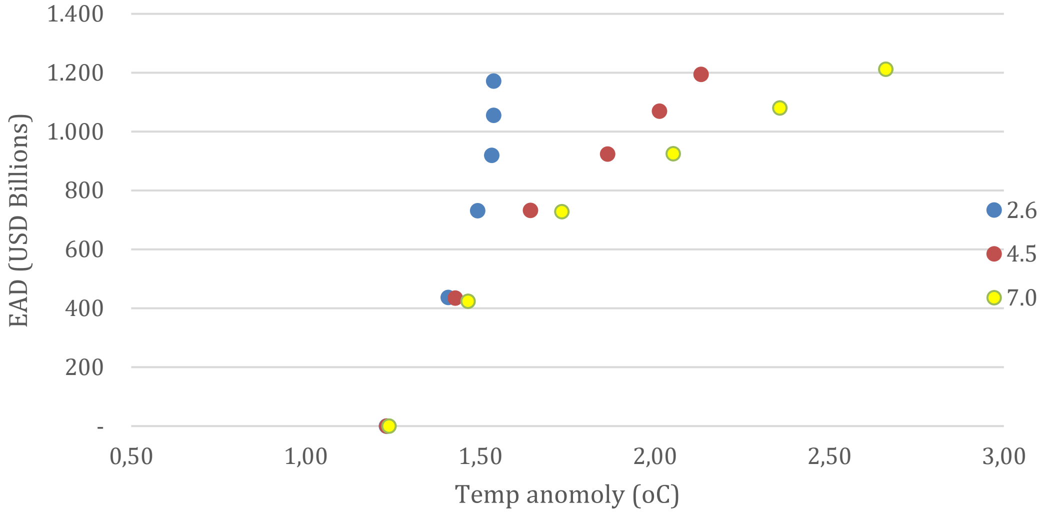
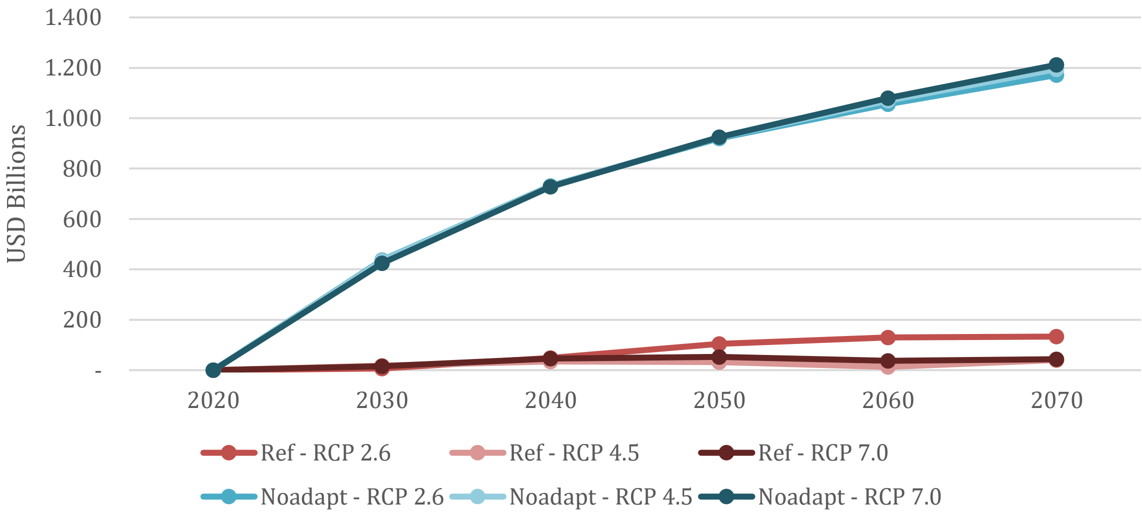
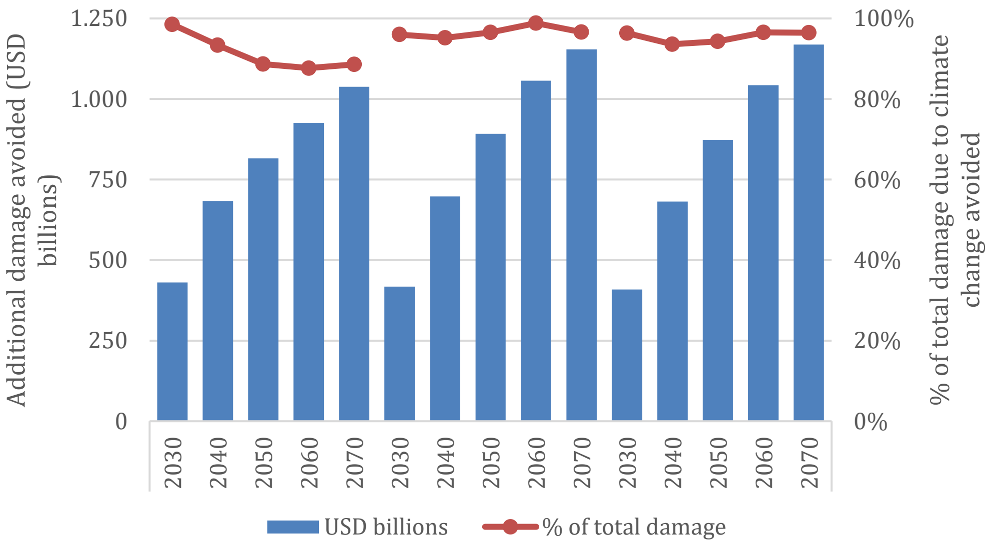


Figure 36 - Lost producer surplus (damage) due to climate change with and without adaptation by RCP



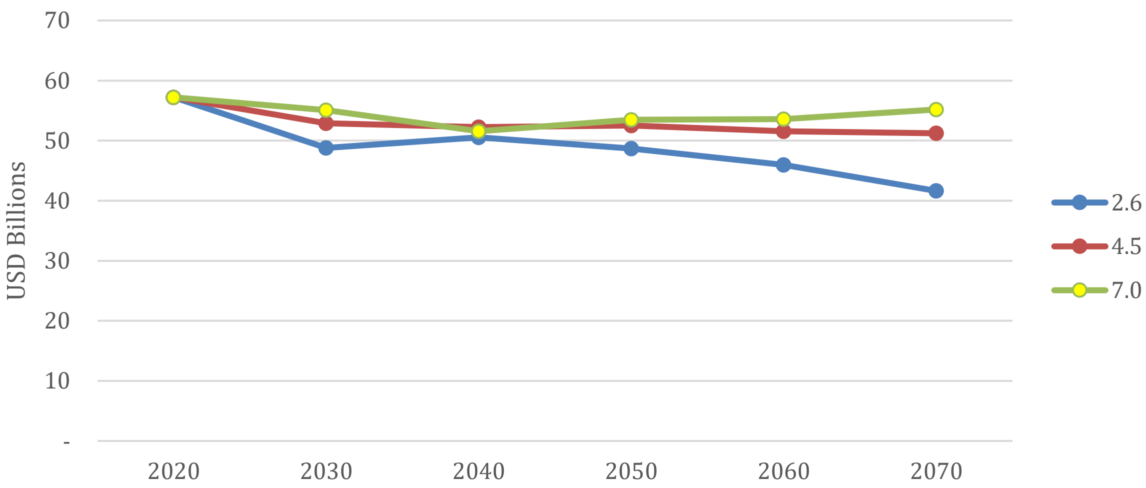
The figure below sets out the damages avoided with adaptation for each RCP which is defined as the loses without adaptation minus those with adaptation. Damage avoided is presented in USD and also as a share of the total expected damages due to climate change, in absence of adaptation. Converting damage avoided into a share of total potential damages provides additional information around how the damages avoided relate to the residual damages which will still be experienced, despite adaptation. Again, there is little variation between RCPs with adaptation leading to the avoidance of at least 88% of total potential damages due to climate change in all years and RCPs. This effectiveness value does seem high when compared to the literature review (for example Rexer and Sharm, 2024) estimate around half this level of effectiveness for agricultural adaptation.

Figure 37 - Damages avoided due to adaptation by RCP in USD billions and as a percentage of total damages due to climate change with no additional adaptation



The adaptation cost and damage data provided by the GLOBIOM model is in the format of decadal averages over the period 2020 to 2070. For this analysis, country and regional level data was aggregated to the global level.

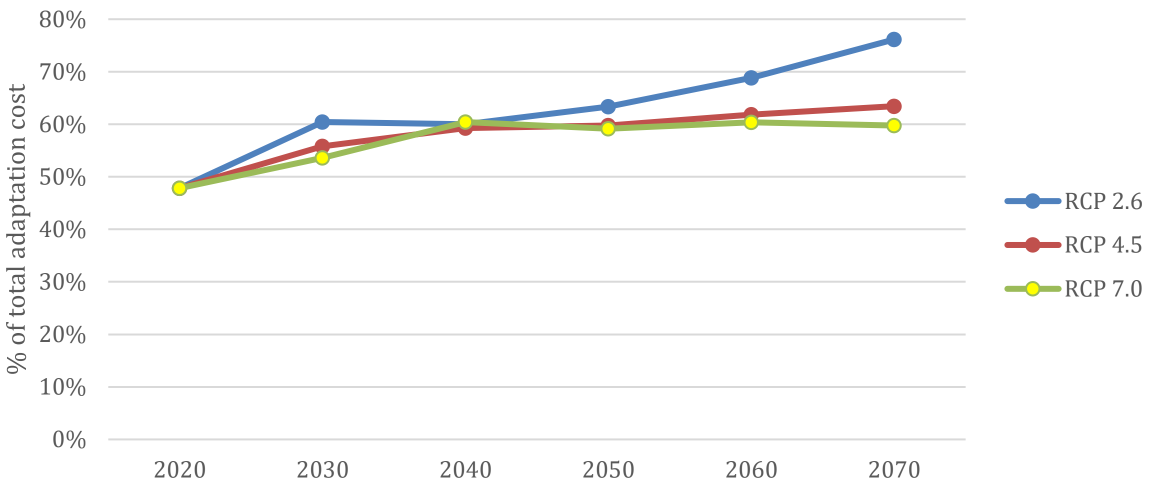
Figure 38 - Reference adaptation costs over time by RCP



The figure below displays the annual adaptation costs over time for each RCP over the period. There is relatively little variation over time and between RCPs. This lack of variation over time is due to the modelling set up in GLOBIOM which optimises for economic surplus. In this case, the optimal strategy is to frontload investment costs. This is supported by the figure below which shows that, across RCPs, maintenance costs initially make up only around 50% of total costs in 2020 but rise to 60-76% by 2070. The corollary is that investment costs make up a decreasing share of total spending over time.

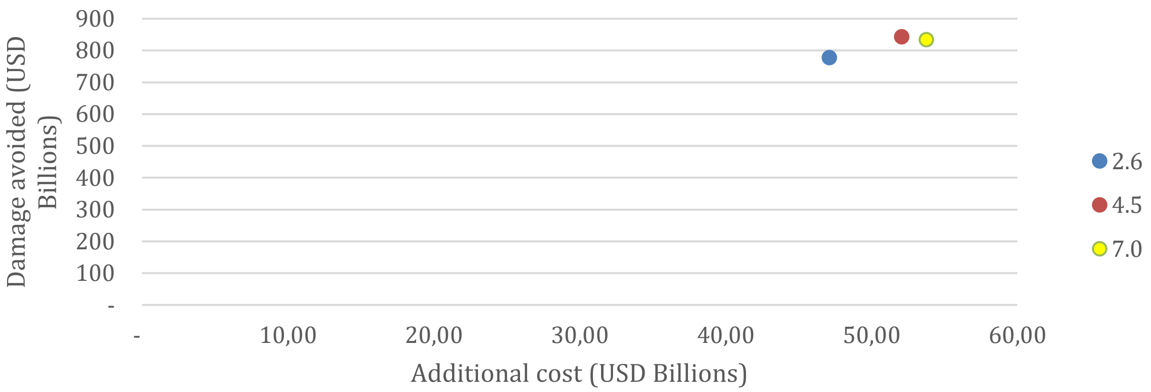
The lack of variation in adaptation costs between RCPs follows from the lack of variation between the anticipated economic losses due to climate change in the agricultural sector in the RCPs according to GLOBIOM. With similar anticipated damage curves for each RCP, the modelled adaptation responses also end up being similar.

Figure 39 - Percentage of total reference adaptation costs which are maintenance costs over time by RCP



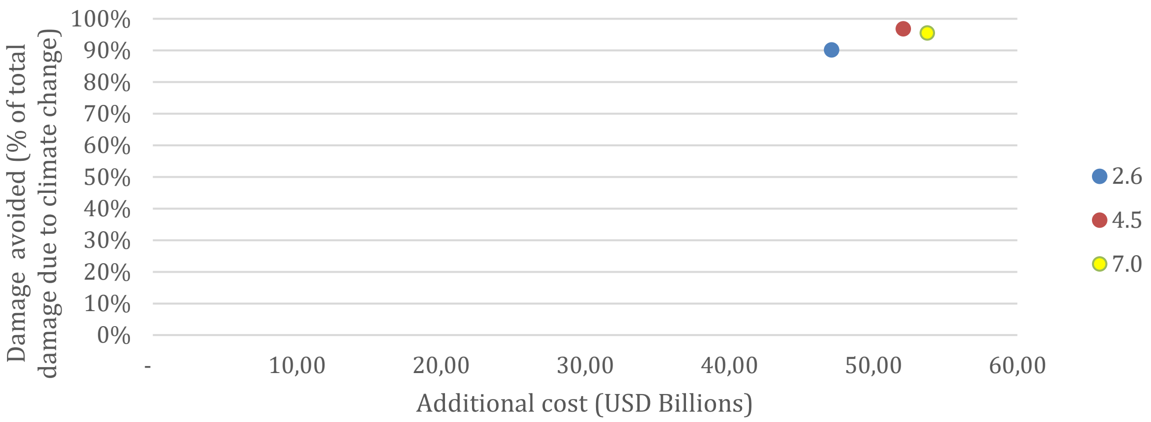
Given GLOBIOM's approach to smoothing adaptation costs over time, costs in a given year are not determined by expected damage in that year but rather the curve of expected damage over the 50-year period. With this in mind, it was deemed that, for this function estimation exercise, it was most logical to compare average annual costs over the 2020 to 2070 period with average annual damage avoided over the same period. As is shown in Figure 5, the downside of this approach is that 15 data points (5 decades x 3 RCPs) becomes 3 (1 per RCP).

Figure 40 – Annual damage avoided (USD) vs Additional adaptation costs by RCP for the reference adaptation scenario relative to the no adaptation scenario.



The data points provided by the model only account for a very small segment of the total adaptation possibilities. They don't provide information on the relationship between damage avoided and adaptation costs when average annual spending is below $45 billion or above $55 billion.

Figure 41 - Damage avoided (% of total damage) vs Additional adaptation costs by RCP for the reference adaptation scenario relative to the no adaptation scenario.



The same issue arises when damage avoided is measured as a percentage of total potential damage due to climate change. What is striking in is that the irrigation adaptation measures lead to the avoidance of over 90% of the total damages due to climate change in absence of adaptation. This implies that only <10% of total possible damages remain as residual damage in GLOBIOM's adaptation scenario. As highlighted earlier, this is high compared to country specific studies, which tend to have modest effectiveness and BCRs that tend to be 2:1 to 5: 1, and thus are much lower.

There are a number of factors which contribute to what, at first, might seem like a very high level of protection and high BCRs.

First, the model assumes that there no friction regarding the reallocation of land – farmers are able to switch crops and/or change land-use quite easily if it is deemed more profitable to do so. This means that there is a lot of no regret action available from an adaptation perspective. In reality, crop switching requires new information and investment in new technologies, a period of land adaptation as well as other transaction costs. Furthermore, food security concerns may lead to governments providing economically irrational subsidies to support the production of a given low yield crop and thus artificially keeping farmers from switching away from or abandoning the crop.

Another factor is the complex relationship between climate change and agricultural productivity. Broadly, climate change will decrease agricultural productivity in certain regions and increase it in others, and this effect is amplified by CO_2 fertilisation effects. In a frictionless world, moving production from one region to another can mitigate loses at a global level. However, this does not account for global (or national) policies, notably around food security, and other frictions which make this challenging.

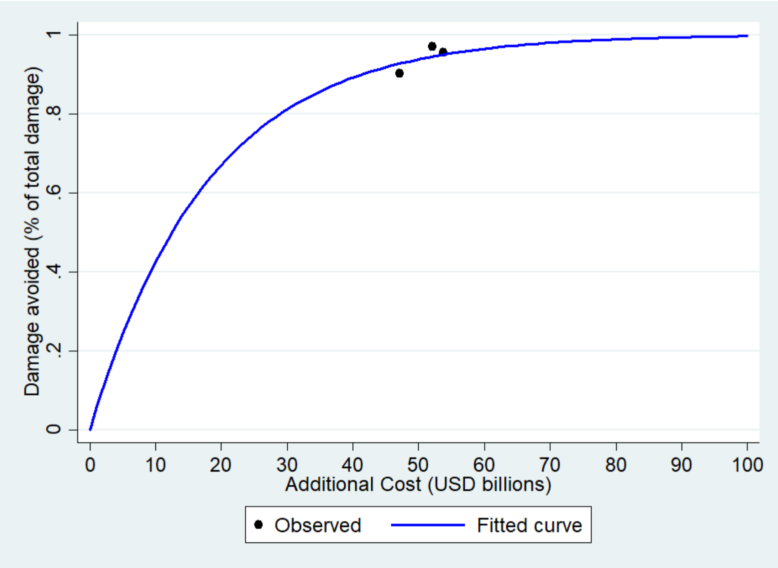
Finally, the definition of damage in this exercise is limited to the loss of produce surplus. It does not take into account consumer loses, loses of biodiversity or implications for inequality for example. One could hypothesise that the irrigation adaptation measures put forward here may be less effective at avoiding damage along these dimensions.

Functions

In a context with limited data points, there is very high uncertainty around the functional form that would be most appropriate to apply. Again, a negative exponential saturation function was chosen because it provides a consistent representation of adaptation: rapid initial reductions in risk, diminishing marginal effectiveness, and an upper limit to the achievable reduction in damages.

Another choice that was made was to impose a limit to adaptation (L) of 100%. An alternative would be to allow the model to estimate, but with just 3 data points, this is problematic. The limit of 100% is arbitrary as, especially in the context of the GLOBIOM framework, adaptation measures could even increase producer surplus relative to a no climate change scenario.

Figure 42 - Fitted curve of the function of the effectiveness of adaptation in GLOBIOM



Using non-linear regression analysis, the following function was estimated:

$$Damage_{\ avoided} = 100\% * (1 - e^{-0.055AC})$$

At face value, the regression results suggest a strong fit to the data. The coefficient has a t-score over 10 and the adjusted R^2 is 0.999. However, with only 3 observations, it is impossible to assess the representativeness of a nonlinear model. In such small samples, the model can interpolate the data closely regardless of whether the underlying functional form is correct, and the parameter estimates may appear precise even when identification is weak. For these reasons, the statistical results should be interpreted with caution

It is also emphasized that compared to more applied studies, the effectiveness and BCRs from GLOBIOM are extremely high. This has the potential effect of assuming adaptation will be much more effective and efficient than is likely to be the case.

3.6 Labour / Energy

Introduction

The ACCREU project has looked at two interrelated issues. Higher temperatures and extreme heat have impacts on the labour force. This includes potential reduced working time (from reduced working hours, affecting labour supply) as well as reduced worker output (from reduced labour productivity per hour worked), though there are also potential benefits for some colder regions or countries (Dasgupta et al., 2024). These effects affect high exposure outdoor work (e.g., agriculture), as well as low exposure work that takes place inside or in shaded areas outdoors (e.g., manufacturing), though the latter is influenced by air conditioning.

Climate change will also affect future energy use, increasing summer cooling demand but reducing winter heating needs (De Cian and, Sue Wing, 2019). These responses are often autonomous and can be considered as an impact or an adaptation. For heat, adaptation can help to maintain desirable levels of temperatures in homes and businesses with mechanical cooling (air conditioning) or passive ventilation and measures. Urban temperatures can also be reduced with green infrastructure or urban planning.

The analysis therefore considered the additional use of air conditioning and its role in reducing the impacts on labour for commercial and industrial buildings, as well as below for residential buildings for health. This builds on the analysis in D2.3 and D2.3

Adjusting adaptation costs in the energy sector for inflation

Adaptation cost estimates were associated with increased energy demand for air conditioning.

Data description:

- Raw data is provided in 2015 USD PPP.
- The data is for 2030, 2050 and 2100.

- Electricity and fossil fuel costs are treated separately.
- There are three RCPs - 2.6, 4.5 & 7.0. All are combined with SSP2.
- There are three adaptation scenarios; low, medium and high. They differ in assumptions of intensive use of appliances/services, extensive adoption of appliances/services & scheduling of generation interruptions.

Review of the literature to provide additional evidence

There is literature on adaptation to labour effects. These include a range of regulatory, behavioural, technical and other options. A review of adaptation options is presented by Dasgupta et al., 2024. Day et al., 2019 set out an indicative array of options, and for 17 options, assess the possible size of costs and benefits, though these are based on expert judgement rather than empirical studies.

The option space for adaptation to labour effects is very different for high activity outdoor versus low activity indoor work. For outdoor work, employers can adopt strategies (Dasgupta et al., 2024) which include shade provision, adjusting hours to cooler parts of the day (or into the night), mechanisation of activities, exoskeletons (mechanical structures that workers can wear to help increase their strength and endurance), as well as change in clothing, rest periods and water, and recovery, and there is some limited information on effectiveness though these are modest (12 – 18%).

For indoor work, there is a more obvious adaptation through the of air conditioning. There are studies that indicate high productivity benefits from AC, though there are still potential impacts on labour supply absenteeism (Somanathan et al., 2021), suggesting that workplace adaptation alone is insufficient to mitigate all the effects of heat (limits of adaptation). There are some studies on the economic benefits of air conditioning on labour productivity (Costa et al. 2016; Phelan et al 2024: Berkeley Lab, 2025). These indicate potentially high BCRs (5:1 and above) but these depend on the exact production and worker value hour, and thus with location and context, so for some studies, similar AC measured generated positive BCRs in higher income countries but not in lower. Over longer time periods, firms do have additional options so AC, which include (Somanathan et al., 2021) increasing automation, relocation, or more structural changes in outputs.

Methodology for data

Adjusting these values used the same approach as for other sectors.

Impacts and Adaptation

Methods

The analysis[9] investigated the effects of high temperatures on labour productivity, with a particular focus on sectoral exposure. The analysis bridges the gap between micro-level evidence on temperature impacts on effective labour (e.g., Dasgupta et al., 2021) and macroeconomic studies using panel data to explore the determinants of productivity and climate-related labour impacts (e.g., Auffhammer, 2018; Hsiang, 2016).

The analysis used a panel dataset at the country-year level, matching macroeconomic statistics on labour productivity with adaptation-related energy use in productive sectors. Labour productivity was defined as the annual value added divided by the number of employed persons. Value added by sector was obtained from UNData ("Gross Value Added by Kind of Economic Activity at current prices"), converted to real terms using a Penn World Table deflator, and combined with employment data from ILO. The analysis aggregated sectoral productivity into total, high-exposure (outdoor) and low-exposure (indoor) sectors. The logarithm of labour productivity is used as the dependent variable.

Thermal stress was measured through Cooling Degree Days (CDD24), computed as the cumulative number of degrees by which daily temperatures exceed 24°C. The analysis used ERA5 reanalysis data and aggregate grid-cell values to the country level using population weights.

Adaptation is captured through the historical country-level predicted energy demand in productive sectors (commerce, industry, agriculture) for cooling services, as set out in Deliverable 2.2. Residential energy demand was excluded in the main specification, focusing on energy directly relevant to labour productivity.

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[9] The analysis was based on the supplementary note 'ACCREU - Labour productivity and adaptation benefits' (CMCC-ECIP (Francesco Colelli, Gabriele Mansi, Shouro Dasgupta, Enrica De Cian).

This approach allows the extent to which energy use for adaptation in productive sectors mitigates the adverse effects of high temperatures on productivity over the historical period.

Econometric Model

The analysis estimated the impact of high temperatures on labour productivity using a country-year panel and a fixed- effects specification. The model accounts for: country-fixed effects (μ_i), which capture all time-invariant country-specific unobservable factors; Time-fixed effects (δ_t), which control for global shocks affecting all countries in a given year; Quadratic regional time trends ($\phi r(i),t$), where $r(i)$ indexes the regional group to which country i belongs, capturing region-specific trends over time. The econometric specification is:

$y_{it} = \text{CDD}_{it}\ (\alpha + \beta\ \text{Energy Adapt}it) + \mu_i + \delta_t + \phi r(i),t + \varepsilon_{it}$ (1)

where:

- y_{it} is the logarithm of labour productivity in country i at time t,
- CDD_{it} is the number of cooling degree days above 24°C,
- Energy Adapt*it* is the logarithm of per capita energy used for adaptation in productive sectors,
- ε_{it} is the idiosyncratic error term.

This specification allows the isolation of the effects of thermal stress on productivity while controlling for unobserved heterogeneity across countries, global shocks, and regional trends.

Regression results

The results estimate the effect of cooling degree days (CDD24, above 24°C) on labour productivity across sectors with different heat exposure: high-exposure (outdoor) and low-exposure (indoor) sectors, and how energy use for adaptation moderates this effect.

The Table presents results without interactions between CDD24 and energy use. In this specification, high-exposure sectors experience a significant decline in productivity with rising CDD24, while low-exposure sectors show no statistically significant response.

Table 8: Effect of CDD24 on Labour Productivity (no interaction with energy)

Dependent Variables:	Total	High Exposure	Low Exposure
Model:	(1)	(2)	(3)
cdd24	-0.0001*	-0.0002*	-7.18e-5
	(7.26e-5)	(8.74e-5)	(8.11e-5)
hdd18	-4.03e-5*	-6.13e-5**	-2.24e-5
	(2.31e-5)	(3.09e-5)	(2.54e-5)
Controls (Capital stock)	Yes	Yes	Yes
Regional time trends	Yes	Yes	Yes
Fixed-effects			
iso3	Yes	Yes	Yes
time	Yes	Yes	Yes
Observations	2,554	2,554	2,551
R2	0.98127	0.98669	0.94999
Within R^2	0.29989	0.34354	0.29423

*Heteroskedasticity-robust standard-errors in parentheses Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

When interactions with energy for adaptation are included (see table), the patterns change. For high-exposure sectors, the direct effect of CDD24 remains largely unchanged. For low-exposure sectors, however, the interaction between CDD24 and energy becomes statistically significant, indicating that higher energy use mitigates the negative impact of heat on productivity. Note that energy for adaptation considers energy used in productive sectors only (commerce, industry, agriculture).

Table 9 Effect of CDD24 on Labour Productivity

Dependent Variables:	Total	High Exposure	Low Exposure
Model:	(1)	(2)	(3)
cdd24	-0.0001	-0.0001	-0.0002**
	(7.58×10^{-5})	(9.92×10^{-5})	(8.66×10^{-5})
cdd24 × log energy	7.09×10^{-6}	2.22×10^{-5}	3.21×10^{-5}**
	(9.8×10^{-6})	(1.87×10^{-5})	(1.34×10^{-5})
cdd24 × log energy ^{2}	-7.11×10^{-6}***	-1.7×10^{-5}***	-4×10^{-6}**
	(1.74×10^{-6})	(2.05×10^{-6})	(1.9×10^{-6})
Controls (HDDs, Capital stock)	Yes	Yes	Yes
Regional time trends	Yes	Yes	Yes
Fixed-effects			
iso3	Yes	Yes	Yes
time	Yes	Yes	Yes
Observations	2,554	2,554	2,551
R2	0.98146	0.98708	0.95023
Within R^2	0.30702	0.36298	0.29753

*Heteroskedasticity-robust standard-errors in parentheses Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

Therefore, the models selected to quantify labour supply impacts of temperatures are the following:

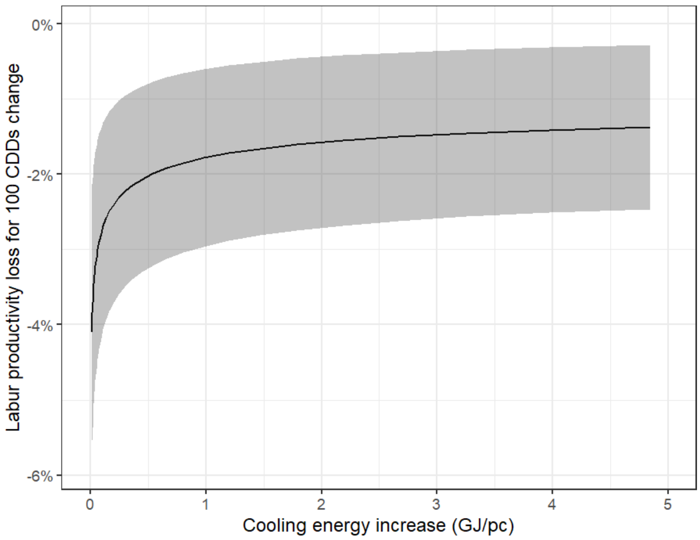
Table 10 Effect of CDD24 on Labour Productivity: selected models

Dependent Variables:	Total	High Exposure	Low Exposure
Model:	(1)	(2)	(3)
Variables			
cdd24	-0.0001*	-0.0002*	-0.0002**
	(7.26×10^{-5})	(8.74×10^{-5})	(8.66×10^{-5})
cdd24 × log energy			3.21×10^{-5}**
			(1.34×10^{-5})
cdd24 × log energy ^{2}			-4×10^{-6}**
			(1.9×10^{-6})
Controls (HDDs, Capital stock)	Yes	Yes	Yes
Regional time trends	Yes	Yes	Yes
Fixed-effects			
iso3	Yes	Yes	Yes
time	Yes	Yes	Yes
Fit statistics			
Observations	2,554	2,554	2,551
R2	0.98127	0.98669	0.95023
Within R^2	0.29989	0.34354	0.29753

*Heteroskedasticity-robust standard-errors in parentheses Signif. Codes: ***: 0.01, **: 0.05, *: 0.1*

An important feature of the estimated relationship between CDDs, energy use, and low-exposure sector productivity is the clear saturation effect (see Figure 43). The marginal mitigation of CDD-induced productivity losses diminishes at higher levels of per capita energy use for adaptation, with most of the effect plateauing beyond 5–10 GJ per capita. This non-linear pattern reflects diminishing returns to additional energy consumption in reducing heat-related productivity losses. In practice, per capita adaptation energy use varies widely across countries. The United States averages around 7 GJ per capita, Europe typically ranges between 1–2 GJ, most developing countries remain below 1 GJ, while Gulf countries exceed 30 GJ per capita. This heterogeneity implies that while additional adaptation energy could substantially reduce productivity losses in regions with low historical energy use, countries already above the 5–10 GJ threshold experience limited additional benefits.

Figure 43 - Marginal change in labour productivity of low exposure sector, from an increase of 100 CDDs, by level of cooling energy, based on results above.



Ex-ante Projections

The analysis combined country-level CDD and HDD projections (ISO3 level) with projected changes in energy demand for cooling under three adaptation scenarios to estimate potential productivity impacts. Using the coefficients from Table 2, ex-ante labour productivity shocks in the low-exposure (indoor) sector were assessed under two cases:

- **Baseline (historical energy levels):**

$$\Delta y_{i,y}^{baseline} = \hat{\alpha} CDD_{i,t} + \hat{\gamma} HDD_{i,t} + + \hat{\hat{\beta}} CDD_{i,t} * \overline{Energy_i} \quad (2)$$

- **With projected adaptation:**

$$\Delta y_{i,y}^{adaptation} = \hat{\alpha} CDD_{i,t} + \hat{\gamma} HDD_{i,t} + \hat{\hat{\beta}} CDD_{i,t} * (\overline{Energy_i} + \Delta Energy_i^{ada}) \quad (3)$$

Where $\overline{Energy_i}$ denotes the historical (2000-2020) average per capita energy used for adaptation in productive sectors, and $\Delta Energy_{it}^{ada}$ represents the projected change under each adaptation scenario. This approach provides a first-order assessment of labour losses due to rising CDDs and the potential mitigation effect of additional energy use for adaptation in productive sectors.

Productivity shocks in the high exposure sector instead are computed as:

$$\Delta y_{i,y}^{high,baseline} = \hat{\alpha} CDD_{i,t} + \hat{\gamma} HDD_{i,t} \quad (4)$$

Note that $\boldsymbol{\Delta Energy_i^{ada}}$ is derived from ACCREU D2.2 and is specified for three adaptation energy sce- narios (low, medium, high), representing different degrees of use of energy for adaptation purposes.

The table below reports projected global-level labour productivity losses in the low-exposure sector under three adaptation energy scenarios for different RCP pathways in 2100. Across all scenarios, productivity losses increase with the severity of climate change, from roughly −5% under RCP2.6 to −15% under RCP7.0 when no adaptation energy is assumed. The introduction of additional energy for adaptation substantially mitigates these losses. For instance, under the high adaptation scenario, losses under RCP7.0 are reduced from −15% to −9%, highlighting that energy use can offset a significant fraction of heat-induced productivity declines. Country-level estimates vary substantially, with projected labour productivity losses reaching up to −20% by 2050 and −30% by 2100 in the most affected countries, in the absence of adaptation (see figure 44). When the mitigating effects of adaptation energy are included, these losses are nearly halved under the ”high” adaptation scenario, highlighting the substantial potential of productive-sector energy use to reduce heat-induced productivity shocks. Consistent with the earlier discussion of saturation effects, the marginal gains diminish at high levels of per capita energy.

Table 11 Projected Labour Productivity es under Different Adaptation Scenarios (2100)

RCP	High-Exposure (%)	Low-Exp.: without Adap. (%)	Adaptation Scenario	Low-Exp.: with Adap. (%)
2.6			Low	-4.2
2.6	-3.6	-5.5	Medium	-3.7
2.6			High	-3.5
4.5			Low	-7.9
4.5	-7.1	-10.5	Medium	-6.7
4.5			High	-6.4
7.0			Low	-11.4
7.0	-10.6	-15.5	Medium	-9.6
7.0			High	-9.2

Figure 44 Ex-ante change in Low-Exposure labour productivity based on CDDs changes and energy adaptation projections.

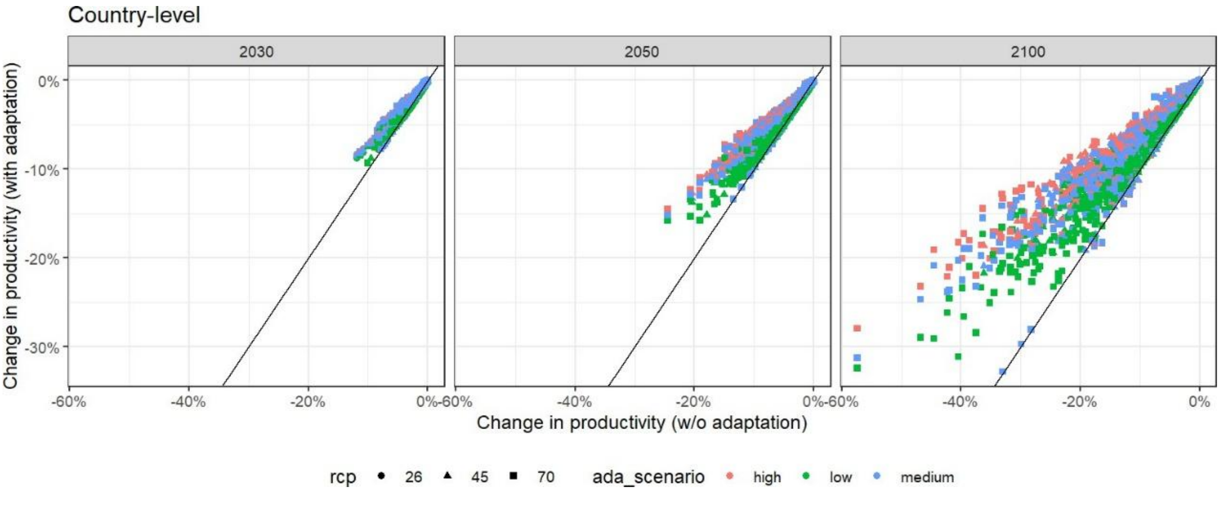
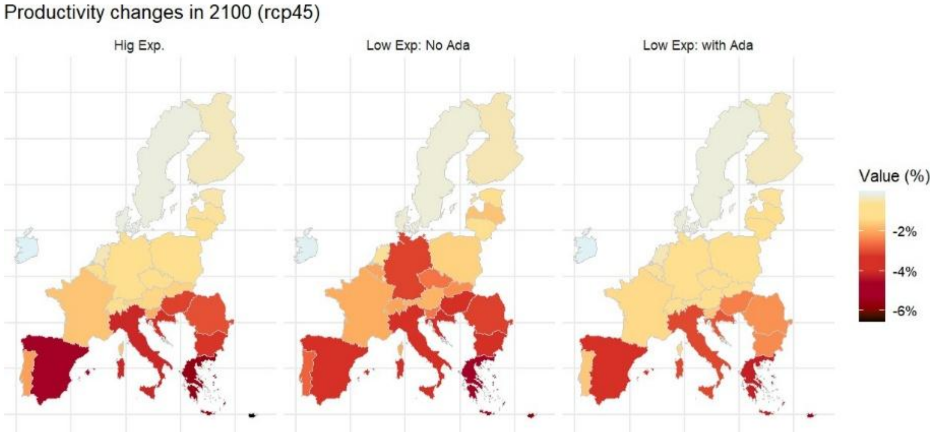


Figure 45 Ex-ante change in High and Low-Exposure labour productivity based on CDDs changes and energy adaptation projections in 2100, RCP 4.5.



Computation of benefits-costs function

These results were used to investigate costs and benefits of adaptation, drawing on ex-ante simulations of future cooling-energy demand and the associated labor-productivity responses to climate change.

The analysis assessed the cost of adaptation in productive sectors as the additional energy expenditures required for cooling services. These costs were calculated using historical region-specific energy prices, which we assume remain constant into the future. Energy expenditures therefore represent the monetized form of the adaptation variable used in the labor-productivity regression model: the projected cooling-related energy demand in commerce, industry and agriculture, estimated across future years and RCPs in Deliverable 2.2. The benefits of adaptation are computed by combining high- and low-exposure value added growth from the historical period to the future. This assumes that historical value added evolves exogenously and in line with country-specific GDP growth in SSP2. Because value added is the central variable in the labor- productivity analysis presented above, this approach allows direct monetization of future productivity losses (Δy^{high}). Note that both changes in energy demand and value added correspond to *ex-ante* changes prior to any market adjustment, since such equilibrium effects will be captured in the IAM simulations.

Baseline monetized labor-productivity losses without adaptation are calculated as the total change in value added in both high- and low-exposure sectors. Losses with adaptation are defined as the sum of (i) the fixed losses in high-exposure sectors, which are not mitigated by cooling-related adaptation in our framework, and (ii) the reduced losses in low-exposure sectors due to adaptation. The benefits of adaptation are then obtained as the difference between the no-adaptation losses and the losses under adaptation. Estimates are produced for different adaptation scenarios (low, medium and high) as well as across RCPs. We report the median, 25th and 75th percentiles of the GCM ensemble for the years 2030, 2050 and 2100. Values are aggregated globally and compared to total adaptation costs, expressed as energy expenditures.

The Table below presents these values by year (2030, 2050, 2100) and across RCP scenarios. For 2030, total global value added is about 112 trillion euros, with projected losses without adaptation ranging from 1.6 to 1.9 trillion euros without adaptation, and adaptation benefits of 0.27–0.36 trillion euros. In relative terms, losses without adaptation range from 1.5% to 2% of value added in 2030 to around 3-10% in 2100, de- pending on the RCP. Note that the projected losses for 2030 are in line with the only comparable study in the literature estimating current global impacts from heat effects on labour productivity, with annual heat- induced productivity losses estimated at $2.1 trillion (2017 PPP$), and projected costs to reach $2.4-2.5 trillion by 2030 under high-emission scenarios (Parsons et al., 2021). Energy expenditures for adaptation in 2030 are relatively small, 0.31–0.35 trillion euros. By 2050, value-added losses increase to 4.5–6 trillion euros, with adaptation benefits of 1–1.5 trillion euros and energy costs of 0.70–1.05 trillion euros. In 2100, under more severe climate scenarios, losses without adaptation rise sharply to 10–33 trillion euros, adaptation benefits to 3–10 trillion euros, and cooling expenditures to 1.3–3.5 trillion euros.

Table 12 Value-added, losses, adaptation benefits, and cooling energy expenditures across years and RCP scenarios (trillions of euros).

Year	**RCP**	**Total Value Added** [Trillion C]	**Loss w/o Adaptation** [Trillion C]	**Loss with Adaptation** [Trillion C]	**Benefit** [Trillion C]	**Energy Costs** [Trillion C]
2030	26	112.32	1.91	1.54	0.36	0.35
2030	45	112.32	1.79	1.47	0.32	0.35
2030	70	112.32	1.64	1.37	0.27	0.31
2050	26	166.14	4.50	3.45	1.05	0.70
2050	45	166.14	5.50	4.21	1.30	0.80
2050	70	166.14	6.03	4.56	1.48	1.05
2100	26	331.15	10.9	7.93	3.02	1.30
2100	45	331.15	21.8	15.3	7.56	2.31
2100	70	331.15	33.4	22.9	10.55	3.52

Note: Values are in trillions of euros. Loss without adaptation refers to projected reductions in value added in the absence of adaptation. Adaptation benefits are avoided losses due to cooling-related adaptation, and cooling energy expenditure shows the associated energy cost. Each row corresponds to a given year and RCP scenario and for the median of GCMs.

Comparing adaptation benefits to their associated costs allows calculation of a benefit–cost ratio. Averaged across all future scenarios, this ratio is approximately 3:1, indicating that each unit of investment in adaptation yields roughly three units of avoided economic losses. However, the ratio differs by adaptation intensity level. Despite variation in the levels of costs and benefits, we find an overall linear relationship between them, across RCPs, years and model runs for each adaptation level (see Figure). Low-adaptation cases exhibit the highest benefit–cost ratios, because additional adaptation generates larger marginal improvements in labor productivity compared with similar increases in cooling energy use under medium or high adaptation. This pattern reflects the decreasing marginal returns to adaptation identified in the empirical analysis above. By contrast, expenditures remain roughly constant at a given adaptation level because unit energy prices are assumed fixed, even when cooling demand increases. Future IAM simulations will allow for market-equilibrium adjustments and supply-side responses that may influence energy prices and thus alter marginal costs. The estimates presented here are therefore ex-ante projections that abstract from such adjustments.

Nevertheless, the near-linear relationship between adaptation costs and benefits across the three adaptation scenarios provides a proxy damage function. This relationship can be used to represent adaptation benefits in IAMs when endogenous modeling of these mechanisms is not feasible, while still reflecting the semi-elasticities estimated in the empirical analysis.

Table 13: Benefit-to-cost ratios by adaptation scenario and RCP, standard errors in parenthesis.

Adaptation Scenario	**RCP2.6**	**RCP4.5**	**RCP7.0**
High	1.54 (0.18)	1.76 (0.28)	1.77 (0.34)
Medium	1.71 (0.25)	1.98 (0.37)	2.01 (0.45)
Low	3.87 (0.68)	4.93 (1.18)	5.45 (1.57)

Figure 46 Global costs and benefits of adaptation across years, RCPs, GCM ensemble (median, 25th and 75th percentiles) and adaptation levels in USD billion (2015 PPP) and as a percentage of total value added.

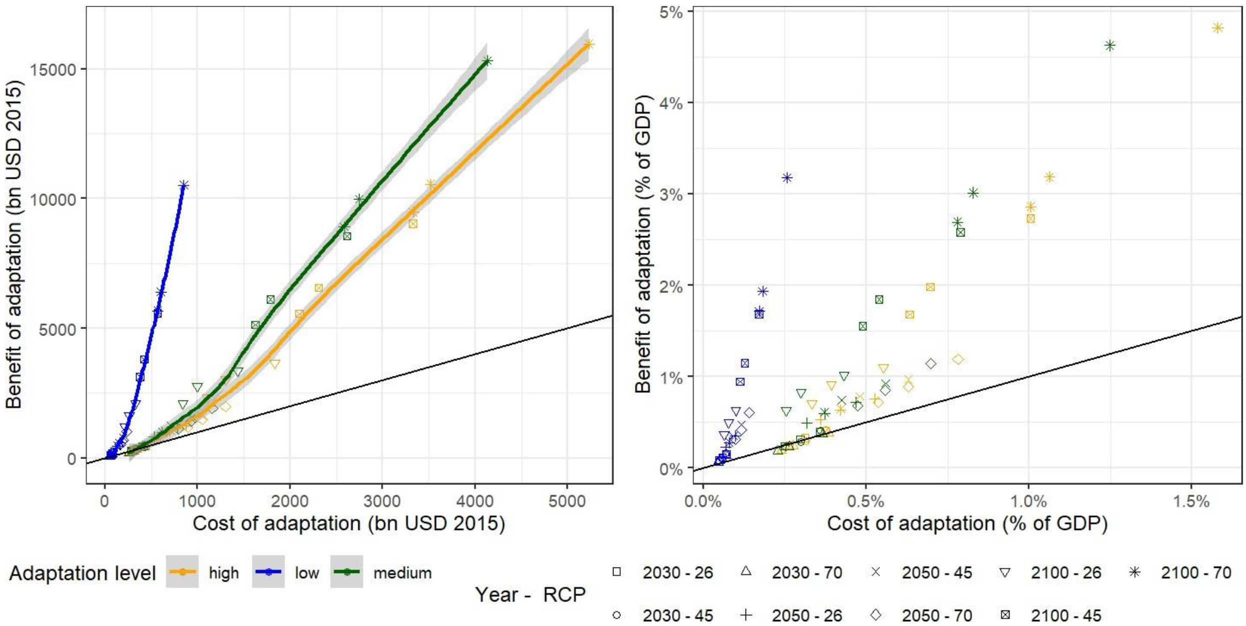
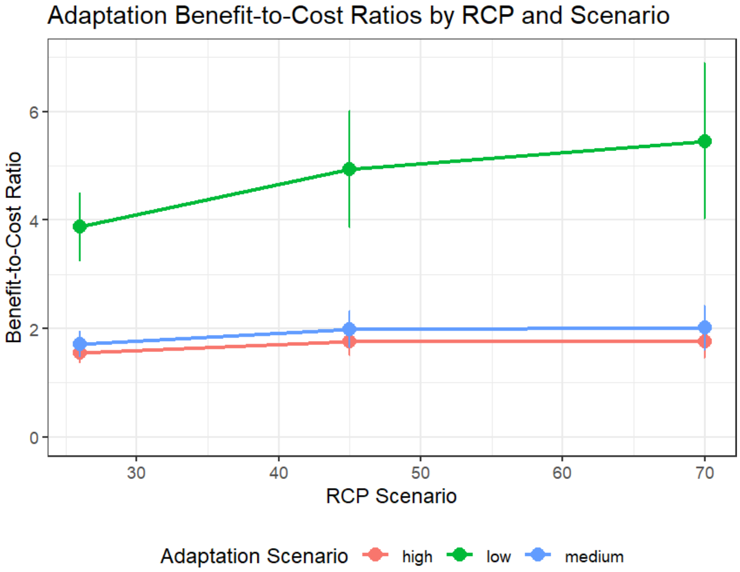


Figure 47 Estimated benefit-to-cost ratios by adaptation scenario and RCP.



These BCRs do seem to be line with the literature, although this is limited. However, these results indicate much lower effectiveness and lower BCRs than for the other sectors, notably for coastal and agriculture sectors. This may be the choice of method, and that econometric analysis identifies more real-world effectiveness levels, as compared to the modelling approach used for other sectors, though it is also possible it relates to the sector, and the generalized use of AC. For example, a targeted programme to deal with heat and labour effects using AC might generate higher BCRs.

3.7 Health

Introduction

Climate change is projected to impact on health, including with direct impacts, such as heat-related mortality, but also indirect impacts from changes in the range, seasonality and intensity of vector borne, food-borne and waterborne disease transmission. These impacts can be then valued by looking at the impacts on welfare, by assessing the combination of treatment costs, lost productivity and dis-utility.

Adjusting impacts and adaptation costs in the energy sector for inflation

ACCREU has assessed the heat-related mortality and morbidity impacts, as set out in D2.3. As with other sectors, the data has been converted to the relevant price year using the same approaches.

The ACCREU 2.3 data for heat mortality, however, was only assessed for Europe (albeit at high resolution, to allow direct analysis in the CGE modelling). Further, there was only 1 adaptation scenario run, the high AC scenario. This makes it very difficult to generate global functions for adaptation costs and benefits.

The adaptation scenario in ACCREU estimated heat related mortality in Europe at high resolution using an epidemiological function, and then took the data from the residential energy deliverable to estimate the health benefits of the additional level of cooling. For the benefits of adaptation, the analysis used literature that identifies air conditioning decreases in heat-related mortality (Barreca et al., 2016; Bobb et al., 2014; Sera et al., 2020). The analysis in D2.3 assumes that the risk of heat-related mortality varies between 14 and 75% for an individual with AC relative to an individual without (based on these studies) and uses a mean of these two values, thereby assuming a decrease in mortality due to AC of 44.5%. However, this is only applied to the increase in AC associated with the energy sector results, and is therefore best seen as a co-benefit, rather than a targeted AC strategy. For example, a more targeted strategy might seek to encourage AC in highly vulnerable buildings (hospitals, care homes) and potentially among highly vulnerable people in the community, recognising that most heat related mortality occurs in people over 65 years of age (notably those over 75) and those with existing health conditions.

Review of the literature to provide additional evidence

There is an extremely large literature on heat related mortality, which include epidemiolocal studies (e.g., Gasparrini et al., 2017: Vicedo-Cabrera et al, 2021; Bressler et al., 2021) and econometric studies (e.g., Carleton et al., 2020; Burke et al., 2025). These also include autonomous adaptation, considering physiological, behavioural and building acclimatisation, as well as other factors such as income.

There is also a literature on planned adaptation. The most extensive literature is on heat-health alert system and benefits, although this literature is extremely variable in reported effectiveness. There is some ex post evidence on the benefits of heat alert systems for reducing urban heat fatalities internationally which indicates very high BCRs in specific locations (e.g. Ebi et al., 2004). There have also been a number of ex ante assessments of economic analysis of the potential BCRs of other heat alert systems, and how these will change with climate change, that takes account of rising benefits but also rising resource costs. Hunt et al., (2016) estimated a baseline BCR for HHWS for London. They derive benefit cost ratios for London for the 2035–2064 time period under alternative climate scenarios. BCRs were found to be 11, 21, 23 and 28 for a baseline, cool, medium and hot climate scenario, respectively. Similar positive high BCRs are also reported for heat alert warning in studies across Europe (UBA, 2012; Bouwer et al., 2018; Chiabai et al., 2018). However in Australia, Williams et al (2022) also undertook a CBA, but found more modest values of only 2 – 3.3:1. These values are site- and context-specific, but BCRs also depend critically on the valuation of avoided fatalities, and whether this uses a Value of Statistical Life, (VSL), or some form of adjustment (e.g. Value of Life Year Lost or Quality Adjusted Life Years) – use of VSL considerably increase the BCRs.

A key issue with these studies is the assumed level of effectiveness of adaptation. This is also related to reviews of effectiveness of heat alert schemes more generally, which report extremely wide results. A review of the literature by Toloo et al. (2013) identified a small number of studies on heat warning effectiveness, with a large range of effectiveness. This identified a French study that reported effectiveness (in reducing mortality) of 68%, but a Florentine study with effectiveness of 9%. There was also higher effectiveness reported from North America by Toloo et al. at 85% and 88% in two cities. However, an analysis of heat alerts in twenty US cities (Weinberger et al., 2018), between 2001 and 2006, found that NWS heat alerts were not associated with lower mortality in most cities studied, i.e., there was no statistically significant beneficial association. The one exception was in Philadelphia, where heat alerts were associated with a 4.4% lower mortality rate or an estimated 45 deaths averted per year. Rao et al (2025) undertook a systematic review of heat-health warning systems – identifying 23 studies - and Burke et al, (2025) also review studies. These identify examples of randomised controlled trials and difference-in- differences studies, and both report benefits, but that these vary widely.

This suggests that are a range of context-specific factors that influence the effectiveness of heat warning systems. However, it is also influenced by the effectiveness of overall information chain from a heat alert forecast to the uptake and effective use by an end user. Importantly, as economic benefits are generated at the very end of the value chain, from avoided fatalities, there are often large efficiency losses (or decay) along the heat alert value chain (Perrels., et al 2013), which lead to much lower actual benefits than potential (maximum) benefits. For example, if a service has a low level of reach (e.g., due to poor dissemination) then the economic benefits will be low, as there will be a smaller number of users. Similarly, if a large number of users receive the information but do not act on it (or do not act effectively), the level of benefits achieved will be lower than the potential benefits. Therefore, to provide a realistic estimation of benefits of W&CI services, a value chain needs to be constructed that considers such efficiency losses.

What is clear is that even with these systems in place, there are high levels of residual fatalities, and because they are only triggered for heatwaves, heat alert schemes do not reduce the heat-related fatalities that occur below these levels, which are significant (as evidence in both epidemiological and econometric studies).

It is also stressed that heat alert systems are now in place in nearly every country in the EU[10], as well as many countries worldwide, and therefore form part of the background policy and existing adaptive capacity. However, both epidemiolocal studies and econometric studies of climate and heat related deaths do not account for this, and thus may overestimate baseline impacts in recent years when transferring functions to the local level.

There are other related measures that extend heat alert schemes to target health related mortality as part of heatwave plans. These include supporting interventions in the health and social care sectors, for example with targeted information, advice or visits to highly vulnerable groups, or cooling centres, when alerts are triggered. There is less information on the effectiveness and economic costs and benefits of these

There are also a set of green measures including. green roofs and park spaces. Markanday et al., 2019 – see earlier Table – identified 20 such studies with an average benefit cost ratio was 2.25:1. It is highlighted that several studies identify that BCRs <1 for green roofs. Further, more comprehensive studies often find that new green space has low benefit to cost ratios for cooling, due to the high opportunity costs associated with land-use (and land-use values) in major urban centres. An important issue here is not to mix up the effectiveness of green roofs and green infrastructure, which is often low for heat, with the benefit to cost ratios, which because these include other benefits streams (carbon benefits, recreational benefits, etc) are often high.

The other main option is with respect to building temperatures. This can be reduced by either passive or mechanical (AC) cooling in residential buildings. These assessments are complicated by the differences in costs and benefits of adaptation in existing houses versus new builds, as well as the specific stock type of houses. They are also influenced at the local and context specific level by baseline and additional cooling demand, income, and valuation methods (health, discomfort), as well as inclusion of non-market benefits or externalities (carbon emission, air quality emissions). This means results will be very site and context specific. Nonetheless, studies in the UK (Wood Plc, 2019; AECOM, 2019) report some consistent trends, for example, it is cheaper to include passive ventilation in new builds than to retrofit. There are also some relative no regret options to reduce (but not eliminate) overheating, such as utilising increased natural ventilation (opening windows), using existing blinds and curtains during the day to limit heat gain. However, they report a very wide range of results depending on more extensive passive options versus AC depending on building type, the baseline versus future level of CCD and thus the net present value of benefits. Burke et al (2025) review the literature on the health benefits of AC and report positive reductions, but with large variability, and highlight income effects, in terms of purchase of AC units, but also being able to afford to run, being a major factor. A further set of options related to where AC is widespread, energy efficiency standards for cooling equipment as well as energy efficiency awareness programmes.

[10] https://www.eea.europa.eu/en/analysis/publications/the-impacts-of-heat-on-health

European functions

The results from D2.3 provide health impacts, valued using VSL and VOLY metrics. For example, the VOLY estimates are presented below. These are then compared to the energy costs from additional AC in residential building, which include the capital costs and the annual running costs. These show benefits and costs are broadly equal in the 2030s, but that benefits exceed costs significantly by the 2050s, as in the table below.

Table 14 Economic cost (€billion/year) of heat-related fatalities in the EU for three time slices and three RCPs (central estimates) using the Value of a Life Year Lost for Valuation. The table also shows the estimated economic benefits (from reduction in heat-related fatalities) from the increase in residual AC. Constant unit prices for VOLY with no adjustment for economic growth. Note if VOLY is included in line with GDP, growth then these benefits would be much higher.

EU27	**Estimated economic costs (€ Billion /year)**		
	2030s	**2050s**	**2070s**
Baseline	Central VOLY		
RCP2.6	229	319	301
RCP4.5	235	338	383
RCP7.0	224	347	468
	Estimated economic benefits (€ Billion /year)		
Adaptation Benefits	Central VOLY		
RCP2.6	5	17	Not available
RCP4.5	8	19	
RCP7.0	7	19	
	Estimated costs (€ Billion /year)		
Adaptation Costs			
RCP2.6	8.4	6.4	Not available
RCP4.5	6.9	7.0	
RCP7.0	7.4	10.1	

Because of the method used, which assesses the co-benefits of AC, rather than a more targeted use, the effectiveness and benefits is low (but note the underlying assumption in the model is a 44% effectiveness with AC).

3.8 Building an aggregate function

The analysis above provides the basis for the functions for WP4.

All of the IAMs assess sea-level rise separately. The DIVA analysis (See 3.2), with migration included as an impact, provides a function that can be used in the IAMs. It is noted that this modelled function does seem to have very high effectiveness and BCRs as compared to the literature review, and it is possible a sensitivity function with lower effectiveness and greater limits of adaptation could be developed and tested.

Most of the IAMs in ACCRUE combine other sectors into a single damage curve, i.e., they do not have separate functionality for flooding, agriculture, etc., but instead have an aggregate damage function. This is more simple to produce, and avoids the highly heterogeneous approach used for adaptation in WP2, which affects the individual damage curves produced here (sections 3.3 – 3.7).

A number of options are being explored and taken forward for this aggregated damage curve. The first is to take the individual sectoral values and their individual EAD/annual damage, and allocate the proportion of the total damages that might fall to each sector. This could then be repeated with adaptation for each sector. An alternative is to take the overall evidence from the sector assessments, and the broader literature review, and then develop an aggregated curve that is representative of the overall literature. This would allow the inclusion of more real-world representation of effectiveness and the lower BCRs, as well as to include limits of adaptation.

The current preferred option is to use both approaches, to derive a modelled function, as well as a more real-world function, and compare the two in the IAMs.

4. Other Literature

4.1 NDCs and NAPs

An analysis of adaptation finance needs submitted to UNFCCC in National Determined Contributions (NDCs) and National Adaptation Plans (NAPs). This is based on an updated analysis of Chapagain et al (2020) and was also published in UNEP (2025).

While most countries have submitted NDCs and NAPs, not all of these include estimated adaptation costs. Recent analysis (UNEP, 2025), identifies that 97 developing countries have specified their adaptation finance needs for the period 2021–2035 in at least one of their submissions, and this is reported as a cost of adaptation (US$). While developed (Annex I) countries have also submitted NDCs, most of these do not have costed adaptation estimates.

This information provides a potential useful set of alternative adaptation costs to the modelled costs above especially as these are country-driven and bottom-up. However, methods for costing adaptation needs (in NAPs and NDCs) vary across countries. They typically begin by identifying adaptation actions, followed by estimating their costs of implementation (UNFCCC, 2022), but, the information provided is highly heterogeneous: the plans differ in terms of their adaptation ambition, consideration of future climate and socioeconomic scenarios, methods employed to identify and prioritize adaptation options, costing methodologies, sectoral coverage and implementation time frame. Moreover, not all adaptation needs identified in the countries' plans have been costed, potentially leading to an underestimation of overall adaptation finance needs. Therefore, the finance needs reported should be interpreted with care.

Analysis and Results

The adaptation finance needs reported vary widely due to factors such as country size, economic structure, climate change impacts and vulnerability, as well as methodological approach. In relative terms (see annex 4 for details), low-income countries report the highest adaptation finance needs, averaging 3.6 per cent of gross domestic product (GDP), followed by lower-middle-income countries at 2.4 per cent, upper-middle-income countries at 2.1 per cent, and high-income countries with lowest at 1.7 per cent. In contrast, per capita needs exhibit an inverse trend: countries with higher income levels report greater needs in absolute dollar terms. Low-income countries report an average of US$31 per capita, lower-middle-income countries US$62, upper-middle-income countries US$158, and high-income countries the highest at US$273. This suggests that lower-income countries have higher needs relative to the size of their economies. LDCs and SIDS report disproportionately high costs on a per capita basis (LDCs 3.5 per cent and SIDS 3.6 per cent of GDP).

Table 15 Annual adaptation finance needs (per capita and as a percentage of GDP) by income group, LDCs and SIDS.

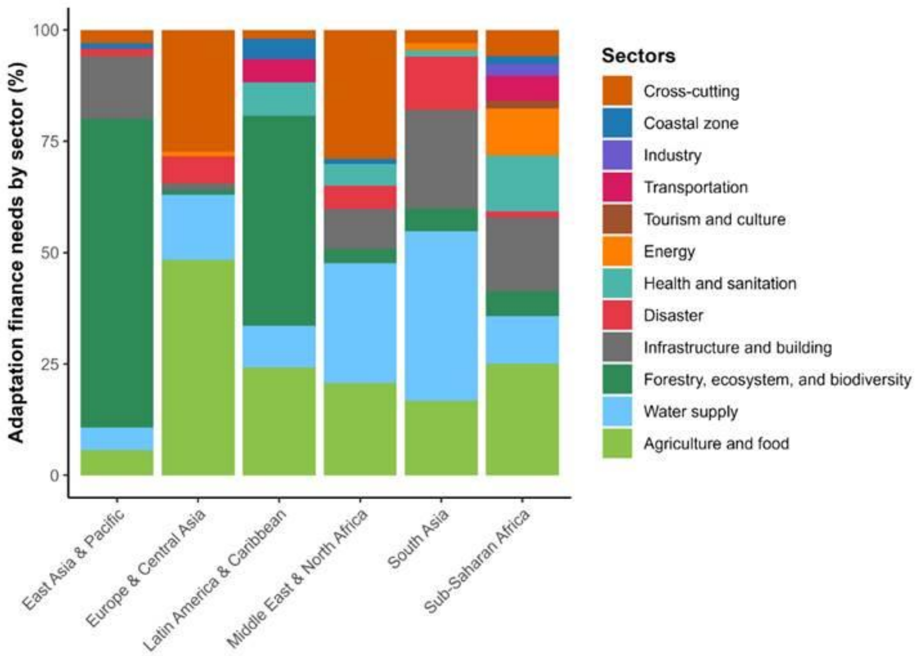
Country group	**Annual per capita adaptation finance needs (2023 US$)**		**Annual adaptation finance needs (% of GDP)**	
	Median	Interquartile range	Median	Interquartile range
LIC	31	11 – 42	3.6	1.5 – 5.2
LMIC	62	30 – 117	2.4	1.1 – 6.2
UMIC	158	8 – 357	2.1	0.1 – 3.9
HIC	273	29 – 501	1.7	0.1 – 3.2
LDCs	36	14 - 62	3.5	1.1 – 5.4
SIDS	254	88 - 511	3.6	1.1 – 9.1

To estimate global adaptation finance needs, reported annual finance needs were extrapolated to all 155 developing countries using a multivariate regression approach. An ordinary least squares regression was applied, with total annual adaptation finance needs as the dependent variable. Explanatory variables included per capita GDP, population size, a SIDS indicator, and the start year of the needs assessment, collectively explaining about 50% of the variation in reported needs. The resulting estimates are presented as predicted values with 90% confidence interval, reflecting the inherent uncertainty and variability in the projections.

At the global level, the total adaptation finance need is estimated at **US$365 billion per year**, with a range of US$144–1,032 billion. This represents around 0.8% of the combined GDP of developing countries, with a possible range from 0.3% to 2.2%, underscoring the magnitude of adaptation finance required even under optimistic scenarios.

Among the countries that provided detailed sectoral information, 55 submitted adaptation cost estimates for at least five sectors. The breakdowns are shown below for each region. Overall, the agriculture and food sector, and water supply, are common priorities across all regions, though even these vary in terms of their relative importance.

Figure 48 Sectoral distribution of adaptation finance needs by region. Shown as a percentage of total reported adaptation finance needs for each respective region.



Adaptation finance needs also differ by income level. Low-income countries tend to focus heavily on agriculture and food, alongside energy and transportation. Lower-middle-income countries prioritize infrastructure, water supply, and agriculture and food, with health and sanitation gaining importance. In upper-middle-income countries, agriculture remains dominant, but forestry, ecosystems, and water supply also receive significant attention. This may indicate that adaptation priorities evolve as countries develop.

It is more difficult to see how these values could be used by the CGE and IAM models, as there is a single time period and no benefits. However, they do provide a way to benchmark the modelling estimates.

5. Dissemination

The key user of this deliverable are the teams in WP4. However, this information is also relevant for other teams outside the project looking to develop adaptation functions for CGE and IAM, especially the ACCREU sister projects (CROSSEU and SPARCCLE).

Results from the D3.4 have been widely disseminated. There were used in the policy brief for WP5 disseminating European results on costs of inaction and costs and benefits of adaptation from the project. This was published at the start of the next reporting period.

The global adaptation costs have also been disseminated and used to inform three major global assessment reports (with a very large number of downloads) on the costs of adaptation, as well as providing inputs to the UNFCCC negotiations.

The work from D3.4 provided inputs to and supported the **Adaptation Gap Report 2024**, leading the Finance Chapter.

Butera, B., et al. (2024). Chapter 4: Adaptation Finance Gap. In. United Nations Environment Programme (2024). Adaptation Gap Report 2024: Come hell and high water. Nairobi. https://doi.org/10.59117/20.500.11822/46497. Available at https://www.unep.org/adaptation-gap-report-2024

This report includes the ACCREU logo, and acknowledgements.

This report has had 38892 downloads. It is very widely cited in the grey and academic literature.

The work was cited in 597 media articles published in 423 media outlets across 64 countries in 12 languages

The work from D3.4 provided inputs to and supported the **Adaptation Gap Report 2025**, leading the Finance Chapter.

Watkiss, P, et al. (2025). Chapter 4: Adaptation Finance Gap. Available at https://www.unep.org/resources/adaptation-gap-report-2025

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This report includes the ACCREU logo, and acknowledgements.

The report has had 11,977 downloads (though this is for 1 month only so far).

The results were cited in 780 media articles published in 587 media outlets across 71 countries in 22 languages

The work from D3.4 provided inputs to and supported the Independent High Level Expert Group on Climate Finance, and the data and acknowledgement of the ACCREU project are also included in the latest **Delivering an integrated climate finance agenda in support of the Baku to Belém Roadmap to 1.3** report, (Bhattacharya et al 2025).

The ACCREU data has, in turn, informed the global UNFCCC negations, with the study results on global adaptation costs cited in the Baku to Belem Roadmap to 1.3 Tr UNFCCC report. (UNFCCC, 2025)

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Appendix 1. Search Protocol

ACCREU Project: Review of Current Evidence Base on the Costs and Benefits of Climate Change Adaptation – Research Protocol

Introduction

This research protocol is a proposal of the review of empirical estimates of the costs and benefits of climate change adaptation. This is in relation to ACCREU *Task 3.4, Assessing adaptation costs and effectiveness for the integrated analysis with CGE/IA models***.** It constitutes a plan of how we could go about it undertaking it. The protocol sets out the methods to be used in this review and provides an explicit plan for the research.

Rationale

Our objective within the ACCREU project is stated in the DOW to be to deliver an inventory on the costs, effectiveness, and benefits of adaptation strategies by combining model-based estimates from WP2 of the project with insights from a systematic literature review. The analysis will rely upon both academic and grey literature including information from Nationally Determined Contributions and reports such the "adaptation finance gap report". It will gather evidence by sector/risk, and consider how costs and effectiveness vary across scenarios, highlighting possible limits to adaptation.

With this objective in mind, the principal protocol components are outlined below. These are partly informed by the work of Page et al. (2021) who have developed a set of guidelines named PRISMA (Preferred Reporting Items of Systematic reviews and Meta-Analyses) that look to provide commonalities in undertaking such review tasks.

The review questions

A useful principal review question for this systematic review could be: What is the published evidence base on the costs and benefits of adaptation at the sectoral level and across countries?

Secondary review questions include:

- What is the evidence for the effectiveness of adaptation options at different sectoral and geographical scales?
- Is there evidence that there are limits to the effectiveness of adaptation options?

Search strategy

The first task in this review is to identify published evidence pertaining to the empirical evidence on the costs and benefits of adaptation. We include academic as well as non-academic grey literature. The latter is included because much relevant economic documentation has been prepared for or by national and international agencies for their immediate use rather than through academic research.

We limit the time period in which studies have been published and are considered in our review as from 2010 to 2025. There is very little published evidence preceding 2010 and it is likely to be methodologically dated in any case.

In order to identify this body of evidence the following searches may be undertaken:

Academic articles: Search using search engines including:

- Google Scholar
- Web of Science
- Scopus

Grey literature: Search using search engines and tools including:

- Google

- Wiki.com
- Generative AI such as ChatGPT, GitHub CoPilot and AlphaCode
- LinkdIn

Search Strings – the combination of words and phrases that could be used in searches include:

Climat* or Climate Change or Global Warming AND adaptation or resilience or risk management or risk reduction AND cost* and/or benefit and/or effectiveness and/or economic appraisal

Study selection criteria

- We suggest that there is no restriction on language though the initial search will be undertaken in English.
- There is no restriction on geographical location or instigator of adaptation (household, business, local, regional, national or international authorities.
- Retained studies will be those with empirical documentation of activities that are directly linked to actual or potential climate risk/vulnerability reduction.
- Retained studies will be those that provide quantitative or semi-quantitative (for example, ranked or indicative scale).
- Documents whose contributions are primarily conceptual or theoretical are treated as non-empirical and therefore excluded.
- Studies that make empirical estimates of costs, benefits, and/or effectiveness of potential or planned adaptation actions are included, as well as actions that have already been made.

The initial screener will utilise these selection criteria, record the study's performance against each criterion, and make a rating of each study, i.e. Yes (retain), No (don't retain), Maybe. The second screener will make their own independent rating before discussing and agreeing whether the study should be retained. Where no agreement can be reached, the screeners will defer to the project lead (Watkiss) for a final decision).

Details of each study will be recorded in the excel spreadsheet template specifically constructed for this purpose. The template identifies the individual details required of a study in order to utilise it in our synthesis, and allows us to avoid bias assessment ion our synthesis. The required details are set out in the Annex to this protocol.

Study quality assessment

The screening process is also intended to act as a quality assessment. For example, if it is not possible to complete the categories included in the study record it is likely that we will have insufficient information to allow us to use the record in our synthesis.

Data synthesis procedure

All monetary data will be converted to 2024 Euro prices using the price index in the country of the study and using the 2024 purchasing power parity exchange rate.

Results tables will be constructed on a sectoral basis, disaggregated by climate risk(s), geographical area, and time period.

The synthesis data tables will briefly summarise the characteristics and risk of bias among contributing studies.

We will present results of all investigations of possible causes of heterogeneity among study results.

We will present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.