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D3.3 Generic adaptation pathways for adaptation decision types

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Changes with respect to the DoA

There are no changes to be reported with respect to the ADTs.

Dissemination and uptake

This report is a deliverable (D3.3) within ACCREU, which focuses on adaptation decisions from micro-level to macro-level. The specific objective is to generalize insights from ACCREU case studies and beyond per adaptation decision type (ADT) and to demonstrate practical adaptation solutions that can support and empower European communities to take concrete action. It aims to provide insights and actionable recommendations for ACCREU stakeholders and other local level practitioners across the EU that are faced with similar policy questions. For each ADT separate workshops have been organized for key stakeholders.

Short summary of results (<250 words)

This deliverable report details the methodology and results focusing on adaptation decisions across seven ADTs as part of Work Package 3. The seven ADTs include flood risk, forestry and ecosystems, water-food-biodiversity, health and justice, finance, transport and supply chains, and cross-cutting decisions. In this document, the full results are shared including the specific decision-making context, common adaptation strategies, key barriers and opportunities for implementation, and lessons learnt. Lessons are drawn from the ACCREU case studies (D3.2) and cases reported in wider literature. The results also draw from the ADT workshops that were held per ADT. The ADT documentation follows a policy-first approach with the goal to support stakeholders in making informed decisions on climate adaptation within their ADT domain, including insights on economic appraisal of adaptation strategies and understanding barriers and opportunities for implementation. The ADT analysis shows that each adaptation field has their own way of classifying adaptation strategies. Despite these differences, there are common barriers across the ADTs, with some barriers more specific to type of adaptation options. The ADTs also highlight the importance of considering distributional effects and broader economic appraisal. The ADTs are synthesized and several directions for future adaptation planning and research are presented.

Evidence of accomplishment

Besides the ADT results reported in section 3, the ADTs also contributed to the following:

Reports

- Caloia, F. G., van Ginkel, K. C. H. and Jansen, D., 2023. Floods and financial stability: Scenariobased evidence from below sea level. DNB Working Paper No. 796. [Also under review for a peerreviewed scientific publication.]
- Zachariadis T., Gavrouzou M., Zittis G., Hadjinicolaou P., Economou T., Kekkou F., Giannakis E. and Zoumides C. (2025). Assessment of Physical and Economic Impacts of Climate Change in Cyprus. Available at <https://www.cyi.ac.cy/index.php/stedi-rc/research-information/stedi-rcscientific-publications.html>
- Zachariadis, T. Investment Needs and Benefits from the Adaptation of Cyprus to Climate Change. April 2025. Available in Greek and in English.

Published papers:

- van Ginkel, K.C.H., Rijken, B., Hoogvliet, M., van Veggel, W., Botzen, W.J.W., Filatova, T. (2025). How an economic and financial perspective could guide transformational adaptation to sea level rise. *npj Climate Action* 4(89). <https://doi.org/10.1038/s44168-025-00297-4>

Manuscripts under review:

- Ingels, M.W., Tesselaar, M., Brusselaers, J., Tiggeloven, T., Aerts, J.C.J.H., Botzen, W.J.W. (*under review*). Projecting the Flood Insurance Protection Gap for Households and Businesses Under Climate Change

- van Tilburg, A.J., van Ginkel, K.C.H., Brusselaers, J., Botzen, W.J.W. (*under review*). Comprehensiveness of cost-benefit analysis in flood adaptation case studies: A systematic review.

Manuscripts in prep:

- Ingels, M.W., Endendijk, T., van Ginkel, K.C.H., Tesselaar, M., Renjie, R.W., Brusselaers, J., Aerts, J.C.J.H., Botzen, W.J.W. (in prep). Assessing financial risk and the role of insurance of flooding for residential and commercial loan portfolios
- McGlade, K., Tröltzsch, J., Dicke, F., van Tilburg, A.J. (in prep). Just2Adapt: a new tool for assessing the justice dimensions of heat-health adaptation strategies
- van Tilburg, A.J., Ingels, M.W., Dalmijn, B., van Ginkel, K.C.H., Brusselaers, J., Botzen, W.J.W. (in prep). Distributional analysis flood compensation: comparison of government compensation and insurance coverage at the household-level for the Netherlands.
- van Tilburg, A.J., Brusselaers, J., van Ginkel, K.C.H., Botzen, W.J.W. (in prep). Preferences and research agenda for future flood cost-benefit analysis: survey and interviews among flood CBA researchers

Weblinks:

- Risky Science Podcast. (2025). Are Insurance Risk Models Failing At Basic Climate Math?. <https://www.riskmarketnews.com/are-insurance-risk-models-failing-at-basic-climate-math/>
- Red&Blue. (2025). From Risky to Resilient Waterfronts – Highlights from the 2025 Red&Blue Symposium. <https://redblueclimate.nl/news/from-risky-to-resilient-waterfronts-highlights-from-the-2025-redblue-symposium/>
- Vereniging Delta Metropool (2025). From Risky to Resilient Waterfronts Highlights from the 2025 Red&Blue Symposium <https://deltametropool.nl/nieuws/from-risky-to-resilient-waterfronts/>
- UK Climate Risk. 2026. The Costs of Adaptation for UK Transport and Land Systems (Paul Watkiss Associates). <https://www.ukclimaterisk.org/publications/the-costs-of-adaptation-for-uk-transport-and-land-systems/>

Contents

Contents	4
1. Introduction.....	6
2. Approach to ADT analysis.....	9
3. ADT results	10
ADT 1 – Flood risk (Deltares).....	10
1. Decision context.....	10
2. Adaptation strategies	10
3. Assessment of case studies.....	11
4. Lessons learned	14
5. Role of sectoral models	15
6. Conclusion.....	15
ADT 2 – Forestry and ecosystems (DTU).....	17
1. Decision context.....	17
2. Adaptation strategies	18
3. Assessment of strategies – Barriers to implementation.....	21
4. Lessons learned for implementation of strategies	27
5. Role of sectoral models for implementation of strategies	28
6. Conclusion.....	28
ADT 3 – Water-food-biodiversity (IIASA).....	30
1. Decision context.....	30
2. Adaptation strategies	30
3. Assess strategies and barriers to implementation.....	32
4. Role of sectoral models for implementation of strategies	33
5. Key recommendations.....	34
ADT 4 – Health and justice (Ecologic)	36
1. Decision context.....	36
2. Adaptation strategies and social justice assessments	37
3. Barriers to implementation.....	42
4. Summary and conclusions.....	44
5. Recommendations	45
ADT 5 – Financial and private sector (Deltares/VU).....	47
1. Decision context.....	47
2. Transmission channels – from climate risk to financial sector	49
3. Studies on climate risks to the financial sector	51
4. Adaptation measures	56
5. Assessment of strategies – barriers to adaptation.....	61
6. Lessons learned for implementation of strategies	64
7. Conclusion.....	65
ADT 6 – Transport and supply chains (Deltares).....	66
1. Introduction	66
2. Adaptation options in transport infrastructure.....	66

3. Who decides: Actors and decision-making levels.....	69
4. Value judgements that shape adaptation choices	72
5. Adaptation decisions in practice: three cases	75
6. Conclusion and recommendations.....	77
ADT 7 – Cross-cutting decisions (PWA)	79
1. Decision context.....	79
2. Adaptation strategies	79
3. Barriers to implementation and lessons on how these can be overcome	81
4. Policy insights	83
4. Synthesis	86
4.1 Key findings	86
4.2 Towards generic adaptation pathways.....	91
4.3 Future directions.....	92
5. References.....	94
Annex.....	110
Appendix A: Generic ADT format	111
Appendix B: ADT1	113
Appendix C: ADT2	115
Appendix D: ADT2	115
Appendix E: ADT5.....	116

1. Introduction

As part of the ACCREU project, one of the objectives is to derive **actionable insights and practical recommendations for common adaptation decisions that European communities and regions** will be confronted with. Within the ACCREU project, we refer to such archetypical decisions as ‘Adaptation Decision Types’. This deliverable (D3.3), reports on the findings of these adaptation decision types. In total, 7 adaptation decision types (ADTs) have been formulated which are closely connected to Adaptation Missions of the EU (see Figure 1). For each ADT, generic adaptation strategies will be formulated that offer a broad range of generalized strategic directions for decision-makers across the EU that face comparable problems. The difference between the case study and the ADT analysis is that in the case study analysis the focus is on the specific needs of one decision maker, while the ADT analysis is addressing more generic needs of other decision makers that face comparable problems. The insights on these decision types are derived from a synthesis from the 15 ACCREU case studies (D3.2, Figure 1), stakeholder consultations, wider literature, and the sectoral WP2 results.

Why is a synthesis needed? Because the case study analysis is *stakeholder need oriented*, whereas the decision types are oriented at the *needs of all European territories*. The case studies give insight in the practical economic adaptation considerations of local, regional or national stakeholders. The decision types are focused on the generic economic adaptation considerations that many decision-makers in Europe face. See Table 1 for a description of the decision problems that each ADT addresses and the decision-makers that are tasked with making decisions on these problems.

This approach is in line with the *Mission on Adaptation* of the European Commission. The objective of this mission is “to support at least 150 European regions and communities in becoming climate resilient by 2030”. By focusing on a *selection* of regions and communities, the mission seeks to build momentum for *all* regions and communities that need to become more climate resilient. Likewise, our case studies focus on a *selection* of regional and national adaptation decisions, while our decision type analysis seeks to learn from these for *all* regions and communities.

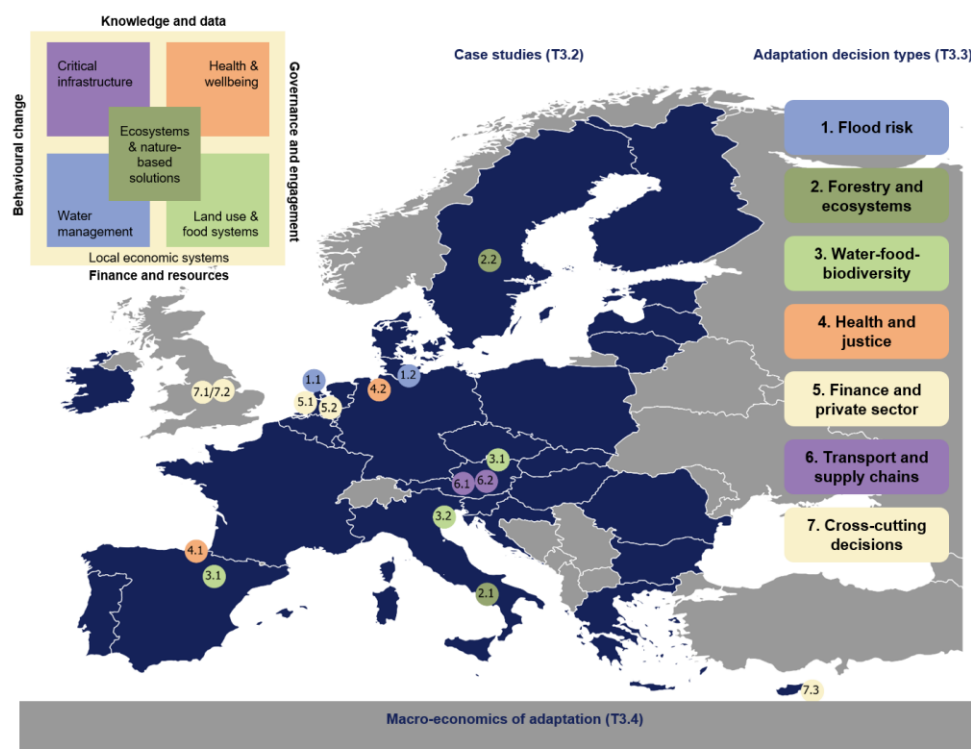


Figure 1. Relation between case studies, adaptation decision types and the European Mission on Adaptation.

Table 1. Decision context and decision-makers within each adaptation decision type.

ADT	Decision Context	Case study stakeholders	Generic stakeholders (decision-makers)
1 (Flood risk)	Regional authorities are tasked with finding ways to cope with increasing flood risks, under limited budgets and while also pursuing other spatial planning goals.	1.1: Water board HHNK & Province North-Holland (NL) 1.2: Leitung WWF Ostseebüro, Hitergrund in Paläoklimatologie und- biologie; IUCN	Local water boards; Regional governments (provinces/states); National governments; Nature conservation agencies; European Agencies
2 (Forestry and ecosystems)	Regional and municipal authorities are tasked with deciding on the creation of new wildfire management plans, for which they need to coordinate with partners beyond the regional and municipal level, such as private forest owners and forest managers.	2.1: STRESS-SCARL, Sorrento and neighboring municipalities in the Campania region 2.2: Forest owner and management company (Miljö och Skog i Leksand Aktiebolag)	Forest managers; Regional governments (provinces/states); Local governments; Private land owners; Private companies
3 (Water-food-biodiversity)	River basin managers have to find ways to allocate scarce water resources, while also optimizing towards food and biodiversity objectives, i.e. trying to find a delicate balance between diverse water users including drinking water, large-scale irrigation, and nature.	3.1: Ebro River Basin Authority; Ministry of Agriculture (Czech Republic); Ebro Hydrographic Confederation (EHC; River Basin Authority); Scientists (University of Zaragoza, University of Aberdeen) 3.2: WWF Italia	River basin managers; National governments; Regional governments; nature conservation agencies
4 (Health and justice)	Municipalities and regions must adapt to heat-related impacts through specific plans and take other adaptation measures to ensure public health, while making sure that such adaptation decisions do no exacerbate social injustice through distributional impacts e.g. harm vulnerable groups	4.1: Basque Environmental Agency (Ihobe) 4.2: Ministry for Environment, Climate and Science of the Free Hanseatic City of Bremen – Directorate for Climate Adaptation (Landeszentrale Klimaanpassung), in coordination with Ministry for Health, Women and Consumer Protection of the Hanseatic City of Bremen and the Health Authority (“Gesundheitsamt”).	Local governments; Regional governments; National governments
5 (Finance and private sector)	Macroprudential policymakers, financial supervisory institutions, and financial sectors such as banks and insurers, face a decision on what (new) role they are going to fulfil in support of the urgent societal need to adapt to climate change, while being pushed by several new EU regulations.	5.1: Dutch Central Bank 5.2: Dutch Association of Insurers	Banks; National Central Banks; European Central Bank; Insurance companies

6 (Transport and supply chains)	The transport sector is tasked with adapting to climate risks while navigating competing objectives and complex interactions between stakeholders.	6.1: Federal Ministry for Agriculture and Forestry, Climate and Environmental Protection, Regions and Water Management (BMLUK; Austria) 6.2: Two companies in Austria	National governments; European-scale governments; Transport companies; Sustainable energy companies
7 (Cross-cutting decisions)	National governments have to know how much financial resources they need to reserve for funding the adaptation needs for a myriad of sectors and hazards.	7.1 & 7.2 : Defra; HMT; OBR 7.3: Ministry of Agriculture, Rural Development and Environment of Cyprus; Ministry of Finance of Cyprus	National governments

The protocol for the ADTs was developed as part of D3.1. An updated version of the methodology is provided in Section 2. The results per ADT are reported in Section 3. In Section 4, we provide a final synthesis with key results and implications.

2. Approach to ADT analysis

Similar to the case study analysis (D3.2), we take a ‘policy-first approach’ in the analysis of the decision types (D3.3). This means that the analysis departs from a description of the decision context and where applicable, an overarching policy question. In some cases, this involves detailed questions that are answered within the ADT, while for others this involves a broader question for which a sub question can be answered in the ADT analysis.

A decision type is archetypical adaptation decision that many European regions and communities will need to make. The difference between adaptation decision types and case studies is best illustrated with an example. For example, let’s consider case study 3.1: achieving sustainable water resource management while ensuring critical water services including drinking water supply and irrigation. This is a specific case study for the Thaya river basin and Czech government. It is representative for a decision type that many European regions and communities have to make: how to allocate water while dealing with competing objectives and increasing scarcity as a result of climate change?

A key ingredient of the ADT consists of formulating archetypical adaptation strategies or directions, further referred to as ‘generic adaptation strategies’. These **generic adaptation strategies** can be considered overarching key strategic choices that are relevant within the policy context of each adaptation decision type. These are used to generalize insights and shape the landscape of policy directions of each ADT. The generic adaptation strategies will guide the different directions that decision-makers can take when faced with similar policy questions as addressed in the ADTs. For this reason, the ADT analysis draws from the ACCREU case studies but also from case studies in the wider literature. Additionally, for each ADT a workshop was organized with relevant stakeholders across Europe. In these workshops, information was shared on the preliminary ADT outputs and information was collected on additional case studies, barriers and enablers to adaptation in the ADT. The ACCREU models could further provide input to the ADTs, as European regions may benefit from knowing how sectoral models could help their adaptation questions.

A generic format for the ADT reporting was provided to the ADT owners. This framework was not intended as a required format for the final deliverable but could be adapted to fit the specific focus for each ADT. The general format can be found in Appendix A.

3. ADT results

ADT 1 – Flood risk (Deltares)

1. Decision context

As a result of both climate change and socioeconomic development, the risk of coastal, fluvial and pluvial floods will likely increase in Europe (Skougaard Kaspersen et al., 2017; Dottori et al., 2020; Vousdoukas et al., 2020). These risks are not distributed equally across Europe, for instance the United Kingdom and France are particularly at risk of coastal flooding (Vousdoukas et al., 2020), and, out of 20 analysed European cities, Antwerp, Brussels, and London are particularly at risk of pluvial floods (Essenfelder et al., 2022).

Under the Floods Directive (2007/60/EC), European Union member states are obliged to take action to reduce flood risks. Within the Floods Directive, member states have considerable independence in addressing these flood risks (Adamson 2018). The relevant stakeholder groups regarding the implementation of adaptation strategies in Europe could range from regional water authorities, other local or regional or national governmental bodies, to also communities, companies or individuals. Within this ADT, the focus is on planned adaptation by public authorities. These authorities decide on funding, strategic directions for flood protection, and design of flood strategies, which is relevant for the ADT analysis. However, besides the ‘implementing stakeholder’ other stakeholders might have an interest in the measures chosen, as also showcased in both flood risk case studies in ACCREU: in CS1.1 the local housing association had an interest in a multifunctional dike on which they could build housing; whereas in CS1.2, nature organizations have an interesting in implementing wetlands and land reclamation for nature conservation purposes. These different interests influence the wider decision-making context, and are hence still referenced here.

Grey adaptation measures have long prevailed due to lock-ins and self-reinforcing mechanisms (Gibbs, 2015; Groen et al., 2023; Seebauer et al., 2023; Wesselink et al., 2015). In part due to the methods used in economic appraisals, as excluding co-benefits and co-costs and make green and soft measures less appealing comparatively (Brouwer & van Ek, 2004; Ruangpan et al., 2024). Although Gallucio et al. (2024) report that a transition towards more green and soft measures for coastal protection can be observed across Europe, various barriers still remain for the adoption of green measures (Moraes et al. 2022).

In light of this context, the focus in this ADT is on the scope of the economic appraisals used for flood adaptation measures. Of particular interest are whether co-benefits are included, the risk assessment goes beyond direct economic effects, and distributional and procedural justice are considered. This was assessed through two systematic literature review of peer-reviewed literature: one on cost-benefit analysis and one on multi-criteria analysis. These two reviews included flood case studies on the global scale. Finally, a third scoping review looked at flood adaptation CBAs in grey literature, restricted to European cases. While the ACCREU case studies only focused on coastal flooding, the review also covered fluvial and pluvial flooding.

In total there were 225 academic CBAs retrieved, of which 97 were further assessed, as they included at least one ‘comprehensive’ component. Of these 97 cases, there were 26 in the European Union (30 in Europe). There were 27 grey literature documents retrieved that included a flood adaptation CBA (23 in the Netherlands), and 27 academic MCAs (12 in Europe).

2. Adaptation strategies

Several different classifications exist for adaptation or disaster risk reduction measures. Here, we use the classifications of grey, green or soft, and of prevention, mitigation, preparedness, response, or recovery strategies (see Sabri et al., 2024 for definitions for this second group). Of the 97 reviewed cases, 82 included prevention measures, and 44 damage mitigation measures. Only four case studies included preparedness measures (Godschalk et al., 2009; Kull et al., 2013; Yaron & Wilson, 2020; Zeng et al., 2023), one included a response measure, i.e. preventative evacuation (Wojciechowska & Kok,

2013) and one included a recovery measure, i.e. insurance (Yohe et al., 2011). Section 6 groups these measures into four strategic directions for flood adaptation (Table 1.4)

For most of the case studies that only included prevention and/or mitigation measures, this entailed hard infrastructure or green measures. However, some of the assessed measures were soft measures, such as zoning (Hudson et al., 2022; Kousky et al., 2013; Yamagami & Kawasaki, 2024), buyouts and land acquisition (Atoba et al., 2021; Hayes, 2004; Lockwood et al., 2024; Zhang et al., 2023), early warning approaches (Johnson et al., 2020; Ocio et al., 2016; Yamagami & Kawasaki, 2024), as well as retreat and relocation (Corderi-Novoa et al., 2021; das Neves et al., 2023; Hayes, 2004; Jiffry & Al-Mohannadi, 2024; Revell et al., 2021; Thacker et al., 2018). Overall, there were 65 case studies that assessed a hard (grey) strategy, 31 a green measure, 30 a hybrid grey-green measure, 20 a soft measure, 9 a grey-soft measure, and 2 a grey-green-soft measure. Hence, the reviewed CBA cases also predominantly focus on grey and prevention measures. Table 1.1 provides an overview of some of the more common adaptation measures per flood type that were analyzed in the reviewed case studies. In the three reviews discussed in this ADT, fluvial and coastal were more common. Pluvial flood adaptation case studies were least common.

Table 1.1: Examples of common adaptation measures in the analysed academic CBA case studies per flood type.

Pluvial flood	Riverine flood	Coastal flood
- Improved drainage systems, like open urban drainage systems, retention & detention areas	- Dikes	- Dikes and seawalls
- Improved infiltration	- Extra space for rivers	- Asset protection
- Larger pipes	- Afforestation	- Green protection (wetlands, marshes, mangroves)
- Green roofs	- Retention areas	- Dunes
	- Asset protection	- Beach/sand nourishment
	- Relocation and zoning	- Relocation

These findings are similar to Azhar et al. (2025), in a review of global flood adaptation studies, that most studies cover green measures, followed by grey measures, and finally soft measures. In Europe: grey is among the most common in Eastern Europe, in Southern Europe green and grey occur roughly the same. Northwestern Europe has the highest number of reviewed studies, the most common measures are grey, followed by soft, and finally green.

3. Assessment of case studies

3.1 Academic flood CBAs

The 97 retrieved case studies were systematically scored across four categories (ecological, social, spatial, temporal) and five groups (risks, co-effects, distributional effects, procedural justice, and uncertainty). The aim was to see if these themes and categories receive equal consideration in flood adaptation CBAs.

The analysis shows that procedural justice and uncertainty receive little attention in CBAs across all four categories. Only temporal distributional effects are included in the majority of the cases, other distributional effects are not commonly included. Around a third of the cases include ecological and social co-effects, but the inclusion of spatial co-effects (spillovers) is not common. Overall, cases score the best across all four categories on the inclusion of risks (Figure 1.1). See Table 1.2 for an overview of the most common risks and co-effects included per category.

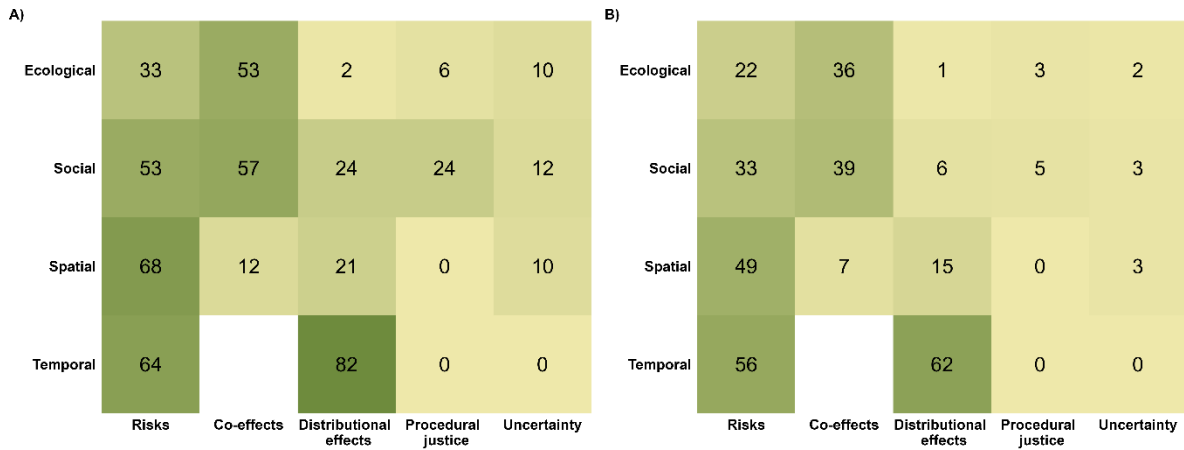


Figure 1.1: Frequency of scoring on each dimension; total number of case studies is 97. A) Number of case studies scoring more than zero points on each dimension; B) Number of case studies scoring more than one point on each dimension. Source: van Tilburg et al. (in prep.)

Table 1.2: Most common types of risks and co-effects included in the analyzed case studies per category.

Category	Risks	Co-effects
Ecological	Damage to nature Livestock loss	Carbon sequestration Habitat quality
Social	Mortality Morbidity	Recreation Aesthetics
Spatial	Business interruption Travel disruption	Tax revenue Shipping

In the temporal category, inclusion of risks was scored based on the inclusion of exposure (socioeconomic), vulnerability, and climate scenarios. Around a third of case studies used one or more exposure scenarios, while around 61% used one or multiple climate scenarios. There were only five cases that used multiple climate and socioeconomic scenarios (Broekx et al., 2011; Farahmand et al., 2024; Penning-Roswell et al., 2013; Scussolini et al., 2017; Yamagami & Kawasaki, 2024).

Out of 97 cases, about half included co-effects¹. However, only 12 included negative co-effects (co-costs), all others were co-benefits (positive co-effects). For a more complete overview of some of the research gaps for each category-group combination, see Table 1.3.

Table 1.3: Gaps in the comprehensiveness of reviewed flood adaptation cost-benefit analyses (academic cases).

Group	Category			
	Ecological	Social	Spatial	Temporal
Risks	Applied in small share of cases	Applied in small share of cases	Few include risk transfers of an adaptation measure to another area	Only one changes vulnerability over time Few apply multiple socioeconomic & climate scenarios
Co-effects	Few include co-costs Applied in small share of cases	Few include co-costs Applied in small share of cases	Few include spatial spillovers	–
Distributional effects	No quantitative disaggregation across species	No intersectional analysis of distributional effects	Few disaggregate effects for areas outside project area	No disaggregation per generation

¹ Since only comprehensive cases were included, the share of flood adaptation CBAs that include co-effects is even lower: less than 25%.

		Few applications of equity weights		Few apply declining discount rates
		No use of other social welfare functions		Few use lower discount rates for social or ecological effects
Procedural justice	No involvement of ecological experts	Little involvement of local stakeholders	No involvement of stakeholders from affected areas outside project area	No involvement of representatives for future generations
		No attention for inclusive participation		
Uncertainty	Applied in few cases	Applied in small share of cases	Applied in few cases	No exploration of changing values/preferences over time

3.2 Policy flood CBAs

Of the 27 European grey literature CBAs reviewed, 23 were on Dutch case studies. These CBAs were assessed on their inclusion of co-effects and equity. In policy CBAs, co-effects were included in over half of the cases, which is a lot higher than the academic CBAs with less than 25% including co-effects. However, it is worth noting this could be because of geographical differences: of the Dutch academic cases also more than half of the cases included co-effects. Compared to ecological and social co-effects, spatial spillovers were less commonly included in both academic and policy CBAs.

None of the policy CBAs present the adaptation outcomes for different social groups, like income or age. Moreover, none of the policy CBAs apply equity weights. The analysis of the policy CBAs was complemented with nine interviews among Dutch CBA experts. These interviews revealed that experts do not agree on whether a CBA is the most appropriate place to analyse distributional effects. One reason provided for this was because CBA tends to be used later in the decision-making process in the Netherlands, whereas considering distributional effects might be more suitable earlier in the process. Further, in the Dutch context, they also stated accounting for distributional effects was not as important, as the flood protection measures for primary flood defences implicitly account for this, for instance through ensuring a minimum protection standards for flood mortality. For pluvial flooding, it was stated that accounting for distributional effects might be more relevant. Distributional impacts could also be assessed through social impact assessments.

3.3 Academic flood MCAs

The 27 retrieved academic MCAs were scored on their inclusion or acknowledgment of equity, procedural justice, uncertainty, intangible impacts and co-benefits & trade-offs. Equity is the only component that is not included in the majority of case studies. Overall, the cases score the best on the uncertainty, as it is either acknowledged or operationalized in all MCAs (Figure 1.2).

Of the 5 case studies that assessed equity, four did so through spatial differentiation; other methods were distributional weights or separate scoring for different socioeconomic groups. One of the cases did all three (Camare & Lane 2015). Of the 20 cases scoring on 'Co-benefits & Trade-offs', 19 included co-benefits while only 5 included trade-offs. This is similar to the pattern in CBA studies where co-benefits are more commonly assessed than co-costs. All 23 cases scoring on uncertainty do so through sensitivity analysis, other methods for uncertainty inclusion where scenario analysis and a discussion of the uncertainty, with 10 cases doing all three.

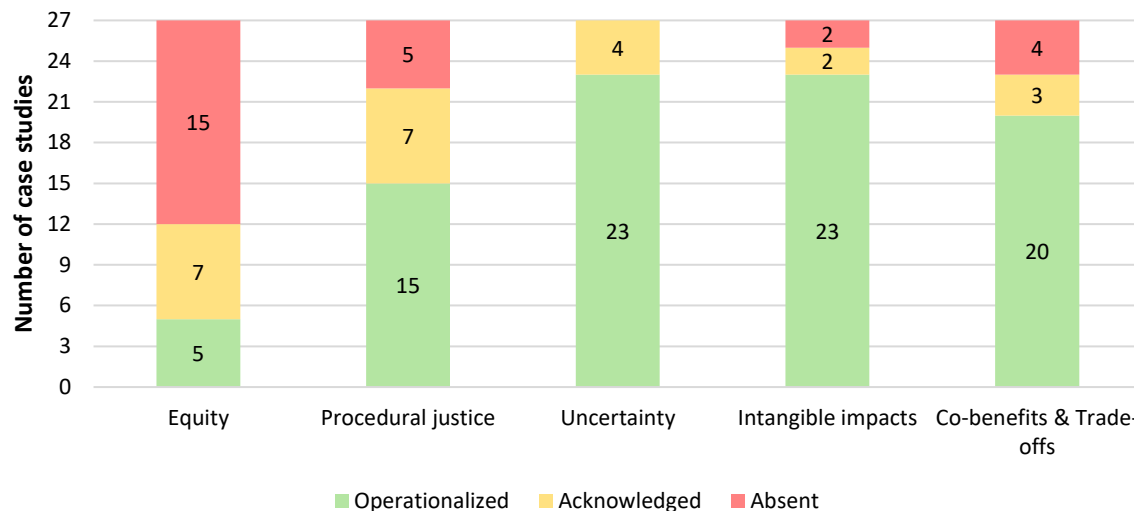


Figure 1.2: Frequency of scoring on each dimension; total number of case studies is 27.

4. Lessons learned

Here, we highlight barriers and recommendations related to co-effects inclusion, equity inclusion and flood adaptation more broadly, in more detail. Firstly, the low share of academic case studies applying co-effects in CBA was one of the gaps identified in Section 3. This relates to the findings of Yamagami & Kawasaki (2024) that adaptation benefits are commonly defined solely on flood risk reduction and not on wider effects, something also stated by one of the interviewees. Several of the reviewed CBA cases highlighted that the inclusion of co-effects affected the CBA conclusions and/or relative ranking of the measures. For instance, nature-based solutions performed better when co-effects were included (Alves et al., 2019; Gokcekus et al., 2024; Ruangpan et al., 2024). Some of the barriers listed in the cases on the inclusion of co-effects were the **lack of data or issues to monetize them** (Bal & Vleugel, 2014; Dittrich et al., 2019; Florec et al., 2017; Kousky & Walls, 2014; Revell et al., 2021) and the **possibility of bias** in the co-effects data (Bal & Vleugel, 2014; Gokcekus et al., 2024). Allocating more resources to “collect (and standardize) ‘green’ data” (Bal & Vleugel, 2014), could help to address this barrier, as could the collaboration between ecological and economics disciplines (Bal & Vleugel, 2014). Interestingly, inclusion of co-benefits was a lot more common in academic MCAs. A way forward to overcome barriers to co-effect inclusion in CBA could be a combined CBA-MCA approach. This is already done by several of the reviewed CBA cases (e.g., Ruangpan et al. 2024; Penning-Rowsell et al. 2013; Porthin et al. 2013; Nardini and Pavan 2012).

Secondly, we found that distributional effects were not commonly included in CBAs. For instance, only three academic cases applied equity weights (Lockwood et al., 2024; Markanday et al., 2021; Zhang et al., 2023), and none of the cases applied multiple social welfare functions, even though the application of equity weights could affect where or whether to act (Lockwood et al., 2024; Markanday et al., 2021). In policy CBAs and academic MCAs the inclusion of equity was also not common. Some aspects that may explain this are **practical barriers**, such as **how to select an appropriate value for equity weights** (Lockwood et al., 2024), or normative barriers, such as **conflicting interests between social and economic performance** (Lockwood et al., 2024; Zhang et al., 2023) or that equity is seen as a **political decision** (Bal & Vleugel, 2014), and there is **no consensus** on whether it belongs in CBA (interviews). A way to address such conflicts would be to focus further deliberation on the desired public policy outcomes (Godschalk et al., 2009), and stakeholder involvement on the preferred distributional effects of flood adaptation measures (Lockwood et al., 2024). The ACCREU cases in ADT 4 address adaptation justice in much more detail through the Just2Adapt framework. The framework is useful for assessing how justice is addressed in individual adaptation actions and could be adapted to a flood risk management context. This relates to input from interviewees that equity may not need to be part of CBA, but could be assessed elsewhere to. More guidance on when and how to assess equity in (flood) adaptation planning could hence be useful.

Thirdly, not all barriers to flood adaptation relate to the economic appraisal. Some of the other types of barriers were the **opposition of stakeholders** (Bal & Vleugel, 2014; Broekx et al., 2011; Florec et al., 2017; Revell et al., 2021; Scussolini et al., 2017; Zhou, Halsnæs, et al., 2012), or the **issues of navigating across different levels of government** (Bal & Vleugel, 2014; Broekx et al., 2011; Scussolini et al., 2017). This also relates to what some of the stakeholders brought up during the ADT 1 workshop: a good ‘business case’ is only one of the enabling conditions for nature-based solutions. Other enabling conditions (that would apply to any type of adaptation): are “Institutional embedding”, “Multi-stakeholder approach”, “Management, monitoring and maintenance”, “Technology and system knowledge”, and “Capacity building”.² The importance of including stakeholders was also highlighted by some of the reviewed cases (Hudson et al., 2022; Keenan & Oldfield, 2012; Lockwood et al., 2024). Since the MCA cases scored well on procedural justice, a combined MCA-CBA approach may also help in that regard.

Box 1: Flood CBA further research

As follow-up research to the systematic literature review, we are conducting surveys and interviews among flood CBA authors (academic papers). Through this research we aim to assess i) what factors affect whether authors decide to incorporate more comprehensive dimensions (e.g. co-effects, sensitivity analysis on discount rates, equity-weights etc.) CBA; ii) whether there is consensus on the preferred scope of flood CBAs; iii) how the limits to CBA applications are understood; and iv) recommendations for flood CBA improvements. This will inform a research agenda for future flood CBAs.

5. Role of sectoral models

Sectoral models were used in many of the case studies. See Appendix B, for a short overview of some of the models used, their advantages and disadvantages, and the academic CBA case studies and ACCREU case studies in which they were applied.

6. Conclusion

In summary, the comprehensiveness of CBAs is limited, even though (some of) the cases that include more comprehensive components find that it can affect the CBA outcomes. While including all components may not be feasible, prioritization of the elements for CBA could be conducted in a participatory manner with stakeholders. Furthermore, other low hanging fruit to enhance the robustness of CBA is to apply more sensitivity analyses on discount rates, moral principles, risks, co-effects, and socioeconomic/climate scenarios.

The European Commission CBA guide refers to disaggregation outcomes by affected groups through a stakeholder matrix as the preferred way of incorporating distributional effects, but also refers to equity weights (welfare weights) as an option (EC, 2014). More detailed guidance on when these approaches are suitable and how to apply them tailored to flood adaptation contexts could be useful. The guides on CBA and economic appraisal (EC, 2014; 2021a) state not to include indirect or induced effects, to avoid double-counting. This, however, assumes perfect markets and that the (re)distribution of effects is not relevant. The guidelines do explicitly recommend the inclusion of externalities (EC, 2014) – although this hardly occurred in the reviewed cases. However, these guidelines are applicable to large-scale investments and might not apply to (all) flood adaptation investments. Within the EU Floods Directive (2007/60/EC) the use of cost-benefit analysis is explicitly recommended in the context of ‘transnational effects’. In other cases, it might depend more on local/national guidelines. For example, Dutch CBA guidelines refer to creating an overview of all the effects as one of the first CBA steps, recommend the use of long time horizons and the inclusion of distributional analysis when distributional effects are substantial (Romijn & Renes, 2013). More practical examples good be helpful, however. As also

² For more information on them, see <https://www.ecoshape.org/en/enablers/>

highlighted in the interviews (Section 3.2), it might be important to consider equity in an early phase of adaptation planning – earlier than CBA is commonly used. This also relates to the findings in ADT4 and what Planas-Carbonell et al. 2023 write in relation to urban greening, that consideration of equity early on may already broaden the scope of the measures that are considered. However, this constitutes a more substantial shift to adaptation planning than a change in guidelines.

Overall, the results of the analysis highlight the risks that could occur when broader societal effects like biodiversity, equity, or procedural justice are not considered. As noted in Section 1, grey measures have long prevailed in European flood adaptation; the reviewed cases suggest this is partly reinforced by current appraisal practice, as the benefits of green and soft measures depend more heavily on co-effects that are usually left out. The main recommendation to reflect on such broader dimensions in climate adaptation planning extend beyond regions where CBA and/or MCA are mandatory – also without the institutionalization of these tools, ignoring equity or co-effects may lead to sub-optimal outcomes. Besides grey adaptation measures there are various other avenues to flood adaptation that can be taken. Table 1.4 classifies these directions into four strategic directions for flood adaptation.

Table 1.4: Strategic directions for flood adaptation.

Strategic directions	Part of risk addressed	Presence in reviewed appraisal cases	Type of measures
Keeping the water out (protect)	Hazard	Most common; 82 of 97 cases include prevention measures and 65 assess a grey measure	Dikes, seawalls, storm surge barriers, dunes, beach and sand nourishment, larger pipes and improved drainage systems
Making space for water	Hazard	Common but less than grey; 31 cases assess a green measure and 30 a hybrid grey-green measure	Room for rivers, retention and detention areas, wetlands and marshes, afforestation, improved infiltration, green roofs
Reducing what is exposed	Exposure	Not commonly assessed: part of the 20 cases assessing a soft measure	Zoning, buyouts and land acquisition, retreat and relocation
Limiting impacts of flooding	Vulnerability/Recovery	Rarely assessed; four cases include preparedness measures, one a response measure and one a recovery measure. Grey measures like floodproofing somewhat more commonly regarded.	Early warning approaches, preventative evacuation, insurance, but also grey measures like flood proofing

ADT 2 – Forestry and ecosystems (DTU)

1. Decision context

Forests play an important ecological and economic role across Europe, but they are threatened by the increasing risk from wildfire due to climate change. In the Mediterranean region, prolonged droughts and high temperatures create favorable conditions for forest fires (Bowman et al., 2017), while areas in Northern and Central Europe, historically less prone to wildfires, are now also experiencing growing risks due to changing weather patterns (Fernandez-Anez et al., 2021). These developments highlight the need for adaptive and region-specific prevention, response, and adaptation strategies for wildfire risk management to protect critical ecosystems while minimizing economic and social impacts.

Glossary

Prevention aims to reduce the likelihood that wildfires will start or spread. The objective is to address the causes and conditions that drive wildfire risk. Examples of measures include fuel management (thinning forests, removing dead vegetation), prescribed or controlled burning, firebreaks and fuel breaks, restrictions on open fires during high-risk periods and public awareness campaigns.

Response refers to actions taken during or immediately after a wildfire event to protect people, assets, and ecosystems to minimize the consequences of a wildfire. Examples of measures and actions include environmental monitoring, fire detection and early warning systems, firefighting, aerial water drops, evacuation, and protection of critical infrastructure.

Adaptation to wildfire risks focuses on reducing exposure, vulnerability and on increasing human and ecosystem resilience to current *and* future conditions. Climate change adaptation to accommodate wildfire risks can refer to any of the four disaster risk management phases: prevention, preparedness, response and recovery (resilience). Adaptation overlaps with and includes aspects of forest management.

Transformative adaptation, according to the definition of Kates et al. (2012), involves fundamental changes to the landscape to make it fire-resilient such as establishing firebreaks or planting fire resistant tree species.

Incremental adaptation includes actions such as reducing tree density and prescribed burning.

The primary policy questions are: How to adapt to increased wildfire risks? What are the most cost-effective wildfire management strategies and financial incentives for minimizing impacts on human-natural systems now and in the future? The main interested stakeholder groups are (i) private forest managers; (ii) public forest managers, (iii) forest owners; (iv) forest owner associations, and (v) insurance companies.

(i) Private forest managers, operating at the local level, play a critical role in implementing on-the-ground wildfire adaptation measures and promoting fire-resilient landscapes. Their responsibilities include several wildfire adaptation strategies such as managing forests through thinning, pruning, removing dead vegetation and prescribed burns, establishing and maintaining firebreaks to limit fire spread, creating evacuation routes, planting fire-resistant tree species, and maintaining biodiversity to improve forest resilience (Dandy, 2012). They also play an important role in monitoring and reporting wildfire risks for early detection of and response to fire ignitions. They are responsible for educating staff on wildfire response and prevention measures. Private forest managers adopt practices to protect their businesses but also reduce wildfire risks for forest owners by following specific regulatory guidelines issued by national authorities such as the Swedish Forestry Agency (Skogsstyrelsen, 2025).

(ii) Public forest managers, such as national and regional forest agencies or environmental protection agencies, coordinate large-scale wildfire adaptation and forest management activities. Their roles include designing and implementing regional fire management plans, laws and regulations promoting wildfire-resilient practices, conducting risk assessments, and restoring degraded forest landscapes to

improve ecosystem health and fire resistance. They also invest in firefighting technologies, including unmanned aerial vehicles (UAVs) and other types of drones, sensors, and rapid response systems.

(iii) Forest owners operating locally are responsible for managing their lands to reduce fire risks and enhance forest resilience. They adapt by implementing wildfire preventive measures such as thinning, pruning, removing dead vegetation, establishing and maintaining firebreaks and fuel breaks to control fire spread, creating buffer zones between forested areas and vulnerable infrastructure, and monitoring forests for early signs of fire threats. Planting fire-resistant tree species and creating diverse forests (avoiding monocultures) further enhance forest resilience. Forest owners can adapt by taking courses on adaptation to wildfires, joining forest owner associations to share knowledge and resources and by purchasing insurance to mitigate financial losses. In post-fire scenarios, they lead the recovery efforts, including reforestation, debris removal, and soil stabilization. Their actions protect their properties while strengthening ecosystems. By implementing relevant strategies, forest owners are crucial for reducing wildfire impacts on human and natural systems.

(iv) Forest owner associations represent the interests of individual forest owners, providing them with resources and training. These associations act as intermediaries, facilitating knowledge exchange and encouraging the adoption of wildfire prevention and adaptation practices among their members. They play a crucial role in advocating financial incentives, subsidies, or insurance schemes that support wildfire resilience. These associations coordinate response efforts by fostering collaboration among forest owners.

(v) Insurance companies operating at the local or national levels contribute to wildfire adaptation by incentivizing risk-reducing behaviors through pricing mechanisms. Insurers encourage proactive wildfire management by offering risk-based insurance contracts that have lower premiums for forest owners that adopt adaptation measures, such as maintaining firebreaks or implementing forest management strategies. Additionally, insurance companies assess and model wildfire risks, contributing valuable data to inform risk mitigation strategies. They play a crucial role in post-fire recovery by providing financial resources for reconstruction and restoration, reducing economic vulnerability among affected stakeholders.

Each stakeholder has a unique role in the wildfire adaptation process, but collaboration is essential for implementing effective strategies that minimize wildfire impacts. Forest ownership patterns, and thus the influence and responsibilities of this stakeholder, differ across Europe, with large holdings by private forest companies common in Sweden and Finland, while more fragmented ownership is typical in Central and Southern Europe (Weiss et al., 2019). For large holdings, it is more common to hire professional forest managers to handle forest management (Roberge et al. 2020), whereas for smaller holdings, forest owners often manage the forests themselves (Kirschner et al., 2024). Forest insurance coverage also varies across Europe, with generally higher coverage in the northern parts. For example, 95% of the private forest area is insured in Sweden, while in countries like Spain, France and Germany, the coverage is below 4% (Brunette & Couture, 2023).

2. Adaptation strategies

Stakeholder groups' adaptation strategies discussed in the previous section to prevent wildfires and increase forest resilience can broadly be divided into three categories based on their current level of implementation across Europe: (i) widely implemented strategies; (ii) less commonly implemented strategies; and (iii) not yet implemented strategies. We reviewed 48 case studies on the topic of wildfire adaptation (see Table A1 of Appendix C for the list of studies). Based on this literature review, we find that (i) widely implemented strategies are forest and fuel management (thinning, grazing, removal of dead vegetation, and prescribed burns); the establishment and the maintenance of firebreaks and/or fuel breaks to limit fire spread; firefighting and rapid response systems; education, training, preparedness, and awareness (capacity building); and the use of advanced technologies for early fire prediction and detection such as drones and satellite imagery. (ii) Less commonly implemented strategies are building fire-resilient structures; zoning regulations in wildfire-prone areas; payments for environmental services (PES); transformative approaches, such as re-thinking land-use patterns; and insurance

policies. (iii) Not yet implemented strategies are carbon credit schemes that incentivize forest owners to maintain wildfire-resilient ecosystems; adaptive ecosystem management such as reforestation with fire-resistant and diverse species to improve forest resilience; risk-based insurance linked to fire-prevention practices; and relocating at-risk communities (Kates et al., 2012).

These strategies can be clustered into five generic adaptation categories as illustrated in Table 2.2. The categories include grey, green, and soft strategies, and incremental versus transformative strategies, based on the definition by (Kates et al., 2012; Table 2.1). Grey strategies refer to technological and infrastructure strategies such as building fire-resilient structures, firefighting and rapid response systems and use of advanced technologies for early fire prediction, detection and warning. Green strategies refer to nature-based approaches such as forest and fuel management, establishment and maintenance of fuel breaks, and adaptive ecosystem management. Soft strategies refer to non-structural strategies such as capacity building, zoning regulations, re-thinking land-use patterns, PES, carbon credit schemes, risk-based insurance and relocating at-risk communities. Incremental strategies involve adjusting existing systems such as forest and fuel management and capacity building while transformative strategies involve fundamentally changing existing systems and structures such as re-thinking land use patterns, reforestation with fire-resistant and diverse species and relocating at-risk communities. Some strategies like building fire-resilient structures are categorized as both incremental and transformative depending on context and scale of change. For instance, improving the existing infrastructure is incremental, while large-scale re-design of fire-resilient structures may be transformative.

Southern European countries have widely adopted green, incremental strategies for forest wildfire adaptation, such as *forest and fuel management techniques* including thinning, grazing, removal of dead vegetation and prescribed burning (Fernandes & Botelho, 2004; Piñol et al., 2005; Mancilla-Leytón & Martin Vicente, 2012; Marino et al., 2014; Regos et al., 2014; Elia et al., 2016; Oliveira et al., 2016; Salis et al., 2016; Lasanta et al., 2018; Nabuurs et al., 2018; Salis et al., 2018; Varela et al., 2018; Palaiologou et al., 2020; Pareja et al., 2020; Marcilla-Leytón et al., 2021; Aparício et al., 2022; Bertemeu et al., 2022; Santuopoli, 2024; FIRE-RES, n.d.; PCCO, n.d.). While examples of such forest and fuel management techniques can be found in Central Europe (FIRE-RES, n.d.), no studies documenting their implementation were identified for Northern Europe. However, this does not necessarily mean that such strategies are not implemented. For example, thinning is actively done by forest managers in Sweden and prescribed burning has been practiced since the 1970s (Cogos et al., 2020), though primarily for ecosystem health and biodiversity protection rather than wildfire adaptation. *Capacity-building strategies* are applied across Europe, but their focus differs by region: Southern European countries tend to emphasize strengthening local knowledge (Lasanta et al., 2018; Uyttewaal et al., 2024; Facing Fire, n.d.; FIRE-RES, n.d.), whereas Central and Northern Europe prioritize training for the fire brigades and stakeholders (Oláh, 2016; FIRE-RES, n.d.; FireURisk project, n.d.; SILVANUS project, n.d.; TREEADS project, n.d.). These strategies are typically implemented as complementary measures rather than standalone approaches. However, generalizing adaptation strategies across European regions remains challenging due to the limited number of documented case studies in Central and Northern Europe.

Overall, wildfire management in Europe has largely prioritized emergency response, with substantial resources allocated to *firefighting and rapid response systems*. While this reactive approach is essential for wildfire suppression, with increased risks of wildfires, existing response capacities may not be enough unless adaptation measures are also strengthened (EASAC, 2025). *Firebreaks and fuel breaks* are commonly implemented in Southern Europe, where several case studies have been conducted to document their implementation (Marino et al., 2014; Oliveira et al., 2016; Varela et al., 2018; Pareja et al., 2020; Adobes Golfe & Dalmau Rovira, 2022; Aparício et al., 2022). In contrast, firebreaks and fuel breaks are less commonly implemented in Central and Northern Europe. While the literature acknowledges their presence in these regions (Tyburski & Szczygieł, 2023), no case studies documenting their implementation have been found. Although we did not find any European case studies explicitly examining *adaptive ecosystem management strategies* such as reforestation with resistant and diverse species for wildfire adaptation, the literature indicates that these strategies are implemented in several European countries, including Sweden (Olofsson & Jakobsson, 2024), Germany

(Milad et al., 2013; Hengst-Ehrhart, 2019), and Belgium (Sousa-Silva et al., 2016), though mainly to address other climate hazards like droughts, storms and pest outbreaks and not as wildfire adaptation strategies (Olofsson & Jakobsson, 2024). No literature describing its implementation in Southern Europe was found.

Table 2.1: Overview of adaptation strategies and types. Rightmost column: Main geographical coverage, S-E = South Europe; C-E = Central Europe; and N-E = North Europe. “+” = example applications can be found in this region; “++” = regular use of the strategy; “+++” = widespread use of the strategy; “-” = no European case studies were found. The numbers in parentheses (e.g. 3.1) in the leftmost column refers to the associated subsections in Section 3.

Section 3:

Adaptation strategy	Incremental	Transformational	Region		
			S-E	C-E	N-E
Grey					
Building fire-resilient structures (3.1)	✓	✓			+
Firefighting and rapid response systems (3.2)	✓				+++
Use of advanced technologies (3.3)	✓				+++
Green					
Forest and fuel management (3.4)	✓			+++ + ++	
Firebreaks and fuel breaks (3.5)	✓	✓		+++ + +	
Adaptive ecosystem management (3.6)		✓		- + +	
Soft					
Capacity building (3.7) ³	✓				+++
Zoning regulations (3.8)	✓				+
Rethinking land-use patterns (3.9)		✓			+
Payment for environmental services (3.10)	✓				+
Carbon credit schemes (3.11)	✓				-
Insurance (3.12)	✓				(+)
Relocating at-risk communities (3.13)		✓			-

The strategies can also be classified by four **strategic directions**, which are clustered by what they act on in the fire system, plus one enabling layer (see Table 2.2):

- **Suppressing fires** (response). These strategies act on the fire once it starts.
- **Managing fuel in the existing landscape** (prevention, incremental). Reduce fuel load and continuity without changing the land use.
- **Transforming the landscape** (prevention, transformative). Change species composition and land-use patterns so the landscape itself will be less vulnerable for burns.
- **Reducing what is exposed** (people and assets). Protect or move assets or people that are in the fire risk zone.

The enabling layer covers financing, incentives and capacity, and does not directly respond to the fire risk itself. They are necessary conditions for the adaptation strategies to be effective and can help in overcoming the cost barrier.

³ Capacity-building is pursued all over Europe, but the focus differs from south to north.

Table 2.2: Strategic directions for forest fire adaptation

Strategic direction	Strategy	Type	Incremental/ transformational	Implementation in Europe
Surpressing fires	Firefighting and rapid response systems	Grey	Incremental	Widely implemented
	Advanced technologies for prediction, detection and warning	Grey	Incremental	Widely implemented
Fire prevention management in existing landscapes	Forest and fuel management (thinning, grazing, prescribed burning)	Green	Incremental	Widely implemented
	Firebreaks and fuel breaks	Green	Incremental/ Transformational	Widely implemented in South Europe / less commonly elsewhere
Transforming the landscape	Adaptive ecosystem management (mixed, fire-resistant species)	Green	Transformational	Less commonly implemented
	Re-thinking land-use patterns (mosaic landscapes, agroforestry)	Soft	Transformational	Less commonly implemented
Reducing what is exposed	Building fire-resilient structures	Grey	Incremental/ Transformational	Less commonly implemented
	Zoning regulations (fire-safe zones)	Soft	Incremental	Less commonly implemented
	Relocating at-risk communities	Soft	Transformational	Not yet implemented
Enabling strategies	Capacity building	Soft	Incremental	Widely implemented
	Payments for environmental services	Soft	Incremental	Less commonly implemented
	Insurance (incl. premium discounts)	Soft	Incremental	Less commonly implemented; risk-based insurance linked to prevention not yet
	Carbon credit schemes	Soft	Incremental	Not yet implemented

3. Assessment of strategies – Barriers to implementation

From our review of case studies, we infer that several factors could constrain the implementation of the adaptation strategies described in the previous section. Firstly, the high cost of forest management is a key barrier, especially given the large forest areas requiring extensive work. Forest management operates on a long-term cycle, where decisions made today can impact outcomes decades into the future. Thus, experimenting with new practices, such as replanting different tree species for wildfire resilience, involves uncertainty and risk, which can make traditional practices seem more appealing. Additionally, not all tree species are suitable for all terrains, which further complicates the decision. There is also a lack of trained personnel to implement these adaptation options, and hiring additional staff can be both costly and challenging due to the limited availability of qualified candidates. The costs associated with adding fire guards, improving infrastructure, or implementing fire prevention measures can be substantial. Limited awareness and familiarity with fire risk applications and warning systems further reduces adaptation. Additionally, the financial burden of staff training and purchasing insurance further exacerbates these barriers. Cultural attitudes can also act as barriers, as some individuals may view insurance as unnecessary or inconsistent with their beliefs. Together, these factors create a complex set of barriers to adopting effective wildfire adaptation measures. In the following, we will discuss barriers to the implementation of each of the abovementioned adaptation strategies (Table 2.1).

3.1 Building fire-resilient structures

One of the identified case studies implements the strategy of building fire-resilient structures (TREEADS project, n.d.), recommending the use of cost-effective fire-treated wood alongside other fire-resistant materials like metal or cement (Gribble et al., 2025). While these materials improve wildfire resilience and possibly increase property market value (Yau, 2015), fire protecting measures generally account for 4–12% of the total construction cost in composite buildings (Gribble et al., 2025). This cost may limit widespread adoption, particularly among low-income homeowners who are less able to invest in resilience. Furthermore, homeowners may lack knowledge of the risk of wildfire and the benefits from investing in resilience (Yau, 2015). In the U.S., a state program offers grants up to 40,000\$ to homeowners in wildfire risk zones to encourage retrofitting their properties (Ma et al., 2024).

3.2 Firefighting and rapid response systems

Firefighting and rapid response systems are among the most widely implemented wildfire management strategies across Europe, receiving the majority of funding. Approximately 90% of the EU budget for wildfire expenditure is spent on suppression, leaving 10% for prevention (Bognar & Van Dijk, 2023). While fire suppression is essential for immediate crisis management, the effects are short-term and do not address the underlying causes of the increased wildfire risk. Investments in adaptation are more cost-effective when it comes to natural hazards (World Bank, 2021). Furthermore, allocating resources to wildfire suppression diverts funding from adaptation efforts. With wildfires becoming more frequent and intense, the financial demands on emergency firefighting systems are escalating, leading experts to warn that relying solely on fire suppression will be insufficient to manage future risks (EASAC, 2025).

3.3 Advanced technologies for early fire prediction, detection and warning

Several methods using advanced technologies for early fire prediction, detection, and warning such as drones and satellite imagery have been assessed in the literature. However, the diversity of these approaches, including differences in modeling techniques, makes it difficult to draw general conclusions about their effectiveness. By enabling early detection of wildfires and prediction of fire spread, these technologies can help optimize the allocation of suppression resources (Climate-ADAPT, 2016; Zeferino, 2020; EC, 2021b; Gonçalves et al., 2023; SILVANUS project, n.d.; TREEADS project, n.d.). Fire spread models have become commonplace and are available operationally to guide emergency managers in many places. For example, Climate-ADAPT (2016) introduces a forest fire simulation tool that integrates meteorological and spatial data to forecast wildfire behavior, thereby supporting informed planning of suppression efforts. While these methods demonstrate effectiveness, it requires mapping spatially extensive areas, possibly limiting its scalability due to resource constraints related to data collection and processing. However, the collected data can also serve other purposes, such as informing the placement of firebreaks and water tanks. Furthermore, another possible limitation is the ability of local authorities to apply the simulation tool, which was solved in the project by providing training sessions.

Using remote sensing and digital technologies to evaluate wildfire risk can support strategically planned and prioritized areas of fuel management. Modeling wildfire risk, often by integrating meteorological and vegetation data, supports stakeholders in making informed decisions about prioritizing fuel management in areas where the risk of ignition and spread is highest (Alcasena et al., 2019; Aparício et al., 2022; Santuopoli, 2024). However, model uncertainties remain. For example, many predictive models (see section 5) rely heavily on the accuracy of meteorological forecasts (Arafin et al., 2025). These models moreover require detailed and updated spatial data, which can be resource demanding to develop and maintain. That said, investing in high-resolution spatial data for wildfire prediction and detection can bring important co-benefits, as the same data can also support activities like ecosystem monitoring and biodiversity assessments.

3.4 Forest and fuel management

Land-use changes across Europe, partly driven by rural abandonment, have contributed to fuel accumulation due to unmanaged landscapes (EASAC, 2025). In Southern Europe, former agropastoral lands are now replaced by dense, low-diversity forests, making severe wildfires more frequent and difficult to control (Fernández-García et al., 2022; Neidermeier et al., 2023). Fuel management

techniques such as mechanical clearing, thinning, grazing and prescribed burning are widely used strategies, but face several barriers. The high upfront and maintenance costs of fuel management are widely highlighted in the literature (Marino et al., 2014; Oliveira et al., 2016; Salis et al., 2016; Salis et al., 2018; Alcasena et al., 2019; Palaiologou et al., 2020; Alcasena et al. 2021; Bertomeu et al., 2022), and a review study concludes that fuel treatments tend to be financially unviable (Hunter & Taylor, 2022). However, considering the benefits to multiple sectors of society, such as improved wildlife habitat and reduced loss of life rather than only the reduction of forest loss, the benefits are more likely to exceed the costs (Hunter & Taylor, 2022). Although forest owners and managers bear the costs of fuel management, the benefits extend broadly to society. In Southern Europe, fragmented land ownership reduces individual incentives to invest, whereas in the Northern Europe, larger holdings and timber-focused management better align adaptation efforts with owners' interests (Lidestav & Westin, 2023).

Prescribed burning and grazing, while generally less costly (Salis et al., 2018), come with their own set of challenges and are often used as complementary methods to mechanical clearing (Mancilla-Leytón et al., 2012; Pareja et al., 2020). Prescribed burning is subject to public controversy and risk, especially in dry Southern European climates with limited safe windows for implementation (Fernandes & Botelho, 2004; Regos et al., 2014; Lasanta et al., 2018). However, familiarity with the technique and trust in the personnel conducting the burn are associated with higher levels of acceptance (Moritz et al., 2014). A notable co-benefit of prescribed burning is its positive effect on biodiversity, as it helps maintain ecosystems that depend on low-intensity fires. Grazing is limited by rural abandonment, ageing populations, low livestock numbers and seasonal pasture availability (Mancilla-Leytón et al., 2012; Lasanta et al., 2018). Overall, fuel treatment costs and benefits vary widely (Hunter & Taylor, 2022), not only by technique but also by region and terrain, making it difficult to draw conclusions true for all of Europe. Enabling conditions and recommendations identified in the literature include i) strategically planned and prioritized areas of fuel management to maximize resources, such as in the form of fuel break segments (see Section 3.5); ii) coordinated management and collaboration across stakeholder groups (Marino et al., 2014; Bertomeu et al., 2020; Santuopoli, 2024); iii) establishing policy guidelines to promote fire-resilient landscapes (Marino et al., 2014; Damianidis et al., 2021); iv) and financial incentives for fuel management (Marino et al., 2014; Lasanta et al., 2018; Varela et al., 2018; Bertomeu et al., 2022).

Coordinated management and collaboration across stakeholder groups supports effective and sustainable fuel management by pooling resources and aligning common objectives (Santuopoli, 2024; Uyttewaal et al., 2024). In areas with fragmented land ownership, disagreements and diverse land management objectives are common and coordinated efforts could help overcome these challenges by promoting a shared understanding (Bertomeu et al., 2022). This is especially important for transformative approaches, such as creating mosaic fire-resilient landscapes, which require multiple land fragments to work together as a unified system (see Section 3.8). Furthermore, policy guidelines can be established to promote long-term, sustainable fuel management and thereby support wildfire prevention (Marino et al., 2014; Damianidis et al., 2021). According to Marino et al. (2014), current forest policies tend to focus on fire suppression and conservation, rather than on proactive fuel management. They recommend better integration of fuel management into forest management plans, along with clear, common guidelines for implementing fuel treatment efforts.

The use of financial incentives to promote fuel management is mentioned in several studies (Marino et al., 2014; Lasanta et al., 2018; Bertomeu et al., 2022). In Spain, most private landowners are only able to carry out fuel management when financial support is provided (Marino et al., 2014). For example, Lasanta et al. (2018) recommends strengthening economic incentives, such as subsidies for livestock farming and targeted grazing. Other forms of financial incentives described in the literature are PES (Varela et al., 2018) (see Section 3.9) and selling biomass recovered from fuel treatments to offset costs (Palaiologou et al., 2020). However, the economic viability of selling biomass to offset fuel management costs depends on factors such as the distance to processing facilities, the quality of the biomass, the market demand and the biomass price (Neidermeier et al., 2023).

3.5 Firebreaks and fuel breaks

Firebreaks and fuel breaks are designed to slow or halt the spread of wildfires by reducing or fully removing the continuity of combustible vegetation. This typically involves fuel removal, i.e. fuel management, and thus the costs of this strategy are like those of forest and fuel management (see Section 3.4). However, in comparison with broader fuel management strategies, establishing firebreaks and/or fuel breaks typically require fuel treatment across a smaller area in total, thus reducing the cost. While this strategy is widely implemented in Europe, its establishment is typically concentrated in high-value forest areas and rarely extends to marginal regions (EASAC, 2025), resulting in reduced protection of people living in less prioritized areas. The identified European case studies focus on constructing fuel breaks rather than firebreaks, i.e. reducing vegetation rather than completely removing it, demonstrating positive results in terms of wildfire prevention (Marino et al., 2014; Oliveira et al., 2016; Varela et al., 2018; Pareja et al., 2020; Adobes Golfe & Dalmau Rovira, 2022; Aparício et al., 2022; Bertomeu et al., 2022). To overcome the costs associated with fuel management for the construction of and maintenance of fuel breaks, productive fuel breaks are used. These are areas where vegetation is reduced not only to limit fire spread but also to serve additional purposes, such as generating economic returns (EASAC, 2025). For example, grazing can be used to manage vegetation while producing dairy and meat products (Varela et al., 2018; Bertomeu et al., 2022), or land can be converted to agroforestry, which can both slow or stop fire spread and provide economic returns through crop production (EASAC, 2025). Furthermore, strategic planning of fuel break locations, targeting areas where they provide the greatest benefit or establishing coordinated fuel break networks based on the broader landscape context, is recommended to maximize resource use (Marino et al., 2014; Aparício et al., 2022; Bertomeu et al., 2022).

3.6 Adaptive ecosystem management

Adaptive ecosystem management strategies, such as mixed-species forests, increase resilience and reduce vulnerability to natural hazards in general (Seidl et al., 2011; Pörtner et al., 2022), and to wildfires in particular (Jactel et al., 2017). However, in Europe the adoption of such strategies has been limited, and we did not find any case studies that describe their implementation to reduce wildfires. This may partially be explained by the higher management costs and generally lower timber revenues associated with mixed species forests compared to monocultures (Jandl et al., 2019), especially in Northern Europe where timber production is often the primary objective. In Southern Europe, fragmented landownership and absent landowners present significant barriers to the implementation of large-scale adaptive management measures. Given that mixed-species forests store more carbon than monocultures (EACAS, 2025), financial incentives such as carbon credit schemes may help overcome this barrier (see Section 3.11). Furthermore, decisions on tree species and planting ratios are influenced by personal preferences. Due to the long-life cycles of trees, choices made today will impact forest conditions for decades to come. The long-time horizons, combined with uncertainty about future climate conditions, may discourage forest owners from adopting new or less immediately profitable management practices.

3.7 Capacity building

Capacity building strategies such as training, education, public awareness raising and empowerment of local populations can be implemented at a relatively low cost. The decrease in local knowledge due to rural abandonment and aging populations underscores the importance of capacity building for preserving and transferring practical knowledge that supports effective wildfire prevention and adaptation (Tàbara et al., 2003; Salis et al., 2016; Salis et al., 2018; Bertomeu et al., 2022). Studies highlight a general lack of understanding of the value of preventive actions and emphasize the need to complement reactive wildfire suppression efforts with a stronger focus on proactive wildfire prevention (Tàbara et al., 2003; Marino et al., 2014). However, the benefits of these strategies can be difficult to quantify, as they often appear over the long term in the form of improved knowledge and risk awareness and more informed land-use decision making. A 2009 study of wildfire prevention education programs in Florida found that every dollar invested generated 35\$ in benefits (Huber, 2018). In addition to supporting wildfire prevention, capacity building can generate multiple co-benefits, including stronger community resilience, greater empowerment of local populations and enhanced environmental awareness (Tàbara et al., 2003; Marino et al., 2014; Bertomeu et al., 2022).

3.8 Zoning regulations

Zoning regulations in wildfire prone areas can be used as an adaptation strategy as in the case study by Gribble et al. (2025), who recommend “fire safe zones” around critical infrastructures such as houses. These recommendations include keeping the lawn near the infrastructure short and alive as well as planting deciduous trees instead of conifers. The fire department in Arizona found that creating such a buffer zone around a house can increase the market value by 40.000\$ (Huber, 2018). In addition, zoning regulations that restrict housing density may increase property values, benefiting some homeowners, however, they also reduce housing affordability and may exacerbate social and economic inequalities if not carefully managed (Manville et al., 2019; SSAM, 2023). Furthermore, determining high-risk zones can be complex as it depends on dynamic factors such as land management practices and vegetation. Examples from the U.S. show that public resistance can pose a significant barrier to implementing zoning regulations. In California, a 150\$ annual fee was introduced in 2014 to cover costs associated with wildfire prevention efforts in high-risk areas but was suspended in 2017 following widespread opposition (Dale & Barrett, 2023). Such opposition often results from concerns about fairness, as it may disproportionately burden vulnerable populations, including rural and marginalized populations (Manville et al., 2019; Dale & Barrett, 2023). Community outreach to increase public understanding of wildfire risks and the rationale behind collected fees could help foster a greater acceptance (Huber, 2018).

3.9 Re-thinking land use patterns

Transformative approaches, such as re-thinking land use patterns, were examined in two of the identified case studies. The first case study by Bertomeu et al. (2022) uses a mosaic landscape approach to strategically combine diverse land uses, such as agroforestry practices and pastures, into a patchwork pattern functioning as productive fuel breaks. The study shows positive results in mitigating wildfire risk, but also highlights the need for strategic planning, incentives for land management and greater participation of rural communities in land use planning. The second case study by Damianidis et al. (2021) uses agroforestry as an adaptation strategy, i.e. “the practice of integrating woody vegetation and agricultural crops and/or livestock” (p.1). Traditional agroforestry systems used to be widespread across Southern Europe, but the large-scale rural abandonment seen in recent decades has led to a decline in these practices. Agroforestry practices reduce wildfire risk by increasing the spacing between and lowering the amount of undergrowth compared to natural forests. This reduces the fuel available for fires, making it more difficult for wildfires to spread. Furthermore, agroforestry has lower emission levels than mechanical clearing, and in general, silvopastoral systems are more profitable than single timber production systems (Pent, 2020). Given these benefits, a policy to encourage agroforestry is recommended by Damianidis et al. (2021).

3.10 Payments for Environmental Services

Financial incentives could work as a strategy to overcome the barrier of scarce resources for land management practices. Payments for Environmental Services (PES) are defined as “...voluntary transactions between service users and service providers that are conditional on agreed rules of natural resource management for generating offsite services” (p.20) (Bottazzi et al., 2018). For example, municipalities concerned about the wildfire risk can establish PES agreements with landowners/managers, compensating them for undertaking adaptation strategies, such as fuel management, creating fuel breaks or creating mosaic landscapes. The case study by Varela et al. (2018), the only identified case study using PES, pays local shepherds for targeted grazing to reduce fuel loads. Barriers to implementing this strategy include spatial conditions, such as steep terrain and dense vegetation, as well as historical conflicts between stakeholders. Additionally, high transaction costs and administrative burdens account for approximately 42% of the total cost of the scheme. Despite these challenges, PES can be an effective strategy in reducing wildfire risk and is less costly than alternatives such as mechanical clearing. A key enabling factor is strong political support, essential for initiating and maintaining the strategy over time. Collaboration and coordination among different stakeholder groups (shepherds, forest managers and government agencies) are also crucial to building mutual trust. Simplifying administrative procedures is recommended to reduce costs, for instance, by lengthening contracts to lower transaction costs.

3.11 Carbon credit schemes

Carbon credit schemes promote sustainable forest management by providing financial incentives for reducing greenhouse gas emissions, allowing companies to buy and sell carbon credits (Freedman et al., 2009). Forests serve as natural carbon sinks by storing carbon, but wildfire releases this stored carbon back into the atmosphere as emissions. By implementing fuel management practices that reduce wildfire risk, forest owners can lower carbon emissions and earn carbon credits. These carbon credits can then be sold to companies that exceed their emission limits, generating revenue to finance fuel management efforts. However, monitoring and verifying carbon sequestration is costly and strategies for engaging local communities in these programs are lacking (Antonova & Critchley, 2023). To overcome these barriers, remote sensing technology offers a more efficient way to verify outcomes (It.org US Chapter, 2022). A clear framework for implementation can facilitate wider adoption of carbon credit schemes (Pan et al., 2022). In high-emission regions, carbon credit programs could potentially cover up to 14% of the costs associated with fuel treatment/management (Alcasena et al., 2021). Since these programs incentivize fuel treatments, the environmental benefits align directly with wildfire risk reduction. However, we did not find any case studies describing the implementation of carbon credit schemes as a wildfire adaptation strategy.

3.12 Insurance

A key barrier to the broader adoption of insurance is low levels of willingness to pay (Sachhelli et al., 2018). This challenge could potentially be addressed through improved risk communication, helping forest owners to better understand the risks and potential consequences of wildfire events (Sánchez et al., 2022). High-income forest owners are generally more likely to obtain insurance coverage than low-income owners, leading to unequal levels of protection. To address this gap, income-based subsidies have been suggested to make insurance more accessible to low-income groups (Hochrainer-Stigler et al., 2014). However, public support may also discourage forest owners from adopting insurance due to reliance on governmental financial support, a phenomenon known as the charity hazard (Brunette & Couture, 2023). This reliance could be counterproductive by reducing incentives for proactive risk management. Additionally, forest owners are generally willing to pay more for insurance coverage if the main objective is timber revenue (Brunette & Couture, 2023). This could possibly explain why insurance is more common in the northern parts of Europe, where timber revenues are often the main objective for forestry. However, this could also be explained by the lower insurance costs in Northern Europe due to lower wildfire risk.

The barriers just discussed also apply to risk-based insurance linked to the adoption of adaptation measures, such as maintaining firebreaks or implementing forest management strategies. In addition, the lack of reliable methods for assessing wildfire risk hinders the effective implementation of risk-based insurance schemes (Sachhelli et al., 2018). Remote sensing technologies offer a promising solution to this barrier by enabling objective, large-scale risk assessments while reducing administrative burdens, thus potentially lowering insurance premiums through more accurate and widespread risk evaluation (Brunette et al., 2017). In addition, offering reduced insurance premiums to forest owners who implement adaptation strategies could benefit both forest owners and insurance companies by encouraging proactive risk reduction (Meldrum et al., 2024).

3.13 Relocating at-risk communities

Relocating at-risk communities is a well-documented adaptation strategy in response to flooding (e.g. EEA, 2017). However, the literature on its application in the context of wildfires remains limited (McConnell & Koslov, 2024). Moving communities away from wildfire prone areas may reduce risk by lowering the potential for human-caused ignitions and minimizing exposure to danger. However, it can also increase wildfire risk by contributing to land abandonment, reduced management and the accumulation of flammable fuel, a pattern commonly seen in Mediterranean Europe, where depopulation and absent landowners are key drivers of increased wildfire hazards (EACAS, 2025). A study from California highlights that communities located in wildfire-prone areas often express the desire to stay and defend their homes during future wildfire events (Tinoco, 2023). Meanwhile, wildfire risk in prone areas is unevenly distributed, with wealthier residents able to invest in protective measures that enhance their safety, while less affluent neighbors remain more vulnerable (Tinoco, 2023).

Table 2.3 provides a summary of the barriers and opportunities for wildfire adaptation strategies discussed above.

Table 2.3: Summary of barriers and opportunities for wildfire adaptation strategies. The numbers in parentheses (e.g. 3.1) in the leftmost column refers to the associated subsections in Section 3.

Adaptation strategy	Barriers	Opportunities
<i>Grey</i>		
Building fire-resilient structures (3.1)	High cost, lack of risk awareness	Increased market value, resilience
Firefighting and rapid response systems (3.2)		Already widely implemented, needs are documented and increasing
Use of advanced technologies (3.3)	Local capacity to use, effectiveness poorly documented, model uncertainty	Co-benefits (environmental management)
<i>Green</i>		
Forest and fuel management (3.4)	High costs (fuel management), public acceptance (prescribed burning, grazing), increased risk (abandonment)	Co-benefits (society)
Firebreaks and fuel breaks (3.5)	High costs (fuel management), strategic planning	Co-benefits (economic)
Adaptive ecosystem management (3.6)	High management costs, personal preferences, lower revenues from timber, fragmented landownership	Increased carbon storage, biodiversity
<i>Soft</i>		
Capacity building (3.7)	Benefits are difficult to quantify and document	Co-benefits (community resilience, empowerment, enhanced environmental awareness)
Zoning regulations (3.8)	Distributional impacts, uncertainty	Increased property values
Rethinking land-use patterns (3.9)	Strategic planning, incentives for land management, participation of rural communities in land use planning	Potential economic and environmental benefits
Payment for environmental services (3.10)	High transaction costs, sustained policy support, stakeholder collaboration	Supports vulnerable communities, less costly than fuel management
Carbon credit schemes (3.11)	High costs (monitoring and verifying carbon sequestration), lack of strategies for engaging local communities	Financial incentives (reducing greenhouse gas emissions) can cover other adaptation costs, adoption of remote sensing can lower costs
Insurance (3.12)	Low willingness-to-pay, distributional effects, “charity” hazard	Adoption of remote sensing can lower costs, incentive for proactive risk reduction
Relocating at-risk communities (3.13)	Distributional effects, abandonment may increase risks, public resistance to moving	High effectiveness

4. Lessons learned for implementation of strategies

The high upfront and maintenance costs of forest and fuel management is a key barrier to reducing the availability of flammable fuels in forested areas across Europe (Section 3.4, Table 2.3). This barrier has in some places been successfully overcome by strategic planning of fuel treatment areas, such as in the study by Aparicio et al. (2022) where prioritized segments of fuel breaks were constructed to disrupt fuel connectivity. Prioritization was determined by testing different fuel treatment scenarios using simulation techniques to assess their impact on wildfire behavior. Such model-based approaches help

ensure that resources are allocated to areas where they provide the highest return on investments, potentially reducing both the managed area and overall management costs, thereby overcoming the cost barrier.

Furthermore, financial incentives such as PES (Section 3.10) have proven successful in the study by Aparício et al. (2022), where governmental agencies paid local shepherds for targeted grazing. The program made wildfire adaptation, a public good, into a source of revenue for private individuals. While PES is less commonly implemented for wildfire adaptation in Europe, it has been implemented for other environmental objectives. Successful examples include conservation of valued landscapes in the UK (Dobbs & Pretty, 2008) and water quality protection in France (Perrot-Maitre, 2006). However, these cases also highlight potential challenges in implementing PES schemes. For example, in the UK case, farmers sometimes chose not to participate in higher-level environmental programs because standard Common Agricultural payments, financial support from the EU for crops and livestock (Brady et al., n.d.), offered higher income than the PES incentives. Furthermore, the French case success depended on building trust between farmers and funders, as well as finding mutually acceptable practices for implementing the PES scheme. These cases highlight the importance of careful design, context-specific considerations and collaboration when designing PES schemes.

The implementation of effective adaptation strategies for wildfire risk management now and in the future will require transformative and landscape level changes, and subsequently there is an urgent need for long-term policies and planning. This will include the need to cope with the associated deep uncertainties and with the potential limits of each of the abovementioned adaptation strategies. As such, wildfire adaptation could lend itself well to an adaptation pathways approach such as the dynamic adaptive policy pathways (DAPP) introduced by Haasnoot et al. (2013). However, we could not find any case studies so far, which has tested such an approach.

5. Role of sectoral models for implementation of strategies

Four main sectoral models relevant for different stakeholder groups in wildfire adaptation have been identified from analyzing our reviewed case studies: (i) fire spread models; (ii) the Treatment Optimization Model (TOM); (iii) the FARSITE model; and (iv) the Minimum Travel Time (MTT) model. See Table A1 of Appendix D for an overview of the models and their use. Fire spread models such as the ForeFire model (Filippi et al., 2018) can be used to test adaptation strategies such as constructing firebreaks and applying prescribed burning. They can support decision-making by informing stakeholders (forest owners, and private and public forest managers) about the potential benefits of the different strategies. Fire spread models are generally best suited for large, forested areas and thus less suitable for smaller-scale applications, such as predicting insurance risks for individual forest plots. The Treatment Optimization Model (TOM) can primarily be used by forest managers and owners to identify optimal areas for fuel treatment to slow or stop fire spread, thereby supporting strategic planning (Palaiologou et al., 2020). TOM is generally more suited for shorter fire event simulations because it can only incorporate one weather scenario at the time, whereas the FARSITE model can handle multiple weather scenarios and is therefore more suitable for simulating longer fire events (Price & Germino, 2022). For this reason, FARSITE can be used to support suppression decisions such as whether a fire should be suppressed or allowed to burn under supervision (Finney et al., 2007). Furthermore, it can sometimes be used to evaluate economic consequences of fires with or without fuel treatment strategies implemented (Finney & Andrews, 1999). The high resolution of the Minimum Travel Time (MTT) model makes it suitable for insurance companies when assessing wildfire risk at smaller scales (Finney, 2022). Additionally, it can be used to strategically plan fuel treatment (Kalabokidis et al., 2013).

6. Conclusion

The risks of forest wildfires are increasing across Europe due to climate change, affecting both traditionally vulnerable areas such as the Mediterranean region and historically less prone regions in the north. Wildfire management has to date focused more on emergency response than wildfire adaptation strategies (EACAS, 2025). A balanced approach that combines both response and adaptation is recommended. However, the high costs of wildfire adaptation strategies are a key barrier to their

implementation, often making them financially unviable without incentives (Hunter & Taylor, 2022). Furthermore, effective coordination is essential, as fragmented ownership structures, limited local knowledge and a lack of skilled personnel hinder the successful implementation of adaptation strategies.

Stronger financial and policy support is needed to address these challenges. Strategies such as payments for environmental services, carbon credit schemes and risk-based insurance linked to fire-adaptation practices can help overcome the cost barrier and create incentives for proactive management. In addition, investments in capacity building, knowledge sharing and coordinated action are essential to ensure aligned objectives and greater efficiency in adapting to wildfires. However, the implementation of such strategies must be tailored to specific local conditions and contexts. More evidence and systematic documentation of case studies are needed to guide implementation and to assess the effectiveness of different strategies in different regions. In summary, the most cost-effective wildfire management strategies are those emphasizing adaptation and prevention over suppression, such as forest and fuel management supported by financial incentives, capacity building and strategic planning. These strategies reduce costs and limit wildfire damage while providing co-benefits, thereby minimizing impacts on human-natural systems now and in the future.

ADT 3 – Water-food-biodiversity (IIASA)

1. Decision context

Future projections for the European Water-Food Nexus indicate significant increases in water demand and severe water shortages across the continent, driven primarily by climate change. Under a 2 °C warming scenario, water scarcity is expected to deteriorate sharply, driving agricultural irrigation demand up by as much as 25% by 2100 and potentially triggering widespread regional water deficits as early as 2050 (EEA, 2019).

This escalating scarcity intensifies multi-sectoral competition among key stakeholders—including farmers, energy producers, municipal suppliers, and environmental organizations—who all compete for limited water volumes and quality. This competition is already acute in heavily regulated basins like the Ebro in Eastern Spain and the Thaya spanning the Czech Republic and Austria. In the Thaya River Basin, multi-sectoral withdrawals can reach up to one-third of total streamflow during dry years, forcing authorities to navigate conflicting demands for drinking water, energy, and intensive lowland agriculture while protecting baseline environmental flows.

To safeguard agricultural productivity against climate stresses, policies often push for irrigation modernization to enhance efficiency and curb losses. However, technological efficiency alone is an insufficient response. While farm-level efficiency gains improve local profitability, they frequently trigger the "irrigation efficiency paradox" (Grafton et al., 2018), where saved water is redirected to expand production, ultimately increasing net basin-wide consumption.

As climate impacts exacerbate hydrological imbalances and severe drought risks across Europe, effective adaptation must move beyond simple efficiency measures. Achieving long-term resilience requires systemic strategy portfolios that combine grey, green, and soft options—such as crop share optimization, trade pattern adjustments, and dietary shifts—to ensure absolute reductions in water use while harmonizing competing stakeholder needs.

At the European level, these decisions take place within a policy landscape in which agricultural production, climate adaptation, water management and ecosystem protection are closely interconnected. The Water Framework Directive (WFD) (Directive 2000/60/EC) requires Member States to manage water at river-basin scale while maintaining the ecological and quantitative status of water bodies, whereas the Common Agricultural Policy (CAP; Regulation (EU) 2021/2115) supports agricultural adaptation through instruments including irrigation investments, eco-schemes and agri-environment-climate measures. This creates an important policy challenge: measures that improve agricultural resilience or water-use efficiency at farm level do not necessarily reduce basin-level water consumption or improve environmental outcomes. The Nature Restoration Regulation (Regulation (EU) 2024/1991) adds a further dimension by establishing restoration objectives for freshwater and agricultural ecosystems, including river connectivity and ecosystem functions. Consequently, relevant decision makers extend beyond individual farmers and river basin authorities to agricultural and environmental ministries, CAP managing authorities, water authorities and EU institutions, which must consider how adaptation investments affect agricultural production, water availability, environmental flows and ecosystem services simultaneously.

2. Adaptation strategies

Adaptation strategies across Europe demonstrate diverse and context-specific responses to biodiversity protection, water management, and the water-food nexus. These strategies can be grouped into four **strategic directions**, according to how they address water scarcity: increasing water-use efficiency, increasing or buffering supply, reducing (or reshaping) demand, and reallocation water between users. Within each direction, measures can be categorized as grey, green or soft, and as widely implemented, less commonly adopted, and not yet implemented measures, providing an overview of ongoing efforts and future opportunities for adaptation in Europe.

Grey adaptation strategies currently widely implemented are relying on engineering-driven solutions. These include the incentives for modernizing irrigation and increasing its efficiency and increasing storage through reservoirs construction. Less implemented strategies, turn towards on-site storage and rainwater harvesting and precision agriculture (Petrović et al., 2024; Barnes et. al., 2019). In the Ebro, on-farm storage is largely argued for, instead of large dams which negatively affect downstream ecosystems which are deprived from sediment flows. Wastewater reuse is slowly being adopted, yet their potential for significant impact is restricted to the local context or to regions where irrigation requirements are relatively low in comparison to the population (Fridman et al., 2021).

Common green adaptation strategies include cover crops which may compete with the main crop over water resources, yet reduce runoff and increase infiltration rates, alongside other benefits (Quintarelli et al., 2022). Adoption rates of conservation soil tillage (CST) are also increasing. CST is also associated with short-term gains like reduced runoff, soil erosion, and increase infiltration. Yet over the long run it is associated with increased soil retention capacity (Jug et al., 2025). Explored in the Thaya, yet less frequently adopted green strategies involve adaptations, such as optimizing local crop shares to align agricultural practices with environmental conditions.

Soft adaptation strategies, such as modifying crop calendars or shifting to drought water saving and resistant crop varieties are relatively common measures, though a thorough consideration of their institutional, technological and economic aspects is required to advance their adoption (Tőzsér et al., 2026). Encouraged by the Water Framework Directive, yet still lacking – cross sectoral integration, is key in promoting win-win policies where cross-sectoral trade-offs are intensified by climate change (Baccour et al., 2025; EEA, 2025). Strategies that have not yet been implemented include comprehensive trade modifications through changes in trading partners and quantities to build resilience against socio-economic shifts. This case underscores the importance of transformative changes in agricultural and water management to address complex challenges while maintaining food security.

Overall, green and soft adaptation strategies are less common but represent critical transformative solutions for long-term sustainability across the case studies. Governance and community engagement improvements remain key challenges. Differences in strategy adoption across regions reflect varying environmental and socio-economic contexts, emphasizing the importance of tailored approaches to adaptation throughout Europe. Across the four strategic directions, current practice and policy support concentrate on efficiency and supply, while demand-side and reallocation strategy remain the least developed. The first two consists mainly of grey and some green measures, while the latter two are almost entirely soft. Table 3.1 summarizes the strategies per direction, type and uptake.

Table 3.1: Strategic directions for Water-Food Nexus

Strategic Direction	Strategies	Type	Uptake in Europe
Increase water-use efficiency	Irrigation modernization (gravity to drip)	Grey	Widely implemented
	Precision agriculture	Hybrid (grey/green)	Less commonly adopted
	Cover crops	Green	Widely implemented
	Conservation soil tillage	Green	Increasing
Increase or buffer supply	Reservoir construction	Grey	Widely implemented
	On-farm and on-site storage	Grey	Less commonly adopted
	Rainwater harvesting	Grey	Less commonly adopted
	Wastewater use	Grey	Slowly being adopted
Reduce or reshape demand	Crop calendar adjustments	Soft	Relatively common
	Drought water saving and resistant varieties	Hybrid (green/soft)	Relatively common
	Crop share optimization	Hybrid (green/soft)	Less commonly adopted
	Trade modifications	Soft	Not yet implemented
	Dietary shifts	Soft	Not yet implemented
Reallocate between users	Abstraction limits	Soft	-
	Allocation rules	Soft	-
	Environmental flow requirements	Soft	-
			Encouraged under WFD, still lacking
	Cross-sectoral integration	Soft	

3. Assess strategies and barriers to implementation

Grey adaptation strategies focus primarily on technological and infrastructural interventions, yet their real-world implementation faces significant socio-economic and systemic paradoxes. For instance, modernizing irrigation by transitioning from gravity-based systems to drip technology offers field-scale benefits such as higher yields and enhanced water use efficiency. However, at a basin scale, these savings are frequently offset by increased consumptive water use and reduced return flows—a paradox driven by the expansion of irrigated areas or a shift toward water-intensive crops (Grafton et al., 2018; Santini et al., 2025). High upfront capital and O&M costs further restrict smallholders, underscoring that technical upgrades must be coupled with strict legal limits on water abstraction. Similarly, while traditional large-scale reservoir construction heavily alters river flows and faces opposition under the (WFD), localized or on-farm storage is increasingly advocated as a buffer against short-term supply shocks (Vico et al., 2020). Yet, local storage still requires substantial capital investment (Palazzo et al., 2019), high-level coordination among farmers and managers, and careful operational planning, all while remaining bound by baseline hydrological limits (Palazzo et al. 2024a, 2024b).

Parallel to infrastructure, data-driven and nature-based "green" agricultural measures offer targeted ecological advantages but encounter distinct operational and socio-demographic barriers. Precision agriculture leverages high-resolution monitoring and automated technologies to optimize resource efficiency, curb pollution, and reduce drought exposure (Petrovic et al., 2025). Nevertheless, widespread adoption is bottlenecked by gaps in rural digital infrastructure, demographic factors such as farmer age and technical training, and high entry costs that disproportionately favour large agricultural holdings (Barnes et al., 2019; Petrovic et al., 2025). On the land management side, agronomic practices like Conservation Soil Tillage (CST) and cover crops reliably enhance long-term soil water-holding capacity and infiltration while cutting runoff. Adoption remains constrained, however, by technical crop-suitability limits and a common misperception that overstates immediate management costs relative to delayed environmental gains (Quintarelli et al., 2022; Jug et al., 2025).

Ultimately, systemic soft measures—such as optimizing local crop shares to align agricultural demands with environmental capacity—require complex governance structures that extend beyond field-level intervention. Although cross-sectoral integration is widely advocated (Baccour et al., 2025), practical implementation remains fragmented and uneven across regions (EEA, 2025). Large-scale restructuring of production systems and trade modifications may trigger political friction tied to perceived threats against local agricultural livelihoods. Compounding these political risks are fundamental institutional

barriers: water managers typically lack direct regulatory oversight over agricultural development, economic planning, and trade policy, creating a persistent mismatch between environmental goals and sectoral governance.

3.1 Economic Appraisal

Economic appraisal itself can influence which adaptation strategies appear preferable. Conventional assessments can more readily quantify direct economic effects, such as infrastructure investment, agricultural production, revenues and water productivity, while environmental flows, biodiversity, ecosystem services and wider cross-sectoral effects are more difficult to incorporate within a single economic metric (Crespo et al., 2022; Kahil et al., 2025). This is illustrated by the Ebro case study, where adaptation options were assessed using agricultural net revenue and economic water productivity alongside hydrological indicators of environmental flows. Local storage increased agricultural water-use efficiency relative to no adaptation, whereas crop switching generated substantial water savings but performed poorly in terms of agricultural revenue. At the same time, the effects of both measures on environmental flows varied spatially along the river, demonstrating that an option performing well according to a farm- or sector-level economic indicator does not necessarily provide the greatest basin-wide environmental benefit.

The comprehensiveness of the appraisal is therefore important for adaptation prioritization. In the Ebro assessment, for example, infrastructure investment and operating and maintenance costs could be represented directly, while several agricultural production costs were excluded and environmental-flow impacts were evaluated separately rather than monetized. Broader effects arising through agricultural markets and trade may likewise require economic land-use models such as the Global Biosphere Management Model (GLOBIOM; Havlík et al., 2014) rather than basin-scale hydrological models such as the Community Water Model (CWatM; Burek et al., 2020) alone. More comprehensive appraisal can therefore combine monetary indicators with hydrological, environmental and distributional indicators, rather than requiring all effects to be expressed through conventional cost-benefit analysis (Palazzo et al., 2024a). Such an approach is particularly relevant for comparing grey infrastructure with green and soft adaptation measures, whose benefits may include ecosystem services, avoided environmental degradation or system-wide resilience that are not fully reflected in agricultural revenues.

4. Role of sectoral models for implementation of strategies

Sectoral models play a crucial role in evaluating and implementing adaptation strategies by providing stakeholders with data-driven insights into the potential impacts of climate change and adaptation measures. In the context of the Thaya River Basin adaptation strategies, sectoral models such as GLOBIOM (Havlík et al., 2014), EPIC-IIASA (Balkovič et al., 2014), and CWatM (Burek et al., 2020) offer valuable tools for informed decision-making, adaptation planning, and adaptation appraisal.

4.1 Global Biosphere Management model (GLOBIOM)

- What the model can be used for: GLOBIOM is a global agro-economic land use model that assesses agricultural production systems, trade, and land-use changes. It is valuable for stakeholders, such as policymakers and agricultural producers, in understanding how adaptation strategies affect agricultural productivity, trade flows, and land-use patterns. For example, in the Thaya River Basin, GLOBIOM can help evaluate the impacts of changes in irrigation efficiency and trade dynamics on agricultural outputs and market prices.
- What the model can sometimes be used for: GLOBIOM can sometimes be used to analyze broader economic and social implications, such as food security and the effects of dietary shifts, including reduced meat consumption.
- What the model cannot be used for: GLOBIOM is not designed for high temporal resolution modeling or highly spatial hydrological simulations, making it less suited for analyzing water scarcity or environmental flow impacts directly. For these issues, more specialized models, such as CWatM, are needed. The model is also not suitable for price forecasting.

4.2 Community Water Model (CWatM)

- What the model can be used for: CWatM is a hydrological model that quantifies the impact of climate change on water balances, such as water scarcity and environmental flows. It is invaluable for stakeholders in water resource management, environmental protection, and policy development. CWatM helps assess how different adaptation strategies, such as irrigation expansion or water use restrictions, will affect water availability and ecosystem services in the Thaya River Basin and Ebro River Basin.
- What the model can sometimes be used for: CWatM can sometimes be used to explore the resilience of hydrological systems to extreme events, such as droughts. While it is primarily focused on water, it can provide insights into how water management strategies influence agricultural production and land use in specific regions.
- What the model cannot be used for: CWatM is not designed to assess economic or market dynamics, such as agricultural yield impacts on global trade or price changes. It also has limitations in modeling social impacts, such as food security, without additional socio-economic models like GLOBIOM.

4.3 Example of Sectoral Model Application – Thaya River Basin Case Study

In the Thaya River Basin, a combination of these models is used to evaluate and implement adaptation strategies under different climate scenarios. For example, the BAU (Business-As-Usual) scenario is assessed using GLOBIOM to model trade flows and agricultural production under a scenario of minimal adaptation measures. Meanwhile, CWatM provides insights into water scarcity and environmental flow implications. Together, these sectoral models enable stakeholders to make informed decisions about adaptation measures that balance agricultural production, water management, and environmental sustainability (Palazzo et al., 2024a, 2024b).

5. Key recommendations

The case studies from the Ebro River Basin, Thaya River Basin, and Oasi Alberoni highlight key challenges related to biodiversity conservation, water management, and climate adaptation across Europe. Several lessons have emerged from these diverse contexts, offering valuable insights for EU-wide stakeholders looking to address pressing environmental and resource management challenges.

1. Align agricultural adaptation support with river-basin water objectives

Agricultural adaptation and water policy should be assessed jointly rather than independently. CAP support for irrigation modernization, climate-resilient cropping, precision agriculture and other adaptation measures should be evaluated against WFD river-basin objectives, including their effects on total water consumption and environmental flows. Efficiency improvements should therefore be accompanied, where necessary, by abstraction limits, allocation rules or other safeguards that prevent water savings from being offset by irrigation expansion or shifts towards more water-intensive production. Case studies like the Thaya and Ebro River Basins underscore the necessity of considering both environmental and economic dimensions when designing adaptation policies. Stakeholders should adopt a holistic view that balances the demands of agriculture, water management, energy production, and ecological preservation.

2. Tailored Adaptation Strategies for Regional Contexts

While adaptation challenges are shared across Europe, appropriate responses depend strongly on regional water availability, agricultural systems, climate risks, and governance structures. EU policy frameworks should therefore provide sufficient flexibility for Member States and river-basin authorities to develop context-specific portfolios of grey, green, and soft adaptation measures. CAP Strategic Plans and associated instruments can support measures such as climate-resilient cropping, improved soil and water management, and precision agriculture, while implementation should remain consistent with WFD objectives and local water-resource constraints. The contrasting conditions in the Thaya and Ebro demonstrate why a measure that is effective in one basin may not provide equivalent economic or environmental benefits elsewhere.

3. Strengthening Governance and Stakeholder Engagement

Effective adaptation requires coordination across institutions responsible for water, agriculture, energy, and environmental protection. The case studies demonstrate that these responsibilities are often fragmented: river-basin authorities may regulate water allocation but have limited influence over agricultural production decisions, while agricultural policies can affect water demand without directly accounting for basin-level consequences. Strengthening coordination between river-basin authorities, agricultural ministries and managing authorities, environmental agencies, farmers, and other water users can help identify and manage these cross-sectoral trade-offs. Transparent and inclusive stakeholder engagement is particularly important where adaptation involves changes in water allocation, crop production, or environmental-flow requirements.

4. Building Resilience through Green and Soft Adaptation Measures

Green and soft adaptation strategies—such as crop diversification and optimization, improved soil-water management, changes in consumption and trade, and ecosystem-based measures—remain less commonly implemented than technological and infrastructural responses but can be important components of long-term resilience. EU and national policy instruments should therefore support portfolios of adaptation measures rather than relying predominantly on irrigation expansion or efficiency improvements. Combining grey, green, and soft measures can reduce dependence on individual technological solutions and help manage trade-offs between agricultural production, water use, climate mitigation, and ecosystem protection.

5. Levering Sectoral Models for more comprehensive appraisals to better Informed Decision-Making

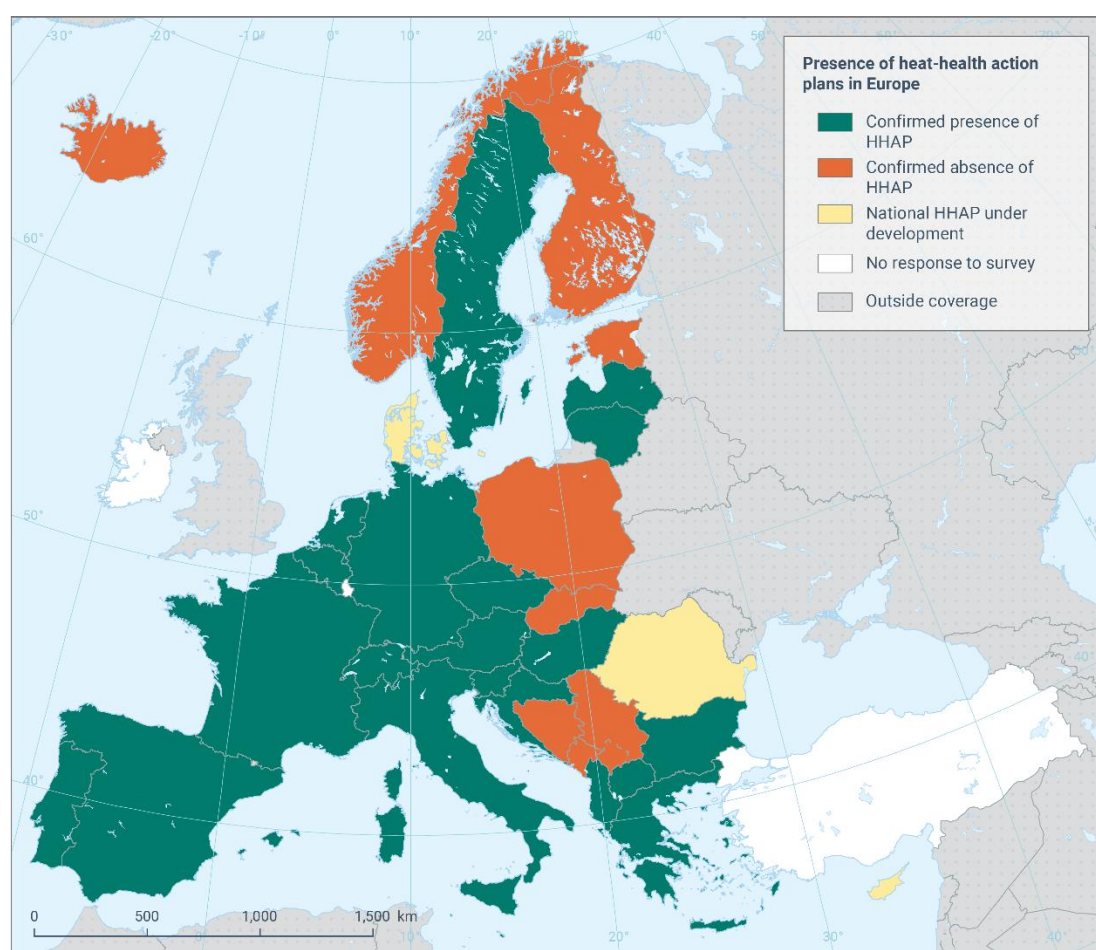
Sectoral and integrated models can support adaptation appraisal by quantifying effects that extend beyond the direct financial costs and benefits of individual measures. Combining hydrological, agricultural, and economic models, such as GLOBIOM and CWatM in the Thaya River Basin case study, can assess changes in water availability and environmental flows alongside agricultural production, land use, prices, trade, and other economic outcomes. These indicators should be complemented, where possible, by environmental and social outcomes that are not readily monetized, including biodiversity, ecosystem services, and distributional effects. More comprehensive appraisal can therefore reveal trade-offs that conventional cost-benefit analysis may overlook and help determine whether adaptation strategies that appear economically attractive at farm or sector level remain desirable when their wider basin-level and environmental consequences are considered.

ADT 4 – Health and justice (Ecologic)

Key questions: *How should we adapt to extreme heat? – What are the social justice dimensions of strategies to adapt to the health impacts of extreme heat?*

1. Decision context

The heat-related challenges of climate change in Europe are becoming more evident and alarming with every year that passes. The effects for ecosystems, society and economy are severe, and extreme heat stress increases the public burden of disease (Stegeman et al., 2026; Kjellstrom and McMichael, 2013). Warming conditions increase morbidity, producing or worsening existing health conditions and mortality, with nine out of ten deaths from extreme weather events in Europe caused by heat (EEA 2024). To address these challenges, adaptive measures in Europe have already been responsible for reducing heat-related mortality by as much as 80% (Gallo et al., 2024). European Member States are also increasingly developing dedicated national heat-health action plans (see Figure 4.1). While these plans give strategic direction, ultimately the planning and implementation of concrete adaptation options also sits strongly with regional and municipal authorities and healthcare providers.



Reference data: © EuroGeographics, © FAO (UN), © TurkStat Source: European Commission – Eurostat/GISCO

Figure 4.1: Presence of Heat-Health Action Plans (HHAPs) in Europe in 2024. Source: European Environment Agency 2024.

Local and municipal governments play a critical role in governance of heat-health adaptation, as they are directly responsible for implementing heat-resilient infrastructure, such as green roofs, urban greenery, and cooling centres (Depietri et al., 2012). This is particularly the case for urban centres where concentrations of heat-retaining infrastructure like concrete and asphalt can produce heat islands that affect the health and wellbeing of populations living and working in these environments. Regional

health authorities are also key stakeholders, tasked with developing early warning systems and emergency response protocols to safeguard public health.

However, regional authorities must address competing priorities, balancing short-term economic pressures with long-term investments in climate resilience. To support governance at these local and regional scales there must therefore be alignment with national policies and funding bodies to ensure equitable resource distribution and support for economically constrained areas (European Environment Agency, 2020). Extreme heat also impacts multiple sectors, e.g. health, energy, water, requiring coordinated actions and policies that transcend traditional silos. Often though, fragmented governance structures and inconsistent funding streams hinder effective collaboration (Macassa et al., 2022; Mallen et al., 2022; Geffert et al., 2024; Tschakert et al., 2025).

Facilitating these enabling conditions is important to the success of heat-health adaptation. However, even where governance is cooperative and resources are available and tailored to local conditions, a major barrier remains that limits the effectiveness of heat-health action plans. One-size-fits all interventions to inform and protect citizens may not sufficiently address heat-health risks for all. Age, gender, existing health status, mobility, social networks, income, living and working conditions are just some of the many dynamic and intersecting factors that can influence and compound experiences of vulnerability and marginalisation. Without developing strategies and measures that explicitly target the drivers of these vulnerabilities, those who are most in need of protection may be sidelined for “the greater good”, which often effectively accrues to those who are already in situations of privilege (Klinsky et al. 2017). For this reason, it is essential that equitable adaptation strategies consider the differential nature of heat-health impacts of climate change.

The primary consideration of this Adaptation Decision Type (ADT) is therefore to understand the social justice dimensions of adaptation to the heat related impacts of climate change on health and to examine barriers, enabling factors and examples of best-practice in heat-health action plans.

2. Adaptation strategies and social justice assessments

2.1 Strategies to address heat and health

Strategies to target heat impacts on health can be grouped into four strategic directions: 1) cooling the environment, 2) reducing the exposure of people and buildings; 3) strengthening coping capacity; 4) addressing the structural drivers of vulnerability (Table 4.1).

Popular strategies to address the heat impacts on health include **heatwave early warning systems** and **public health campaigns**. Many regions have implemented early warning systems to alert communities about impending heatwaves (Martinez et al., 2022; Casanueva et al., 2019). These systems help residents prepare in advance, but their efficiency depends on the dissemination of information and the ability of diverse populations to act on warnings, which can be limited by language barriers or digital knowledge. **Educational campaigns** about the risks of extreme heat and preventive measures, such as staying hydrated and avoiding outdoor activities during peak heat hours, are commonly employed (Casanueva et al., 2019).

While alert systems form the most popular type of action, **greening urban spaces** and **cooling spaces** play an important role in the solution space for addressing heat impacts on health (Martinez et al., 2022). Planting trees, creating parks, and promoting green infrastructure are increasingly adopted strategies to reduce urban heat islands (Ulpiani et al., 2024). These interventions can provide shade and cooling while improving air quality and mental well-being (Banwell et al., 2024; Wong et al., 2021). Creating **cool spots** in public areas, such as **shaded bus stops or benches** or **heat-reflective pavements**, is an approach that has been piloted in some regions such as Vienna but these remain underutilized, particularly as a widespread strategy. An exception is the case of Barcelona, which has rolled out a network of ‘Climate Refuges’ that aim to provide widespread public access to cooling across the city (Amorim-Maia et al., 2023).

Heat-resilient housing standards and **heat adaptation against vector-borne diseases** are interesting but have not yet been implemented as wide-spread strategies. Mandating building designs and retrofits that enhance thermal comfort in homes, particularly in low-income housing, remains largely unexplored. Incorporating heat-resilient features such as **reflective roofs, better insulation, and passive cooling systems** can reduce heat exposure and associated health risks for vulnerable populations (Houghton & Castillo-Salgado, 2019). As extreme heat influences the spread of vector-borne diseases, proactive measures to address their health impacts, such as improved surveillance and public health interventions, remain in early stages of planning.

Table 4.1: Strategic directions heat-health adaptation plans. With selected examples from the four case studies (Section 2.3)

Strategic Direction	Strategy	Adopted in HAPs	Selected examples of measures for vulnerable communities from four HHAPs ^a
Cool the environment	Urban greening: trees, parks, green infrastructure	Commonly included	Prioritizing planting trees in areas with lower tree canopy coverage (Tucson)
	Cool spots: shaded bus stops or benches, heat-reflective pavements	Piloted in e.g. Vienna, but remains underutilised	
	Network of cooling centres and climate refuges	Rare, only known in Barcelona	
Reduce exposure of people and buildings	Heat-resilient building standards and retrofits, reflective roofs, insulation, passive cooling	Not yet widely implemented; largely unexplored for low-income housing	Assistance for low-income households to increase energy-efficiency of homes (Tucson)
	Workplace adaptation: formal heat policies, protective equipment, shift changes, longer breaks	Rarely addressed	Training and protective equipment for city workers; supporting legislation regarding breaks, water access, shade (Tucson); providing information to contractors, exploring mandatory heat protection measures, and adjust working hours (Vienna)
	Heatproofing of settings where vulnerable groups spend time (hospitals, care homes, schools)	Addressed in European plans; less so in Tucson	Increasing shade at schools/day cares and insulating windows for care facilities (Bremen), school playgrounds, assisted living-flats etc. (Barcelona); cooling systems in transitional homes (Tucson)
Strengthen coping capacity	Heatwave early warning systems	Commonly included; the most popular type of action	
	Public health and educational campaigns	Commonly included	Protective equipment for homeless people (Bremen; Vienna); Training for staff on ensuring safe environment in cooling facilities for homeless people (Barcelona)
	Targeted outreach through multipliers and tailored, multi-channel communication	Applied in Bremen and Barcelona	Multi-language and simple language heat advice (Bremen)
	Vector-borne disease surveillance and response	Early stages of planning	

Address structural vulnerability	Vulnerability mapping linked to the spatial targeting of measures	Bremen and Barcelona; absent in Vienna
	Participation of affected groups in design, implementation and monitoring	Extensive in Barcelona; stakeholder-based in Vienna, with the general public unmentioned
	Recognition of and response to structural and historical injustice	Only in Tucson

^a This is not an exhaustive list of examples from the four case studies (see Section 2.3), but intended only to provide some examples from plans where measures were specifically designed to address vulnerability or marginalization.

2.2 Social justice in heat-health adaptation

The heat-related impacts of climate change pose a very clear challenge to human health and wellbeing. However, the heat-health action plans emerging to address this challenge (Figure 1) must be closely monitored. Heat-health risks are unequally distributed within the population and are affected by **underlying and intersectional** vulnerabilities (Amorim-Maia et al., 2023; Lyra et al., 2026). This means that effective and equitable strategies must also account for the **unevenness of vulnerabilities and risk distribution** across the population and consider how the benefits and disadvantages produced by adaptive response strategies will be shared among the population (Kotsila and Anguelovski, 2023). For example, while interventions such as public communication campaigns (Casanueva et al., 2019) can be effective for the general population, they may not always reach those who are most vulnerable e.g. persons experiencing intersecting forms of marginalisation and language barriers.

In their review of structural injustices in relation to equitable urban heat adaptation, Lyra et al. (2026) cite a number of examples of how heat-health interventions can produce differential effects. In London, **a lack of binding heat-adaptation requirements and unequal distribution of cooling infrastructure** has left lower income households in London with less adaptive autonomy (Cole et al., 2017). The cost of heat-resilient housing often excludes low-income households, highlighting the need for subsidies or incentive programs to ensure equitable adoption (European Environment Agency, 2022).

Urban greening strategies can, as mentioned above, have many benefits for reducing heat-island effects and improving thermal comfort for citizens. However, their distribution can often **favour wealthier neighbourhoods**, raising equity concerns (Haase et al. 2017; European Environment Agency, 2021; Bertassello et al., 2026). In Curitiba (Brazil) and Barcelona (Spain), studies have highlighted the ways in which forestry policies and urban tree-planting can **maintain and even exacerbate existing inequalities** in relation to access to greening (Baró et al. 2019; Cuchi et al. 2024). Efforts must thus ensure greening projects prioritise underserved areas to address social justice dimensions. **Networks of cooling centres and shaded public spaces are particularly critical for those experiencing vulnerability** such as older persons, those who are unhoused, on low-income and/or who are unable to cool their homes. Ensuring equitable access to cooling infrastructure in a way that takes into account the intersectional dimensions of vulnerability is vital to reducing disparities in health outcomes during extreme heat events (Amorim-Maia et al., 2023).

To **avoid compounding underlying structural inequalities**, heat-health adaptation strategies must thus make social justice and equity a cornerstone of action (Reckien et al., 2017).

2.3 Review of approaches to integrating social justice in heat-health adaptation

The **Just2Adapt tool** was developed to analyse how different European regions and cities are incorporating social justice dimensions in their heat-health adaptation plans. The first step of the tool is to analyse consideration of **four dimensions** of justice:

- **recognition** (of groups, needs, knowledges);

- **participation** (of those affected by adaptation decision making);
- **distribution** (of risks, impacts, costs and benefits);
- **restorative** justice (consideration of structural, historical injustices).

The second step of the tool is to assess the distributive justice dimensions of measures in more detail, evaluating the strategies' concrete measures across four categories:

1. **Labour;**
2. **Assets, buildings and transport;**
3. **Public health and safety; and**
4. **Blue and green infrastructure, mental health and leisure.**⁴

The tool was initially applied in **Bremen** (See Section 2.3.1 below and ACCREU Deliverable 3.2). To derive further insights for the present study of the wider European context, we sought out additional plans for analysis. As this is an emerging area, the search focused on identifying frontrunner heat-health adaptation plans making discernible efforts to address social justice. At the ACCREU ADT 4 workshop on Heat and Health, Ana Amorim Maia presented aspects of the **Barcelona** heat action plan that addressed social justice and vulnerabilities, indicating that this would be suitable for further analysis. We also applied structured criteria to screen cities in the Global Heat Health Information Network database of municipal climate and heat adaptation plans⁵, searching for plans with a dedicated emphasis on heat-health risk and with relevance for high-income contexts. The ten resulting plans were then examined in more detail for explicit references to justice, which led to the selection of **Vienna** and **Tucson** strategies. In the following section we provide an overview of the strategies' distinguishing features; a forthcoming publication is planned and will contain more detailed information and cross-case analysis.

2.3.1 EU Region: Bremen, DE

Bremen is the smallest German federal state, comprised of the two cities of Bremen and Bremerhaven with a regional population of around 700,000. The region's Heat Action Plan (HAP) was developed by the State Ministry for Environment, Climate and Science in parallel to the regional Climate Adaptation Strategy (KAS) (Federal state of Bremen, 2024). The HAP has been interpreted by the administration as the policy through which the more 'social' components of the KAS are implemented and includes clear attempts to address the distributional and social justice dimensions of heat. Developed collaboratively across the regional administration with particular engagement from the state ministry for Health, Women and Consumer Protection and with civil society, the HAP identifies and targets a number of vulnerable and marginalised groups through its measures. Spatial mapping also supports more equitable planning by identifying areas where climate risks intersect with locations of those groups with higher levels of vulnerability to heat. HAP activities target risk communication, networking and training activities, support cooling solutions and drinking water provision, and increasing green areas. However, important gaps remain: the distributional effects of greening investments are not yet considered in a systematic way. On this basis, it is still possible that investments in heat-health adaptation may end up being captured by higher income groups and/or implemented in locations where the need for greening is not as high from a social or environmental perspective. Longer-term and more secure funding is also needed to retain skilled staff and realise the expected benefits of heat protection measures. As the first of several planned iterations, the HAP will be monitored through an online portal, with proposed indicators offering an opportunity to strengthen the assessment of social justice over time (see ACCREU D3.2)

2.3.2 EU Municipality: Barcelona, ES

The metropolitan area of Barcelona has a population of 3.4 million and is the capital of the autonomous region of Catalonia in Spain. As a city on the Mediterranean that has a long experience of tackling heat, Barcelona has already implemented many adaptation measures in this area. In 2025, the city devised a

⁴ The full description of the tool and its application to the Region of Bremen is included in ACCREU Deliverable 3.2.

⁵ Global Heat Health Information Network resource library; <https://heathealth.info/resource-library/>

highly ambitious municipal heat action plan in which climate justice is an explicit focus (City of Barcelona, 2025). Its development was based on wide-ranging consultation process involving different ministerial departments, public bodies and civil society organisations and is clearly integrated with a number of supporting urban planning instruments. The public participatory process is transparently documented in the plan and moved through stages of informing, to debate, to drafting and response to follow up. Sub-topics in the consultation process included *inter alia* public spaces, unhoused people, health and aging, and municipal facilities. The process allowed for online and in-person contributions at workshops and the numbers of participants and the proposals made are clearly documented. Indeed, 76% of proposals from the consultations were taken up in the final plan, which clearly notes where a measure was derived through the participatory process. The plan is wide-ranging in scope, covering actions to promote societal change and expand research to increasing urban thermal comfort to emergency plans. Of particular note, is the integration of the outcomes of the EU [LOCALISED](#) project that focused on active listening to vulnerable groups to support climate justice and the heat action plan places a strong emphasis on the differential effects of climate change. Further, the plan not only identifies the needs of ‘vulnerable groups’ but has a whole section of the plan dedicated to measures for these groups. It also clearly distinguishes itself from other strategies by recognising the temporal dynamics and intersecting nature of vulnerabilities in the designed measures. However, it has less emphasis on inter- and intra-generational justice issues and it will be important to see how well an intersectional approach to vulnerability is pursued in practice (Amorim-Maia et al., 2023).

2.3.3 EU Municipality: Vienna, AT

Vienna, the capital of Austria with nearly 3 million inhabitants, produced its Heat Action Plan in 2021–2022 to strengthen resilience against rising temperatures. The plan was devised by the city's Climate Affairs Department in cooperation with health, education, planning and communications experts and municipal technicians (City of Vienna, 2022). It sets out 15 measures for the general population, 13 targeted at specific vulnerable groups and nine long-term measures. A dedicated chapter recognises how vulnerable and marginalised populations are disproportionately affected by heat, and a distinct set of measures addresses their needs. Beyond identifying these groups, the plan considers their differential adaptation needs and directs targeted measures towards them, for instance tailored risk communication and support for those most exposed. Participation is a further strength: responsibility for each measure is assigned to stakeholders, and monitoring and evaluation is likewise conducted in consultation with them. The plan has a clear focus on public health and safety (compared to measures that address other categories such as labour or grey and green infrastructure). Overall, it attends well to aspects of justice and lives up to its stated linking of climate and social equity policy. Important gaps remain, however: while Barcelona and Bremen have both engaged in mapping activities to understand the geographies of vulnerabilities in their regions, Vienna’s plan lacks a process for locating vulnerable groups spatially, it also provides no differential risk assessment and neglects the spatial inter- and intra-generational distributional effects. Selected stakeholders are well integrated into the process of implementation and monitoring, but involvement of the general public goes unmentioned and vulnerable groups feature mainly as passive recipients. No monitoring indicators are specified, and the plan neither acknowledges past harms nor calls for compensatory action.

2.3.4 International municipality: Tucson, US

Tucson has a population of around 550,000 and is the second largest city in Arizona, USA. The city offers an interesting international comparison to the European plans analysed. The city’s heat action plan was developed by a core team of city officials with input from a diverse set of stakeholders, including universities, faith-based groups, tribal nations and labour organisations (City of Tucson, 2024). The plan identifies vulnerable groups, devises an Equity Priority Index, and in contrast to any of the European plans, acknowledges historical injustices such as racist land-use practices that led to reduced tree cover in disadvantaged neighbourhoods. Compared with the European HAPs that we assessed, certain vulnerable groups and concerns receive less attention, notably kindergarten and school children and the heatproofing of spaces where vulnerable groups spend time, such as hospitals, care homes and schools. We understand this to be the result of a broader cultural difference between the US and Europe, which have vastly different air conditioning adoption rates of 90% and 23% respectively

(IEA, 2026). This implies that Tucson residents who might otherwise be vulnerable on account of their physiological attributes already have a different base-level of protection from heat. Instead, with regards to equity and justice concerns, greater emphasis falls on energy efficiency and cost management for low-income households and on expanding cooling centres and people's transport to these locations. Most of the measures in Tucson's heat action plan address assets, buildings and transport alongside public health and safety, yet target the general public rather than specific vulnerable groups, and only a quarter of the 62 measures show a clear focus on vulnerable or marginalised groups. In summary, the Tucson HAP addresses vulnerability and justice well, while distributing its attention differently from its European counterparts and with the novel aspect that it attends to questions of historical injustices, a feature which is markedly absent from the European strategies analysed.

3. Barriers to implementation

3.1 Introduction

Adapting to the health risks associated with extreme heat requires cross-sectoral adaptation measures at different governance levels. For this reason, there are a number of institutional, financial, technical, social, and political factors that can hinder or enable the planning and implementation of heat-health strategies. Understanding these cross-cutting barriers and enabling factors is therefore essential for identifying the conditions under which heat-health adaptation can move from planning to implementation and deliver equitable and lasting reductions in heat-related health risks.

3.2 General barriers and enablers to heat-health adaptation

When consulting literature on the barriers and enablers of heat-health adaptation, **funding and financial resource constraints are the most cited obstacles**. Often there is a lack of accessible financial means by public authorities as well as private households or limited capacities and resources to apply for it (Geffert et al., 2024; Käyhkö et al., 2024; Macassa et al., 2022; Mallen et al., 2022; Martinez et al., 2019; Turner et al., 2024). Especially small or poorer municipalities in Europe struggle to access national funds e.g. because bigger cities are more likely to comply with funding criteria (Macassa et al., 2022). Moreover, heat-health adaptation measures are oftentimes treated as an “extra” in local budgets (Turner et al., 2024) and they can be confronted with competing demands on health sector budgets (Geffert et al., 2024; Mallen et al., 2022). Furthermore, especially the retrofitting of existing buildings with cooling systems can be costly and technically challenging (Käyhkö et al., 2024).

Next to a lack of funds, there are **knowledge, expertise and awareness gaps in local authorities** that hinder heat-health adaptation. Oftentimes, local authorities – especially in eastern Europe – lack staff capacity and technical expertise for the topic (EEA, 2020; Turner et al., 2024). In addition, there is often a lack of relevant and local data (Macassa et al., 2022; Mallen et al., 2022; Turner et al., 2024). Experiences show that also in the **public** there is a lack of **awareness** and a lack of awareness in communities regarding heat-health impacts. This however, is crucial for enabling adaptation, as an understanding of heat risks is a precondition to take action (Geffert et al., 2024). **Public health campaigns and education** can increase awareness and knowledge about heat adaptation (Abunyewah et al., 2025; Baack et al., 2024) and targeted outreach and communication improve uptake and effectiveness of adaptation measures (Mayrhuber et al., 2018).

Legal, institutional and governance issues can hamper adaptation to heat. Barriers arise from unclear internal structures, mismatched planning horizons, and the misallocation of responsibilities for heat adaptation between technical and health domains (Abunyewah et al., 2025; Baack et al., 2024; EEA, 2020). Contradictory policies and shifting political priorities further undermine integration of adaptation into urban planning (Käyhkö et al., 2024). Inaction is reflected in the absence of heat planning and long-term strategies, weak legislation, and fragmented or siloed decision-making processes (Tschakert et al., 2025) as well as poor coordination between stakeholders and weak cross-sectoral collaboration (Macassa et al., 2022; Turner et al., 2024). At the national level, heat health action plans sometimes fail to define roles and responsibilities in sufficient detail, which undermines coordination and effective implementation (Vanderplanken et al., 2021).

In this regard, mainstreaming heat adaptation requires local planners, engineers, and water managers to integrate measures into housing, social, and health sectors, while national programmes can help replicate such approaches more broadly (Baack et al., 2024). Accordingly, existing initiatives and **broad collaborative coalitions and cross-sectoral networks** should be leveraged. Political and social shifts can create policy windows that enable prioritisation of adaptation and the redirection of resources toward climate and health resilience (Geffert et al., 2024; Mallen et al., 2022).

A further **barrier can be posed through the existing built environment and urban form** which can constrain adaptation efforts (EEA, 2020). The implementation extent of heat adaptation measures in municipalities is limited, mainly appears as a co-benefit of green-blue infrastructure rather than systematic heat reduction in the built environment. Large-scale adjustments are not prioritized (Baack et al., 2024). Physical space limitations further restrict changes to urban layouts, e.g. green or blue wedges around central areas are difficult to execute (Gupta et al., 2025). Building characteristics add to the challenge, as older housing lacks compatibility with modern cooling devices, densification policies support designs that ignore heat risks, and a focus on insulation for the cold season, especially in Nordic countries, increases exposure during prolonged heatwaves (Käyhkö et al., 2024).

Ineffective monitoring and warning systems hinder protection against heat risks (Abunyewah et al., 2025). Robust heatwave warning systems are essential for effective adaptation, while planning in advance ensures rapid activation of responses when extreme heat is forecasted (Abunyewah et al., 2025; Korfmacher et al., 2025). Multi-channel communication strategies including social media, apps, phone calls, and leaflets alongside tiered outreach to at-risk patients, strengthen emergency response capacity and protect vulnerable populations (Korfmacher et al., 2025). In the longer term, an orientation towards green infrastructure can reduce exposure (Abunyewah et al., 2025; Käyhkö et al., 2024).

Moreover, a **lack of political commitment and visible leadership can hinder adaptation** (EEA, 2020). Due to the nature of extreme events, awareness tends to increase immediately after an heat event but declines over time, making it difficult to maintain the issue on political agendas at all levels (Abunyewah et al., 2025). Leadership and staff turnover e.g. after elections, can change priorities, require repeated training, and fragment projects (Mallen et al., 2022). In the ACCREU case study in Bremen, challenges were identified regarding human resources, including recruitment and retention of appropriately trained personnel to manage new urban green areas in ways that are climate resilient.

In the **workplace**, adaptation is hindered by employers underestimating heat stress risks and the under-reporting of impacts, while poor facility layouts and inadequate working conditions further heighten occupational vulnerability to climate-related health impacts (Abunyewah et al., 2025; Käyhkö et al., 2024). In this regard, formal workplace heat policies, protective equipment, shift changes and longer breaks can reduce risk (Abunyewah et al., 2025).

3.3 Specific barriers to addressing social justice in heat-health plans

In some geographic areas a strong **reliance on a particularly-exposed employment sector** can restrict adaptive capacities of the local population if there are few alternative sources of income Käyhkö et al. (2024). Käyhkö et al. consider the heightened exposure of bus drivers and mobile health care professionals during heat waves. Yet in some instances, it may be the precisely bus drivers and mobile workers who are more protected, due to having access to air conditioning, while those who only work from home or are unemployed and live in buildings that cannot be cooled for structural or financial reasons have lower adaptive capacities. Furthermore, **within sectors, particular job types can be more exposed** than others e.g. agricultural field workers vs those working in chilled dairy processing units. This is further affected by the dynamic and differential nature of health vulnerabilities of those within these groups e.g. whether the workers have pre-existing health conditions.

Taking the needs of those experiencing vulnerability into account in all aspects of policy design and implementation are an essential component of the equitable distribution of the benefits and burdens of heat-health adaptation policies (Abunyewah et al. 2025; Klinsky et al. 2017; Reckien et al. 2017). While some efforts exist to map vulnerabilities based on physical characteristics in the population and to

combine these with climate risks—as carried out in Bremen—there is often a **lack of relevant and local data** e.g. on heat impacts and the dynamic ways in which vulnerability is distributed and experienced across the population (Macassa et al., 2022; Mallen et al., 2022; Turner et al., 2024). Moreover, there can be a **perception barrier** regarding heat-health impacts, with those categorised as vulnerable, not perceiving themselves to be at risk e.g. where residents do not consider themselves as old while identifying others in their age group as especially vulnerable (Martinez et al., 2019; Mayrhuber et al., 2018; Tschakert et al., 2025; Turner et al., 2024).

Furthermore, those who are vulnerable may be underserved due to **insufficient public access** to cooling, alongside general issues such as limited health infrastructure and inadequate responses to homelessness (Abunyewah et al., 2025; Tschakert et al., 2025). In addition, poor accessibility, affordability, and inclusivity in public transport further restrict mobility and access to essential services during heat events (Tschakert et al., 2025). This is exacerbated by **inefficient or culturally inappropriate information dissemination systems** which can limit the ability to reach individuals experiencing vulnerability or marginalisation (Tschakert et al., 2025). However, working with existing multipliers as was the case in Bremen and Barcelona for example, as well as targeted outreach and tailored communication programmes, particularly those using language appropriate for vulnerable populations can improve the uptake and effectiveness of adaptation measures (Mayrhuber et al., 2018). This can be further assisted by multi-channel communication strategies that include social media, apps, phone calls, and leaflets alongside tiered outreach to at-risk patients, including the involvement of outreach workers, which can strengthen emergency response capacity and protect vulnerable populations (Korfmacher et al., 2025).

4. Summary and conclusions

The starting point of this ADT is that heat is the most threatening climate hazard for European citizens. A growing number of strategies and heat-health adaptation plans have emerged in response to this challenge, which at Member State level are being tracked by the EEA. However, effective action to address the consequences of heat on health relies primarily on locally specific actions that target particular local heat hotspots, groups and contexts. For this reason, we have focused on examining the actions, barriers and enabling factors of heat-health adaptation at regional and municipal level. Popular actions of heat-health adaptation plans include: heatwave early warning systems, public health and educational campaigns, urban greening and the provision of public cooling. In contrast, less attention has so far been given in European heat-health plans to building standards and regulations or protective measures against vector-borne disease.

A crucial issue however is that for heat-health adaptation plans to be effective, they must identify and target actions towards those who are most vulnerable. The public burden of disease from heat is substantial and can only be reduced by ensuring that underlying structural inequalities, uneven vulnerabilities and distribution of risks are accounted for in plans. Heat-health adaptation strategies must thus make social justice and equity a cornerstone of action (Reckien et al., 2017). To this end, the ACCREU team has developed the Just2Adapt tool, to facilitate analysis of the social justice dimensions of heat-health adaptation plans. In our analysis of the region of Bremen and the municipalities of Barcelona, Vienna and Tucson we found a number of promising features to this end. In Bremen and Barcelona, climate hazards have been mapped in relation to the spatial location of people who may be experiencing vulnerability or marginalisation allowing targeted measures to be developed; in Vienna and Barcelona the strategies clearly identify who they understand as being vulnerable and have dedicated sections attending to the needs of these persons. Tucson, in its representation of a non-EU context is particularly interesting, showing how vulnerabilities and the definition of socially just measures shifts in a context where there is an almost complete coverage of air conditioning in the built environment. Two general shortcomings across the plans are that while they consider the differential ways in which heat affects the health of groups within the population, firstly, very few directly address the structural nature of the inequalities driving these inequalities and differential vulnerabilities and secondly, that the plans do not address the potential that the heat-health plans have to themselves compound vulnerabilities and produce injustice and take preventive actions in response.

Barriers to the rollout of heat-health adaptation are not dissimilar to those present in many other areas of environmental policy making. Financial resources, political will and cross-sectoral coordination are all issues that equally apply to the reasons why heat-health plans may not progress as hoped. However, there are also heat-health specific barriers such as the ways in which the built environment has been constructed, the lack of effective monitoring and early warning systems and of employer awareness of the need for adaptation of procedures and activities in the workplace. Furthermore, there are also a number of barriers that specifically relate to the uptake of social justice concerns in heat-health plans. These include a lack of data about the dynamic and intersecting nature of vulnerabilities, their temporal and geographical spread. They also include communication issues such as the barrier that many who might be classified as vulnerable may not receive information in an appropriate format or language and or may not understand themselves to be ‘vulnerable’. Finally, while strategies may seek to improve cooling in general, these measures will be ineffective for protecting the public unless they ensure that the locations of these sites are known and physically and financially accessible to those who are experiencing vulnerability or marginalisation. In conclusion, while many strategies to mitigate the health impacts of extreme heat are in place, the social justice dimensions require greater attention. Efforts to scale up less commonly used and not yet implemented strategies, with a focus on equity, can create more inclusive and effective heat adaptation systems

5. Recommendations

On the basis of the above findings, we propose a number of targeted recommendations to support the implementation of heat-health climate adaptation strategies.

- **Enable collaboration of different actors:** Heat affects health in diffuse ways and requires the collaboration of diverse actor landscapes. This includes the development of cross-sectoral heat action plans that draw in national, regional and municipal authorities working on health, education, urban planning, business and industry as well as research, technology and innovation and finance. In the most effective heat-health plans, this collaboration does not stop at the phase of plan design, but involves stakeholders playing active roles in plan implementation, monitoring and evaluation in a way that heat-health action can respond dynamically to emerging risks and challenges.
- **Design action to respond to vulnerability and marginalisation:** Measures that provide general access to cooling infrastructure can support improved population health. However, for truly effective heat-health adaptation, targeted interventions that factor in vulnerabilities and marginalisation are required. This can be done through spatial mapping that allows decision-makers and those working with affected communities to determine where heat impacts may pose increased risks to those experiencing vulnerability or marginalisation. Heat-health plans should strive not only to target these areas and groups through awareness raising actions but should integrate analysis of how structural factors such as urban planning or discrimination may be driving heat-health inequalities; this information should be used to ensure that measures respond to rather than worsen intersecting heat-health vulnerabilities and injustices.
- **Activation of multipliers for targeted outreach and engagement:** To reach those experiencing vulnerability or marginalisation, it is essential to activate regional and local-level coalitions of civil society, public service workers such as doctors and teachers, social services, operators of public buildings and infrastructure such as hospitals, care facilities and schools as well as private sector employers and retail. Through these interactions, targeted measures and cooling networks can be identified in support of groups with particular needs.
- **Update early warning and emergency response:** Early warning and alert systems remain an essential part of heat-health responses. In many parts of Europe, such as Spain, Italy and France, strategic heat action is complemented with the publication of annual plans outlining emergency response strategies and information for key workers. This is ongoing work that requires continuous financial support for ongoing testing, training and awareness raising that adapts to

changing risks posed by heat. Based on the findings in this ADT, emergency measures should seek to reflect growing research and awareness about the complex nature of vulnerability and to take actions to support affected groups in these response plans.

- **Sufficient long-term financing:** One-off investments in cooling infrastructure, can be a good way to reduce risks to health, particularly where these are located based on vulnerability-centred heat hazard maps. Focus should be placed as much as possible on interventions with lower trade-offs such as green infrastructure/shading and other passive cooling systems, reverse heat pumps or establishing cooling networks across the city or where the effect would be greater for those most at risk. However, the maintenance of these investments, particularly in green infrastructure is essential to ensure continued cooling effects. Heat adaptation requires a steady municipal budget, not only single investments. Such actions should be understood as social investments that not only reduce the public burden of disease by reducing morbidity and mortality from heat but also reduce inequalities.

ADT 5 – Financial and private sector (Deltares/VU)

1. Decision context

Compared to the other ACCREU ADTs, this ADT on *finance and the private sector* has a relatively large research gap concerning how climate change will even affect financial stability, and through what mechanisms. The mechanisms from climate risk to the financial sector are referred to as ‘transmission channels’. The degree to which climate change will impact the financial sector is a topic of debate (Caloia et al., 2026). Some emphasize the potential impact of transition risks linked to the shift towards a low-carbon economy, others identify the physical risk such as floods as a major threat, and others deem any significant impact on the financial sector unlikely. Our reflection on adaptation strategies can only be understood in the context of this wider discussion on whether there is a substantial impact. Recent review articles (Reinders et al., 2023; UNEP, 2024; De Bandt et al., 2025) highlight the following research gaps: physical climate risks have received much less attention than transition risks and existing methodologies deliver a fragmented and incomplete picture of financial sector impacts. As we will see in the remainder of our analysis, this leads to a paradox: most studies report relatively small (banking) impacts from physical climate risks, while at the same time, indicate that these risks are strongly underestimated due to limitations in their methodologies. This raises the question how robust the ‘limited impact’ conclusions are, given the physical and economic modelling limitations. And to what extent adaptation in the financial domain is needed.

The research questions of this ADT are as follows:

1. Do climate hazards pose a substantial threat to financial stability, and what are the possible implications for macroprudential policy?
2. Which transmission channels are likely to have the most impact/are most important?
3. What are the financial adaptation measures with which biophysical/technical adaptation measures can be complemented. What are the advantages, limits, and barriers?

Decision making context

This ADT provides insights to a range of key stakeholder groups in the financial domain, each of which may play a role in implementing, steering or evaluating adaptation strategies. These stakeholders operate under different mandates, such as maintaining price stability, ensuring financial stability, supervision, or supporting economic growth, and can operate on multiple governance levels, including national, European, European Monetary Union, G7, G20, and international bodies. These groups can be broadly categorized as follows:

1. *Macroprudential policy makers* design policies for the mitigation of systemic risk and maintain stability for the financial system. These policies aim to reduce or prevent the impact of systemic risk for the financial system, which may be influenced by climate risks. These policymakers can operate on multiple governance levels:
 - *At the national level:* this includes central banks (e.g. Dutch National Bank (DNB) – stakeholder of case 5.1, Bank of England or Bank of Canada⁶) and ministries of finance. In addition, the national bank may act as an economic policy advisor towards the ministry of finance⁷.
 - *At the European level:* the European Central Bank (ECB) holds the macroprudential policy mandate for euro-area banks, complementing national authorities. The European Parliament, together with the Council of the European Union, co-legislates EU financial law by adopting regulations that affect capital requirements.
 - *At the international level:* institutions such as the Financial Stability Board (FSB) contribute to the macroprudential policy framework through risk identification, coordination, and the development of guidelines and best practices.

⁶ These examples are selected because work of these institutions is discussed in this deliverable.

⁷ <https://www.dnb.nl/en/about-us/mission-and-tasks/>, accessed 7 Jan. 2025.

2. *(Financial) supervisory institutions* oversee compliance with regulatory frameworks by monitoring, inspecting and enforcing established standards. Within the euro area, large and systemically significant⁸ banks are directly supervised by the European Central Bank (ECB), while smaller, less significant banks are supervised by competent national authorities, under the framework of the Single Supervisory Mechanism (SSM). In this supervisory context, climate-related risks are increasingly treated as risk drivers. Several other supervisory institutions exist, more aimed at specific parts of the financial sector including the European Insurance and Occupational Pensions Authority (EIOPA) for insurers and pension funds, and the European Securities and Markets Authority (ESMA) for securities markets and market participants. Currently, supervisors such as the ECB are developing and applying climate stress-testing methodologies to assess both banks' exposure and capability to identify climate-related risks, including through EU-wide climate stress tests used as supervisory learning and benchmarking exercises (ECB, 2025).

Additionally, at the international level financial stability and regulatory coordination is supported by institutions such as the International Monetary Fund (IMF), which focus on systemic wide financial risks which climate risk is increasingly a part of. Even though they do not directly act as supervisors of institutions they play an important role in global coordination and policy guidance. Further cooperation activities have been established such as the Network of Central Banks and Supervisors for Greening the Financial System (NGFS), which aims to share knowledge on climate-risk-finance related topics. Part of this is the creation of the NGFS climate scenarios which are aimed at supporting supervisors and central banks in assessing the financial sector exposure to climate-related risks, including through stress tests.

3. *Financial sectors including banks, insurers, investment funds* are individual entities (corporates) that are required to adhere to National and European regulations set by the supervisors. These institutions might have assets that are exposed towards climate-risk and can also take proactive measures to reduce this exposure. Alongside individual institutions, sectoral associations operate at national and European levels to represent the collective interests of financial institutions, facilitate knowledge sharing, and engage in policy dialogue. For example, the Dutch association of insurers, stakeholder in case 5.2, represents insurance companies that belong to this group. They discuss and research climate related consequences and measures related to insurance with the national government and within Europe with for example the European Insurance and Occupational Pensions Authority (EIOPA).
4. *The non-financial sector includes governments, households, non-financial businesses.* Governments can introduce adaptation measures such as climate-risk labelling, national climate insurance and initiatives to enhance climate-risk data availability. Additionally, governments can emphasize the need for specific (financial) adaptation towards parties such as macroprudential policy makers or within the European commission. While households and non-financial business can take adaptation measures for their individual properties to reduce their financial risk, they are highly dependent on the decision made by the stakeholder mentioned above for overall financial stability.

⁸ A bank is classified as significant if it adheres to at least one of the following criteria: size (>30 billion assets), economic importance (assets >20% of national GDP), significant cross-border activity or has received emergency support through ESM/EFSF: <https://www.bankingsupervision.europa.eu/framework/supervised-banks/html/index.en.html> Accessed 11 March 2026.

Table 5.1: Stakeholder groups within the financial domain and their associated governance levels

	National	European Monetary Union	International
1. Macroprudential policy makers	Central Banks; Ministries of Finance	European Central Bank, European Systemic Risk Board (ESRB)	Financial Stability Board (global coordination)
2. Supervisor financial sector	National competent authorities	European Central Bank (ECB), European Banking Authority (EBA), European Insurance and Occupational Pensions Authority (EIOPA), European Securities and Markets Authorities (ESMA)	International Monetary Fund (IMF) Network for Greening the Financial System (NGFS)
3. Financial sector	Individual banks, insurers and other actors. Cooperation initiatives such as the Dutch Association of Insurers (VvV)	European sectoral associations (e.g. Insurers Europe)	International associations and standard-setting institutions (e.g. International Association of Insurance Supervisors (IAIS))
4. The non-financial sector	National governments, households and other non-financial businesses.	European commission	International political coordination: G7, G20

2. Transmission channels – from climate risk to financial sector

Climate change can impact financial stability through multiple transmission channels. First, we provide an overview of the various transmission channels linking climate risks to the financial sector (2.1). In Section 3 we then review empirical studies that quantify these impacts, offering insights into the scope and magnitude of financial vulnerabilities.

2.1 Transmission channels & the financial system

Traditional risk assessment methods often focus on short time horizons and historical risk patterns, whereas climate risks are typically long-term, increasing in frequency and severity, uncertain, and non-linear. To address this, the Financial Stability Board (FSB⁹) developed a framework for the assessment of climate vulnerabilities to the financial sector (Figure 5.1). The framework differentiates three major domains: *climate-related domain*, *non-financial macro-economic domain*, and *the financial sector domain*. The framework highlights the transmission channels between these domains, feedback and amplification effects. A helpful aspect of the FSB-framework is its differentiation between the broader (non-financial) macro-economic domain that covers all economic sectors, and the specific financial sector domain that covers the provision of financial services by banks, insurers and investors.

Climate risk is differentiated between transition and physical risks or both simultaneously.

- *Transition risks* originate from the shift towards an economy in which less greenhouse gases are emitted, which can lead to gradual and abrupt changes in consumer and investor behaviour and associated risks. These include the risk of ‘stranded’ assets that are no longer needed in the new economy, new regulatory requirements and supply chain disruptions.
- *Physical risks* refer to the damage that extreme weather events may cause.
- The combined transition and physical risk is referred to as “*compound risk*”, which can result in uncertain non-linear impact for both climate and economy.

⁹ The Financial Stability Board (FSB) is an association that monitors the global financial system and makes policy recommendations. It was established by the G20. Next to the G20 countries, their members are large international organizations including the IMF, World Bank, OECD, EC, and the ECB, and standard-setting bodies such as the Basel Committee on Banking Supervision and the International Association of Insurance Supervisors.

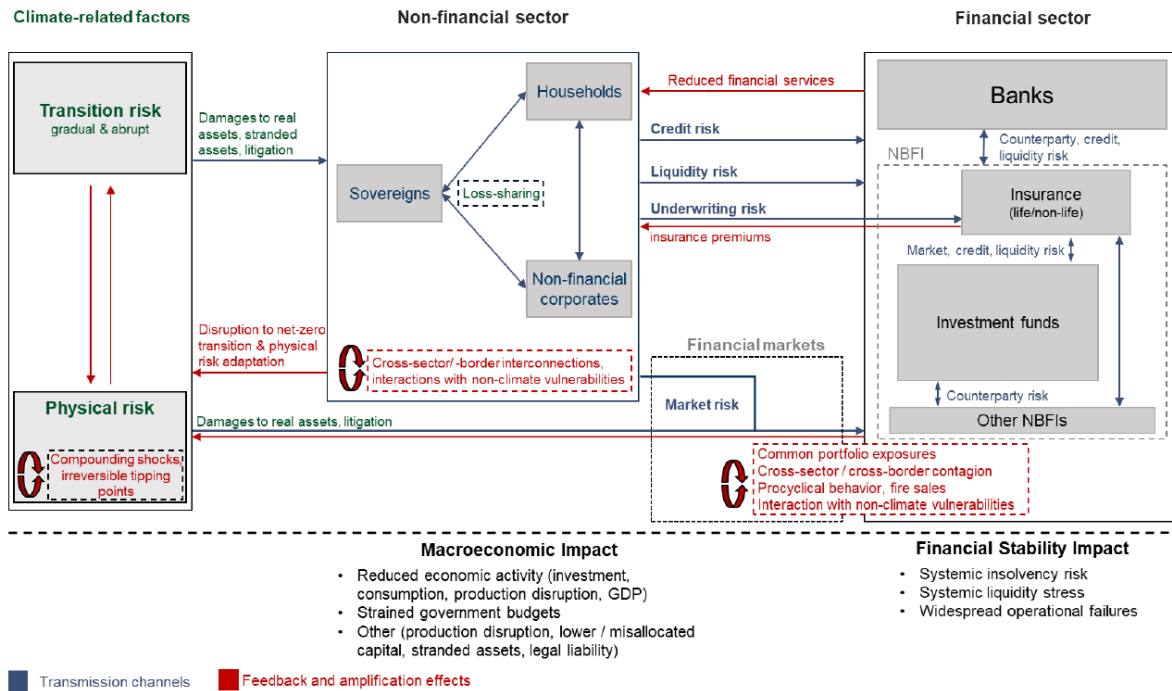


Figure 5.1: FSB framework for the assessment of climate vulnerabilities (FSB, 2025) NBFIs stands for non-bank financial intermediation.

The different risk types from the FSB framework are described below, with an example for the Dutch context with a focus on physical risk. Inflation rate risk is added as an additional dimension.

Table 5.2: Risk types applied to the Dutch context based upon FSB framework (FSB, 2025)¹⁰

Risk type	Description	Example of the Netherlands
Credit risk	Originates from concerns about the ability of counterparties affected by climate shocks to meet their obligations. For example, if a flood would destroy real estate, making homeowners unwilling to pay their mortgage, and leaving the bank with a worthless collateral for mortgages in their portfolio.	Large scale flood destroys assets that serve as collateral for bank (Physical risk) [CS5.1] Sudden announcement of 'retreat' -> reduces value of assets that serve as a collateral for bank (Transition risk)
Market risk	Triggered by abrupt asset repricing as market participants incorporate expectations associated with new transition paths or unfolding physical risks, increasing risk premiums and market volatility.	A decline in house price of flood-prone properties, due to flood event (Physical risk) or perception shock (Transition risk)
Liquidity risk	Driven by withdrawal of funding by counterparties (e.g. depositors, investors) from financial institutions that are perceived to be overly exposed to climate risks or liquidity outflows due to margin calls as a result of abrupt repricing and reduced access to funding due to reputational damage.	Dutch banks have difficulties attracting capital to maintain liquidity, in the aftermath of a flood event. Fiscal risk for government losing AAA status (Physical risk)
Underwriting risk	Insurers face increased exposure due to increased asset damages and deterioration in human health from acute and chronic physical risks.	Flood event causes high underwriting losses; insurers increase premium or withdraw from market (Physical risk)
Inflation rate risk	Due to a large climate risk event or transition towards a net zero economy, prices significantly increase, requiring monetary policy to maintain a "healthy" rate.	Physical climate event such as drought in 2018 causes significant damage to crops. As a result,

¹⁰ This table was filled out during the ADT workshop of October 10, 2024

		producers ask higher prices causing inflation ¹¹ . (Physical risk)
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3. Studies on climate risks to the financial sector

Recently, several studies have attempted to model the impact of climate risks to the financial sector. We first discuss three modelling studies that have attempted to model the impact of floods on financial stability in the Netherlands, including ACCREU CS5.1 (section 3.1). We then examine how flood risk has been studied in other countries (3.2). Third, we discuss studies for other climate hazards and transmission channels (3.3) and conclude (3.4). An overview of all studies is given in Appendix E.

Climate stress-test exercises currently take two main forms. The first form is a (bottom-up) stress test initiated by a macroprudential policy maker or a financial supervisor¹² such as the ECB who provides a framework to its participants. A typical event is suggested, and data is collected from individual financial institutions (group 3: individual banks). For climate risk this is currently still often a participatory process where banks can apply different methods of data collection and applying methodologies.

The second type consists of portfolio-based stress tests or risk assessments, which may be conducted either by supervisors (group 1&2) or by individual institutions such as banks (group 3). Top-down, supervisor-led studies, such as the Bank of Canada (2023) flood assessment, apply a methodology at the system level using loan level data from regulated institutions. Portfolio-level analyses are also conducted by individual banks or researchers, such as the German Bundesbank (Shala & Schumacher, 2024) study, but these exercises typically don't include the assessment of system-wide financial stability.

3.1 Three studies on flood risk to the Netherlands

This section discusses three recent modelling studies that examined the impacts of floods on the financial system of the Netherlands. All three are pioneering studies; they are first attempts to quantify various pieces of a complex puzzle. They differ in terms of research question and policy relevance, methodology and time scale.

The first study is ACCREU CS5.1, with the DNB Dutch Central Bank (Caloia et al., 2026). Caloia et al. study how floods affect financial stability through one specific transmission channel: credit risk of commercial and residential real estate. They focus on how the capital position of major lenders in the Netherlands would be affected if the real estate, that serves a collateral for mortgages, would be damaged from river and/or coastal flooding. This capital depletion is measured through a decline in the CET-1 ratio. The main stakeholder they address are policy makers on financial stability. They find that flood-related property damages lead to capital declines that mostly range between 30 and 50 basis points. The third and second worst flood scenarios are higher: 75 basis points, whereas the most extreme scenario leads to a depletion of 110 basis points. This amount of capital depletion seems manageable. For example, the most extreme scenario (110 basis points) represents a capital depletion from 15% to 14%. This depletion is substantially smaller than the impact of a severe economic shock, which was estimated at 459 basis points in a 2023 banking stress test of the European Banking Authority (EBA, 2023). The outcomes of this EBA stress test did not lead to large concerns about the stability of European Banks. At the same time, these results should be interpreted with caution. After all, Caloia et al. only examined one transmission channel: how the flood damage (repair costs) on residential and commercial real estate would impact the balance sheets of banks. Even within this transmission channel, there is some indication that they might have underestimated the real estate damage (see the uncertainty

¹¹ While floods are used to illustrate financial stability through asset losses, drought is used for inflation risk in the Dutch context since it creates a more EU-wide supply shock that can impacts prices is therefore a more appropriate example.

¹² (see section 1; group 1 & 2)

analysis in ACCREU D2.5). More importantly, there are several other transmission channels through which financial stability may also be impaired in the aftermath of a big flood. For example, elevated risk perception in the aftermath of a flood event may also reduce real estate prices, even for assets that are not affected in this event but are known to be at risk. Also, this study did not examine the wider macroeconomic consequences of flooding, such as infrastructure damage or the suspension of production activities, both of which can significantly disrupt economic systems.

The second study is the country report of the Netherlands, part of the Financial Sector Assessment Program of the International Monetary Fund (IMF, 2024; Lepore and Mok, 2024). Where Caloia et al. (2026) only uses a financial stress test model, the IMF (2024) uses both a financial stress test and a macroeconomic model. The IMF *financial stress test model* finds a credit risk impact of 30-60 basis points, which is somewhat lower than 40-110 basis points that Caloia et al find, for the same Worst Credible Flood scenarios. This part of the IMF study therefore seems to confirm that the credit risk impacts are manageable. In the words of Lepore and Mok: ‘Overall, we find that the banking sector can cope with credit losses from flood events.’ (2024, p. 4). This holds from the present climate till at least 2050, assuming that all planned physical adaptation measures (dike heightening) will be implemented.

Surprisingly, the results of the *IMF macroeconomic model* do give very large GDP impacts for the worst credible flood scenarios (WCF). Three WCF-scenarios give relatively similar results, ranging from 5 to 7% decline in GDP. The most adverse WCF-scenario causes a 14% decline of GDP (IMF, 2024, p. 25). This seems at odds with the relatively small banking sector impacts they find for the same scenarios. The IMF attributes this inconsistency to three factors: ‘first, the significant heterogeneity in the size of the impact across banks, in part due to incorrectly-reported data in some banks; second, our probability of default (PD) model for the Netherlands suggests a relatively smaller impact of GDP changes on future PD trajectories; and lastly, the absence of other risk channels (interest risk and market risk) in this analysis is another caveat to this analysis.’ (IMF, 2024, p. 24). We perceive the first factor as unconvincing, because Caloia et al. used more accurate data, and also found small impacts. The second factor seems more relevant: is the probability of default model still applicable for such a catastrophic flood event? The third factor also seems highly relevant: a catastrophic flood will impact the financial sector through more transmission channels. Concerning this last factor, in the 2026 version of Caloia et al. (2026), some uncertainty analysis was added around this PD-effect. This confirmed that indeed, any reduction in economic growth would cause a very substantial PD-effect.

The third study is Endendijk et al. (2024). In contrast to the other two studies, Endendijk et al. take the perspective of one individual real estate investor. Their DIFREI model captures both the direct and indirect flood-related risks for both residential and commercial real estate. As such, this approach is somewhat richer in terms of transmission channels accounted for. Like Caloia et al., Endendijk et al. examine credit risk, but not only due to physical real estate damage but also through business interruption losses. Nevertheless, they also find that floods lead to minor portfolio value reductions. They conclude that mortgage lenders are resilient to a sudden capitalization of flood risk on the housing market. In this context, they note that despite this small impact to the lenders, the impacts to individual households may still be severe. Another strength of the study of Endendijk et al. is its explicit exploration of financial adaptation measures. The adaptation measure they investigate is lowering the maximum LTV from 100% to 90%. In practical terms, this would mean that a mortgage can only fund up till 90% of the value of the house. Households would need to bring in more of their own capital when buying a house. Endendijk et al. show that this would significantly reduce the exposure of the bank to flood damage.

While these studies do not show large impacts on financial stability, they each focus on a limited set of transmission channels, mainly credit risk related to real estate. Therefore, the current studies do not provide a basis to conclude that climate-related flood risk poses a low threat to financial stability.

3.2 Flood risk studies in other countries

One of the most complete analysis of flood risk is done by the Bank of Canada (2023): covering all flood types (coastal, fluvial, pluvial) for the present, 2050 and 2100 under both RCP4.5 and RCP8.5.

For their event-based approach, they pragmatically split a 100-year return period flood map along the 121 census metropolitan area boundaries, assuming that an entire metropolitan area would be affected by a single event in time (independent from other areas). The residential damage caused by these events would be 9.1 billion CAD¹³ for Vancouver, 6.1 billion CAD for Montréal and 1.6 billion CAD for Calgary. Properties in the flood zone receive an average damage of 29,000 CAD. The effect on lender's LGD is 24 basis points, on average. For RCP8.5, they find an increase to 60 basis points, on average. An interesting feature of the Canadian study is that it also examined the sensitivity to a reduction in homeowner equity. The study results appear to be very sensitive to this; assuming a 10% house price depreciation leads to tenfold increase (LGD increase from 40 to 420 basis points) of the flood impact. This shows that the large amount of homeowner equity has a strong dampening effect on the impact of physical risks in this type of stress-tests. In other words, the flood damage would still affect the wealth of a household, but not necessarily spill over to the lender and the financial system. Both Canada and The Netherlands are known for having seen rapidly increasing housing prices¹⁴ (Bank of Canada, 2023) and large homeowner equity. The sensitivity analysis shows, that under market conditions with less homeowner equity, the impact of flooding could have much larger impacts to financial stability. Such adverse market conditions may occur during an economic recession. However, flooding itself may also lead to less favourable market conditions: for example, due to reduced demand for flood-prone properties.

The German Bundesbank (2024) studied the impact of the summer flooding in the Elbe in 2013. The focus is on domestic loans, held by regional savings and cooperative banks. The type of loans that are assessed are corporate loans to non-financial firms (farmers, manufacturing) and retail loans (mortgages). They find that banks in the affected regions have statistically significantly larger impairment flows (+0.029 percent points) than banks in unaffected regions. Most of this is caused by the corporate loans in the agriculture and manufacturing sector. These are more affected than the retail loans. This is likely caused by the fact that public financial support only targeted the direct damages, and not the indirect damages. Indirect damages and losses such as business and supply chain interruptions were not covered, while these are important for the repayment capacity of these firms.

In the ECB's 2022 climate stress test, the scenario considers a severe flood that would hypothetically affect Europe on 1 January 2022. The scenario is used to model a shock to residential and commercial real estate, at NUTS-3 level (ECB, 2022B). Flood risk data is of the European Commission LISFLOOD-model. Based on results of LISFLOOD, the NUTS-3 regions in Europe were classified into 4 categories: minor, low, medium and high. This results in commercial real estate price shocks from -3%-43% and residential real estate price shocks from -4%-45%. On the flood risk scenario, the ECB (2022) writes the following: *"In the flood risk scenario, real estate collateral in high(er) flood risk areas is assumed to experience severe damage. This affects the value of the collateral underlying mortgages and corporate loans secured by real estate. The main driving factor for credit risk materialisation under the flood risk scenario stems from the assumed negative shock to real estate prices in areas hit by floods. This in turn pushes up loan-to-value (LTV) ratios, which ultimately leads to an increase in LGDs and hence expected losses."* (p. 43).

The cumulative losses on loans that would be made in the flood scenario, with values ranging up till some 100 basis points, that is 1 percent point, since these estimates do not account for insurance and public natural disaster relief, these numbers likely are an overestimation. An important conclusion is that banks have relatively little exposure to the areas with high flood risk. In other words, the assets of the banks are not concentrated in the riskiest regions. In loan-to-value the medium flood zone shows the highest LTV increase, of some 18%.

¹³ A Canadian dollar (CAD) is about 0.67 EUR (average exchange rate between 21 april 2016 and 21 april 2026).

¹⁴ Especially when benchmarked against household incomes. <https://www.oecd.org/en/data/indicators/housing-prices.html> , accessed 22 April 2026.

3.3 Other hazards in other countries

The Financial Sector Assessment Program (FSAP) of the IMF, in collaboration with Canadian authorities, analysed the impact of wildfire risk on bank financial stability under current and future climate scenarios (IMF, 2025). The study focuses on one main transmission channel: credit risk arising from damage to residential real estate used as collateral for mortgages, using an anonymised loan-level dataset covering mortgages of seven systemically important deposit-taking institutions. Wildfire risk is assessed using climate projections under RCP2.6, RCP4.5 and RCP8.5 for 2041–2070 and 2071–2100 at a 10×10 km resolution. Wildfire risk is based on indicators including the Fire Weather Index (FWI), Buildup Index (BUI) and Fire Season Length (FSL), classified from low to extreme. These are linked to wildfire damage functions to estimate impacts on loss-given-default (LGD). Under both RCP4.5 and RCP8.5, around 65 percent of mortgage loans are in areas vulnerable to very high or extreme fire hazards by 2041–2070 compared with roughly 38 percent in the historical baseline. LGDs of affected loans in Western Canada increase by about 1.6 percentage points under RCP4.5 at mid-century and up to 6.4 percentage points under RCP8.5 by the end of the century. In high risks areas in Saskatchewan this can even increase up to 17.5 percentage points under RCP8.5. Currently, property and casualty insurance absorbs a large part of wildfire damages, resulting in only around 20 percent of losses being passed through to lenders. This may become more problematic in the future if insurance becomes unavailable or prohibitively expensive in high-risk areas, increasing banks' exposure. Wildfire risk is likely underestimated in this study and is can be higher for individual banks depending on asset type and geographical concentration. Furthermore, the study emphasizes it still focused on a single hazard and transmission channel, underestimating the compound climate risk.

As part of the ECB 2022 economy-wide climate stress test, the impact of drought and heat scenario models the impact of an acute heatwave through a reduction in labour productivity. To keep the exercise manageable, the ECB only considers one transmission channel: the effect of heat stress on labour productivity and its impact on sectoral gross value added (GVA). Given the one-year time horizon, a 100% pass-through from labour productivity losses to GDP is assumed. The largest impacts are observed in outdoor sectors, particularly agriculture, construction and mining, while impacts on manufacturing and service sectors are more limited. In countries considered vulnerable to drought and heatwaves, imposed GVA shocks range from approximately -1% to -4% for agriculture, around -1% for mining and around -3% for construction. Loan losses increase most strongly in sectors and regions exposed to heat and drought risk. For some vulnerable sectors, projected cumulative loan losses reach approximately 100 to 140 basis points relative to the baseline scenario, particularly for mining, agriculture and construction.

The ECB concludes that acute physical risks such as heatwaves and droughts can materially affect bank portfolios through lower economic output and deteriorating borrower creditworthiness. Together with the flood risk scenario and the short-term disorderly transition scenario, total projected credit and market losses amount to approximately €70 billion across the 41 participating banks. This figure is likely to underestimate actual climate-related financial risk because the scenarios are not fully adverse, climate risk modelling remains at an early stage, and only a subset of bank exposures was included in the exercise.

3.3.1 NGFS

An important, voluntary, collaboration initiative for central banks and supervisors is the Network for Greening the Financial System (NGFS). One key output of this initiative are the NGFS scenarios. These exist in two flavours: the NGFS long-term (for 21st century) and the NGFS short-term scenarios (for coming 5 years). The long-term scenarios are developed with the same type of integrated assessment models (IAMs) that are used in WP4 of ACCREU. Such models seek to model the global climate system and the global economic and financial system in an integrated manner. They are meant to explore how the economy and financial system could evolve under different climate-policy and climate-impact assumptions. The outcomes of these IAMs are future trajectories of greenhouse gas emissions and global temperature increases; macroeconomic variables such as GDP growth, inflation, interest rates and employments; breakdowns of these variables to different sectors such as energy, transportation and agriculture; and their interplay with mitigation (e.g. carbon pricing) and adaptation policies. The choice

of NGFS scenarios is more tailored to the context of central banks and supervisors, by organizing them around the axes of degree of physical risks and degree of transition risk in the scenario.

The latest version of the NGFS long-term scenarios is version 5.0 (Richters et al., 2024). It calculates the chronic physical risk from climate change to the economy through country-level damage functions. However, the econometric study from which these damage functions have been derived has been retracted. Moreover, the ‘impact’ indicators (derived with sectoral impact models such as in ACCREU WP2) are presented on a coarse resolution and in a rather generic form, some examples are: Mean Air Temperature, Precipitation, Wind Speed, Drought intensity, Number of days with extreme fire weather, River Discharge, Labour productivity, Loss due to Heat Stress, Rice yields¹⁵. It is not immediately clear how such impacts should be connected to stress-testing models of central banks. The ECB (2022) reports that they used the NGFS data to calibrate their labour productivity data in their assessment of heatwave impacts.

The NGFS short-term scenarios (Battiston et al., 2025) are meant to capture near-term (5 years) shocks to the economy and financial sector. They provide scenarios for climate policy and extreme weather events, and study how these are transmitted and amplified by the financial sector. It covers both transition and physical risks. It takes a compilation of global physical risk data as an input. Technically, it connects three models, that represent (1) macro-economic developments such as industrial production, household consumption, labour markets and international trade (GEM-E3 CGE model), (2) macro-financial interactions such as GDP, inflation and interest rates (EIRIN macro-financial model) and (3) credit risk such as probability of defaults and spreads (CLIMACRED credit risk model).

What goes into the framework is: wildfire data from the CLASSIC model, synthetic storm tracks from CLIMADA, winter storms from Copernicus, river and coastal floods from Aqueduct, drought index data from the CMCC SPEI dataset and heat wave data from ISIMIP. This is per country, sector and year converted to the following: capital destruction, production/output loss, and labour productivity loss. Each of the three models in the framework gives specific outputs: (1) macro-economic: GDP, employment rate, sectoral production, carbon emissions, interest rates and cost of capital etc.; (2) macro-financial: central bank short-term interest rate, speed at which these rates change, inflation, price level changes; (3) credit risk: probability of defaults per sector, corporate bonds and spreads, sovereign bonds.

Appendix E shows that several central banks have sought to do pioneering financial stability assessments using the long-term NGFS scenarios. They are facing a couple of difficulties when doing so. One difficulty is the resolution and quality of the hazard data. For example, the Bank of Japan (2022) reports: *“The NGFS scenarios provide information related to physical risks, such as the frequency and scale of natural disasters by region based on temperature increases. However, they do not include detailed hazard map information that are already used by Japanese banks to assess flood and typhoon risks—e.g., information on land elevation, topography, and river basin. Therefore, the banks were allowed to apply the estimation methods with hazard maps, instead of the NGFS scenario data, that the banks had used in their past analyses with scenarios of the past IPCC ARs, while ensuring their consistency with temperature levels in the NGFS scenarios.”* This limitation is also reported by the Australian Prudential Regulation Authority (2022) that did an analysis using the NGSF Phase II scenarios. They examined postcode-level risks for tropical cyclones, precipitation stress, drought stress and heat stress. They write that this data was provided to them by Munich Re, suggesting they needed a third party for provision, processing and operationalizing the physical risk data to achieve the desired postal-code data granularity. The Bank of Malaysia (2024) reports that have done an ‘exercise’ with the NGFS scenarios, but their study does not present any results yet.

3.4 Conclusions

As demonstrated by the case studies, the variety of research and stress test focus on different types of risk, asset types, transmission channels and spatial level. With respect to the central question, does

¹⁵ [Climate Analytics — Climate impact explorer](#)

climate risk poses a substantial threat to financial stability, current findings generally suggest that impacts on the financial sector and the broader economy remain limited. However, climate stress testing is still often presented as an exercise in an emerging field which is acknowledged and communicated by the institutions conducting these assessments. Overall, the overview provides the following insights:

- For physical climate risks, research has mainly focused on the credit risk channel of mortgage exposure due to physical damage to assets. Other risk types, such as market risk, are typically overlooked, primarily due to the complexities involved in modelling them. These risks are heavily influenced by human behaviour, which introduces a level of uncertainty that is difficult to quantify. The focus on credit risk is at least partly due to feasibility rather than other transmission channels being less relevant.
- A recurring limitation across the case studies concerns data availability, quality and granularity, which can lead to an underestimation of physical climate risks. From the balance sheet data of banks and the data available to the supervisor, it is often not possible to derive the precise geographical location. For business especially, often only the address of the headquarters is known whereas most of the economic exposures may stem from remote plants which are exposed to entirely different climate hazards.
- Across many case studies, it is mentioned that in the countries increased housing prices currently buffer lenders against capital losses. Since damage shocks are largely absorbed through homeowner equity rather than bank balance sheets. For example, in the Bank of Canada (2023) flood study there is a high sensitivity to a reduction in homeowner equity. A 10% house price depreciation leads to tenfold increase (LGD increase 0.4 to 4.2 percent point) of the flood impact.
- Stress tests aim to assess the robustness of the banking sector under adverse financial and economic conditions, including those related to climate risk. In practice, the impact of physical climate hazards is likely to be larger when they coincide with other shocks, such as business and supply-chain disruptions, income losses of households combined with a broader economic downturn affecting asset prices. These compound effects may show a stronger result relative to assessments that consider single risk channels in isolation. Furthermore, the absence of a financial stability impact does not imply the absence of substantial regional or sectoral impacts. Climate-related risks may therefore represent a significant sectoral or societal concern well before they materialise as a systemic threat to the financial sector.
- Several climate stress-tests such as the Bank of Japan, Malaysia and Australian authorities, make use of the scenarios developed by the Network for Greening the Financial System (NGFS). In practice, banks and supervisors report difficulties in operationalising the NGFS physical risk data for stress-testing purposes, particularly due to the limited spatial resolution of hazard indicators and the need to translate generic impact metrics into asset-level risks, often requiring supplementary data or modelling assumptions.

4. Adaptation measures

Adaptation measures can be seen as building blocks for the potential strategies to reduce climate-related risks to financial stability, the strategies are described in Section 4. A strategy is defined as a carefully selected package of different measures that can be used to reduce the vulnerability of financial system to climate-related risks. These measures can be grouped into macroprudential policy instruments, insurance mechanisms, and climate risk information and labelling.

4.1 Macroprudential policy measures

To address the potential impact of climate risk on financial stability, macroprudential policy makers (Group 1) can implement a range of options, as illustrated in table 5.3¹⁶. These measures are closely linked to micro prudential policies targeting individual institutions and to public policies aimed at adapting to climate change and reducing systemic risk. Therefore, implementing macroprudential

¹⁶ A more detailed description with reference to specific current legislation can be found in *The macroprudential challenge of climate change* ECB (2022).

policy is closely interdependent between macroprudential (Group 1), micro prudential (Group 3) and public policy (Group 4). When the financial system's exposure to climate-related risks is considered too high, macroprudential interventions may be necessary. This emphasizes the importance and need for the further development of climate risk stress testing to evaluate the financial system's resilience towards climate risk.

It is important to note that many of the options are not yet operational, and some require change in regulatory guidelines and legislation. With most of the options currently facing methodological and data constraints. Additionally, the size of the potential effects is still unclear. For example, the impact of differentiating pricing or lending standards based on climate risk could potentially impact credit availability, but the extend of this effect is currently unknown. The potential benefits and adverse effects of such measures may differ for individuals, banks, governments, and financial supervisors.

Table 5.3: Macroprudential policy options for climate risk adjusted from ECB (2022)

Adaptation measure	Description	Potential advantages	Potential limits and barriers
Capital climate risk buffers ¹⁷	A requirement of banks under the supervisor to hold additional capital on their balance sheet to increase resilience to a systemic shock, in this case a climate event due to physical or transition risk.	Increases resilience to unexpected climate risk. Promotes climate-risk reduction behaviour	Climate risk assessment limitations on asset level, can reduce profitability, can reduce credit availability
Differentiating pricing or lending standards based on climate risk (Borrower based measures, BBMs)	This would indicate a restriction or pricing policy for borrowers in areas that are exposed to high climate risk	Reduces exposure for households towards climate risk and promotes climate-risk reduction behaviour. Reduces the exposure and build-up of climate risk in banks portfolios.	Climate risk assessment limitations on asset level, can reduce profitability, can reduce credit availability
Concentration charge	A requirement to hold extra capital for assets in areas that are exposed to high climate risk	Limits climate risk exposure in bank portfolio and promotes climate-risk reduction behaviour.	Climate risk assessment limitations on asset level, can reduce profitability, can reduce credit availability
Concentration threshold	A requirement that limits a bank's portfolio for assets exposed to climate risk	Limits climate risk exposure in bank portfolio, and promotes investments in "low" climate risk assets	Requires classification system of sectors/geographical areas exposed to climate risk
Sectoral climate risk requirements	An increase in risk weights for assets exposed to climate risk (physical or transition) incorporating the climate risk in the banks risk profile	Provides resilience towards sudden repricing of assets (market risk)	Requires sectoral climate risk classification system, lower credit availability, lower profitability
Make risk tradeable, securitize at-risk loans.	Banks can combine climate risk exposed assets and sell them to investors who are willing to be exposed to climate risk	Limits climate risk exposure in bank portfolio	Requires complex risk modelling for true risk pricing. Reduces transparency of risk

¹⁷ Or sectoral system risk buffer (SyRB)

4.2 Insurance arrangements

By spreading risks of climate-related disasters through time and space, insurance provides financial security for unfortunate individuals affected by such a disaster. A high level of insurance coverage for riverine flooding has been associated with a more rapid reconstruction process (French & Kousky, 2023; Kalfin et al., 2022), which in turn limits indirect macroeconomic impacts (von Peter et al., 2024, Knittel et al., 2023). Besides functioning as a financial ‘cushion’ for disaster impacts, insurance has the potential to stimulate risk awareness and risk-conscious decision-making by those at risk. Due to behavioral fallacies, individuals are found to discount low-probability high-impact risks, such as many natural disaster risks (Camerer & Kunreuther, 1989). Because of this, households tend to underprepare for such events from a rational economic perspective. By transforming the low-probability high-impact event into an annual insurance premium, the household is faced with a much more graspable risk signal. If this premium is also impacted by the decisions they make concerning risk (e.g., risk reduction measures, settlement in- or outside a floodplain), it may reduce future climate risks (Kunreuther, 2008).

Insurance arrangements come in many varieties across Europe, each with their pro’s and con’s. Broadly, we can identify two main (contrasting) objectives, which are to ensure solidarity in the face of increasing climate impacts, and to stimulate economic efficiency. Solidarity is maximized by ensuring that everyone is covered by insurance and fully cross-subsidizing the risk through flat-rate premiums. Economic efficiency is pursued by stimulating adaptation by policyholders through risk-based premiums. An important downside of flat-rate premiums is that it does not stimulate risk-conscious decision-making. An obvious downside of risk-based premiums is that coverage can become unaffordable for low-income households living in high-risk areas. Countries such as France, Belgium, and Spain can be assigned as a group of countries prioritizing the solidarity objective. Germany, the Netherlands, and Italy to varying degrees seem to prioritize economic efficiency. As both systems have obvious pro’s and con’s some countries choose to combine these insurance arrangements. For example, the UK developed a system where private insurers covering flood risk work together in a public-private reinsurance pool that aims to maintain a limited degree of risk cross-subsidization. This is enforced through a cap set on risk-based premiums, where excess risk (the amount of risk above this cap) is transferred and shared amongst low risk households.

Increasing risks of natural disasters due to climate- and socio-economic change pressures the functioning of insurance for such disasters. In countries where private insurers set risk-based premiums, coverage becomes increasingly unaffordable (Tesselaar et al., 2020), causing increasing inequalities in future flood impacts (Tesselaar et al., 2026). If risks increase too rapidly, or insurers are uncertain about the changes in risks, they may decide to cancel an insurance product in these areas. The Los Angeles wildfires in 2025 are an infamous example of this. Besides unaffordable or unavailable insurance coverage, if insurance uptake is voluntary, the insurance penetration rate is usually low (Tesselaar et al., 2020), which is largely because many individuals discount low-probability high-impact events. Low insurance penetration implies a large insurance protection gap, which poses a considerable implicit liability for governments (Knittel et al., 2023), who generally finance such uninsured damages. Public insurance systems, with flat-rate premiums, also face challenges due to climate- and socio-economic change. A prominent challenge is that of moral hazard, which may lead to higher future flood damages compared to an insurance system with risk-based premiums (Tesselaar et al., 2023). Although unaffordability of premiums is less of a concern in this system, the overall economic costs of floods may be higher.

From the previous discussion it becomes clear that there are several consequential policy choices regarding flood insurance market design. Table 5.4 gives an overview of the fundamental insurance market design choices, their corresponding advantages, and limitations. Preferences concerning these choices are based on political ideologies, and it is in the political arena that these choices must be contemplated.

Table 5.4: Insurance mechanisms, advantages, limits & barriers

Adaptation measure	Description	Potential advantages	Potential limits and barriers
Risk-based premiums	Let insurance premiums reflect the level of climate-related risk on a detailed spatial level.	Providing a risk-signal to the policyholders, potentially stimulating investment in building-level adaptation measures.	Affordability issues and decreased insurance uptake over time, especially in high-risk areas and under climate change. Requires accurate risk quantification.
Flat-rate premiums	Premiums reflect the risk over a large geographic area, and are insensitive to the risk faced by individual policyholders	Premiums remain affordable in high-risk areas	No financial signal of risk is given, which may lead to moral hazard. Flat-rate premiums are only compatible with mandatory insurance coverage and a high level of government involvement in the insurance market
Risk pooling mechanisms	Pooling multiple (climate) risks	Increases insurability of low-probability high-impact events due to increased risk pooling capacity.	Requires collaboration, regulatory alignment and accurate risk quantification.
Premium discounts for building-level adaptation measures	Offering a discount on the insurance premium of policyholders if they invest in building-level adaptation measures.	Reduces insurer exposure. Reduces absolute risk.	Adaptation investment needs to be verified. Risk-reduction of adaptation measure has to be accurately quantified.
Public-private partnerships	A collaborative agreement between the government and private insurance companies to keep insurance premiums affordable and keep the coverage broad.	Reduces insurer exposure. Increases insurance affordability. Potentially increases insurance availability.	It can be politically complex to design and manage a public-private partnership.
Reinsurance and/or catastrophe bonds	Insurers may transfer risk to third parties, either reinsurance firms or private investors. Often this is done in an excess-of-loss construction, where the most extreme and unlikely losses are transferred.	Reduces insurer exposure. Potentially increases insurance affordability	Reinsurance products from private firms are often expensive due to premium markups. Alternatively, governments may offer reinsurance coverage at an actuarially fair price

Box 1: Distributional effects of flood risks and compensation in the Netherlands

As part of still ongoing research for this ADT/ACCUREU, we are analyzing the distributional implications of different flood insurance structures and government compensation schemes. The main objective is to determine if accounting for the distributional effects of adaptation affects the desirability and design of flood compensation policies. Distributional effects will be assessed by both disaggregating across multiple social groups and applying multiple social welfare functions (SWFs). This analysis is limited to the Netherlands and will compare the distribution of risks to government compensation and insurance compensation outcomes.

A initial analysis of the flood risk distribution in the Netherlands shows that exposure (having expected annual damages higher than zero) hardly differs across income quintiles (varies between 19.7–20.4% where 20.0 would represent fully equal distribution). In terms of magnitude of the risks, there are larger differences. The share of total expected annual damages increases by income quintile (Figure below). However, when applying equity weights, the picture is reversed, with more than 30% of the total weighted damages being experienced by the bottom income quintile.

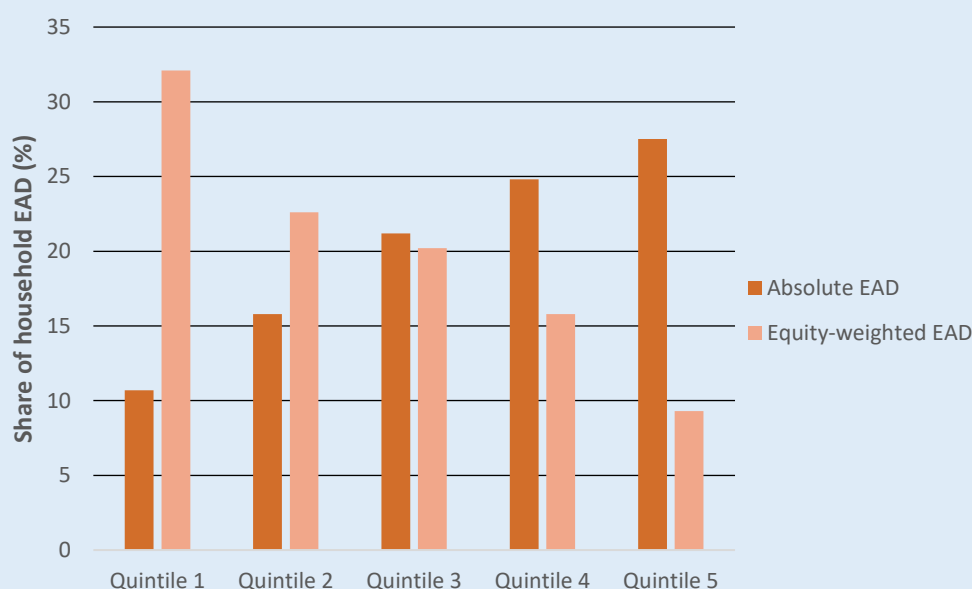


Figure Box 1: Share of total household expected annual damage per quintile (dark orange) and the share of total weighted household expected annual damage per quintile (light orange).

4.3 Information provisioning & Climate labels

To mitigate the financial risks associated with climate change, it is essential that asset prices reflect their “true value”, accounting for both exposure to climate hazards and resilience measures. Transparency tools such as climate risk data portals and standardized property labels can support this process by enabling households, investors, and financial institutions to make informed decisions. By signalling risk early, these tools can influence market behaviour and reduce systemic exposure, as prices in high-risk areas adjust based on perceived or actual vulnerability. Broadly, these measures fall into two categories: general information provision and targeted climate risk labelling.

Information provision refers to publicly available data on climate hazards. Governments and public agencies often support this through risk maps, hazard dashboards, or online climate data portals. For example, the Delta Programme in the Netherlands is a key provider of climate risk data, including information on floods (pluvial & fluvial), heat stress and droughts, supporting long-term adaptation planning. Other EU countries have taken similar steps: in Flanders (Belgium), a mandatory disclosure policy requires property sellers and landlords to inform prospective buyers or tenants if a building is

located in a flood-prone area, using scores¹⁸ officially issued and registered in the national property passport. Likewise, the UK’s Environment Agency provides public flood zone maps that support both spatial planning and insurance assessments, contributing to early climate risk awareness and behavioural adaptation. While these “soft” measures help raise awareness and encourage adaptive behavior, they rely on users’ ability to correctly interpret and act upon the data.

A more targeted strategy involves the implementation of a *climate risk label* for properties. Such labels assign specific risk levels to individual properties. This approach is similar to the introduction of energy labels, which became mandatory for property transactions in the Netherlands in 2008 and have since been shown to affect housing prices. In the Netherlands, stakeholders including the financial sector have advocated for the integration of climate risk into the housing market, potentially through a standardized climate label. However, the development of such a system faces significant challenges. Accurate climate risk assessments at the individual property level require high-resolution data and detailed information on property-specific characteristics. These requirements are currently unmet due to technical and data limitations (van Ginkel et al., 2024). Misinterpretation of climate risk data at the individual asset level can lead to incorrect risk assessments, potentially showing high risk for low-risk properties, this wrong information can impact housing prices and therefore individual homeowners.

5. Assessment of strategies – barriers to adaptation

In assessment of the strategies, we focus on flood risk specifically, since from the physical hazards this is the one which has the strongest evidence base in climate stress tests and policy discussions. Building on the measures described in Section 4, we distinguish three **strategic directions** that could be taken for macroprudential policy (Table 5.5). They differ in who is expected to steer adaptation: the government through physical protection, the macroprudential policy maker through financial regulation, or the market through pricing and insurance. The directions are not mutually exclusive, but they imply different roles, instruments and trade-offs.

Table 5.5: Strategic directions.

Strategic direction	Type of measures	Established practice?
1. Rely on government-led physical adaptation	Dike strengthening, storm surge barriers, tidal marshes and other flood protection structures; stress testing as a basis for advice on required technical measures	Established in the Netherlands, grounded in the principle of solidarity and assessed through formal cost-benefit analysis within the national flood protection programme
2. Use existing macroprudential options for climate risk management	Capital buffers, borrower-based measures, concentration limits and other existing regulatory instruments, applied to climate risk	Not established: untested for climate risk and dependent on data, methodologies and possible changes to the regulatory mandate
3. Give the private sector a key role in spatial planning and insurance	Risk-based insurance premiums, insurance as a condition for obtaining a mortgage, climate risk information and labels, decisions on location and adaptation	Not established as a strategy, although several of its instruments are already in use: risk-based premiums are applied in the Netherlands, Germany and Italy (whereas France, Belgium and Spain use flat-rate, solidarity-based systems), and public hazard maps and mandatory disclosure exist in some countries, while property-level climate labels do not (Sections 4.2 and 4.3)

These directions differ not only in the instruments they use, but also in the principle underlying them: the first is grounded in solidarity, with protection organized and financed collectively, while the third relies on economic efficiency, with risk-based prices signalling risk and steering decisions on location

¹⁸

These scores are issued for every plot (P) and building (G); and reflect a score from a to d, with a referring to no flood risk modelled and d being a mid to high chance of flooding under current climate conditions

and adaptation. The same contrast runs through the insurance arrangements discussed in Section 4.2. Below, each direction is assessed in terms of its limits, barriers and risks.

5.1 Strategy: Macroprudential policy makers fully rely on government-led physical adaptation options

The essence of the first strategy is that flood risk adaptation is strongly focused (and limited) on the physical domain: the strengthening of dikes, storm surge barriers, creation of tidal marshes and other flood protection structures. In the Netherlands, this strategy is considered macroeconomically efficient (ENW, 2023), as investments are assessed through formal cost-benefit analysis within the national flood protection program to achieve an economically optimal level of risk reduction. The role of (soft non-physical) financial adaptation instruments to reduce risk is limited to a minimum. In this strategy, managing flood risk remains the domain of engineering: through technical means the flood risk is kept within tolerable levels. In the Netherlands, flood risk management is strongly grounded in the principle of solidarity: protection against major floods is organised and financed collectively, although flood probabilities can still vary between regions. By providing broad-based protection, this approach supports long-term spatial planning and reduces systemic exposure to flood-related disruptions.

In this strategy, the task that is left for the macroprudential policy maker is to regularly stress test the macroeconomic and financial system impacts of flooding. The results of such stress tests can serve as the basis for an advice on the required technical adaptation measures. For example, the outcome could be a recommendation to take more technical measures to make sure the risk remains within tolerable levels.

Limits, barriers & risks

Limit:

- **The assumption that the flood risk can be kept at a tolerable level.** This not only applies to the flood risk at each location of the country, but also for the systemic risk that the country is facing as a whole (van Ginkel et al., 2025). The risk must not only be acceptable now, but also in the future. The strategy requires that the country indeed has the technical capabilities to manage the flood risk under various climate scenarios and spatial planning developments. If there is a limit in terms of technical capabilities, this will also make the strategy fail from a macro-financial viewpoint.

Barrier:

- **The effectiveness of this strategy depends not only on whether risk is objectively manageable, but also on how it is perceived.** Financial markets must trust in the government's ability to control flood risk. This is essential to remain a good investment climate and a thriving economy, and a sound credit rating for the government. Even if actual risks remain low, a rare but severe flood event could trigger a sharp rise in perceived risk, leading to market reactions. More fundamentally, sustained confidence requires trust in capacity of the government to adapt over time. **Therefore, this strategy depends on a countries capability to demonstrate that it can indeed cope with the risks.** One way through which trust may be obtained is through macroeconomic and financial stress testing.

Risk:

- This strategy may encourage development in high-risk areas that are now perceived as safe (levee effect). Over time, this can create a lock-in dynamic, where the economic value of these developed zones becomes so significant that retreat or alternative adaptation strategies are no longer politically or financially viable.
- This strategy assumes government will be able to compensate in case of a disaster, which can be challenging in periods of recession.

5.2 Use existing macroprudential policy options for a new purpose: climate risk management

The essence of the second strategy is that macroprudential policy makers would use their existing toolkit for a new purpose, namely climate risk management. This strategy involves adapting financial regulation, such as capital buffers, borrower-based measures, and concentration limits, to reflect climate

risks. For example, existing capital requirements for banks to cope with economic shocks could be extended with capital requirements to cope with climate shocks. Another example would be that existing requirements for portfolio diversification among different economic sectors are extended with requirements to diversify among high climate risk and low climate risk zones.

These existing measures have not been implemented or tested for climate risk and require high level climate risk data and frameworks for implementation. The key benefit of this strategy is that it can create financial incentives for the market to invest in climate-resilient assets and reduce exposure to high-risk areas. Compared to large-scale technical adaptation measures, macroprudential policies are relatively low-cost to implement. If these tools succeed in shifting capital toward low-risk assets and business models over time, they may also reduce the long-term need for public investment in protective infrastructure. This approach may have distributional consequences, for example, limiting credit access in highly exposed areas. However, the scale and significance of these effects are currently uncertain.

Limits, barriers & risks

Limit:

- Macroprudential policy could be used for maintaining financial stability and potentially steer adaptation but does not eliminate the underlying climate risk.

Barrier:

- Implementing macroprudential policy for financial stability is within the mandate of central banks. However, climate adaptation is currently typically not.
- Implementing this strategy requires high level climate risk data and frameworks for implementation that are currently not yet at a mature level.

Risks:

- One disadvantage, for example, is that people may have reduced access to credit, which could affect the accessibility of the housing market. (The full effects of this are still not well understood.) With this strategy many different policy goals such as economic growth and housing market accessibility are pursued. This creates the risk that you may have to compromise on some objectives in order to achieve others. The question is whether the trade-offs are proportionate to the goals you aim to achieve.
- This strategy can create a lack of trust in (physical) climate adaptation, which can in turn result in financial instability.
- If perceived as a substitute for physical protection, these measures could reduce trust in public (technical) adaptation.

5.3 Give the private sector a key role in spatial planning and insurance

The essence of the third strategy is that adaptation and spatial planning is left to the private sector and market dynamics. This strategy relies on financial markets to reflect and respond to climate risk through pricing mechanisms, such as insurance premiums and declining asset prices in high-risk areas. Market signals can potentially change faster than regulatory frameworks or spatial planning. Over time, investors, insurers, and consumers will reallocate capital away from vulnerable regions and toward climate-resilient assets.

In this strategy, it is not the government who leads through top-down physical adaptation measures (such as in strategy 1). Instead, adaptation dynamics are determined through dynamics in the real estate development, mortgage provision and insurance markets. There is a close collaboration between (flood risk) adaptation experts and the financial sector. For example, to obtain a mortgage from a bank, one needs flood insurance. The insurance company therefore has an incentive to thoroughly understand the flood risk and represent this accurately in a premium. If premiums get high, there will be less demand for houses in this area as fewer households will be able to afford insurance of the houses in that area. However, there is a risk that this mechanism provokes the adverse effect of the houses themselves losing value, as demand for housing in these areas declines. Consequently, the low-valued houses might also attract vulnerable households to these vulnerable locations. Through this mechanism, mortgage providers and insurers obtain a larger role in spatial planning. The role of macroprudential policy

makers will be more towards financial sector oversight, monitoring market imperfections, and making sure that the market responds based on correct climate risk information.

Limit:

- In a strategy where the private sector plays a central role, market actors may withdraw from high-risk areas if risks are deemed too high or too uncertain. This means that insurance or credit may become unavailable, regardless of broader social or spatial development goals. An example of this are the recent fires in California, where insurance companies have been declining to renew insurance.

Barrier:

- Risk-based insurance premiums require accurate risk calculations which are hard to achieve due to data limitations.
- In high-risk areas, insurance premiums based on risk may be so high that they discourage participation, making it difficult for the insurance system to remain sustainable.
- It is uncertain whether climate risk is effectively priced in.

Risk:

- The government can lose control of their spatial planning. If the market is deeming the risk too high in certain areas, instruments such as mortgages are unavailable.
- If governments intervene after large scale events, market actors have an incentive to underprice risk (similar to “too big to fail” issue in financial sector).
- Risk-based pricing might lead to a lock-in situation for poorer households, which are unable to move and also cannot afford insurance.

6. Lessons learned for implementation of strategies

Climate risk ultimately has to land somewhere, whether the government, the private sector, or individuals; the critical question concerns how this risk is structured, shared, or transferred. To develop effective financial adaptation strategies, a better understanding of how climate risks translate into financial stability risks is first required. While a number of important pilot studies have already been conducted, these are often exploratory in nature and remain incomplete, with ongoing efforts to refine and expand them. Limits and barriers of financial adaptation measures are identified, but the actual size of the limits and risks for different stakeholders remain uncertain. Therefore, not all measures and their impacts are known and operational.

To strengthen knowledge development and support stakeholders in making more informed, evidence-based decisions, we advise governments, central banks, and other relevant institutions to take the following steps:

1. **Improving data quality for physical hazards is needed for almost any adaptation measure or strategy.** If the underlying information is unreliable or incomplete, many measures cannot be designed or implemented properly. Consistent hazard data and asset classification systems are needed to justify interventions (also confirmed in the stakeholder workshop). Without complete information the risk of maladaptation can increase, resulting in unintended side effects, and undesirable distributional impacts¹⁹. First steps have been taken into stress testing the financial system & climate risk. However, macroprudential policy has not been implemented for climate risk. Experience from recent climate stress tests shows that data limitations are widespread. For financial adaptation this requires further cooperation between central banks, supervisors and institutions with climate and hazard expertise. The importance and current limitations regarding data is emphasized in both the case studies themselves as many review articles (Reinders et al., 2023; UNEP, 2024; De Bandt et al., 2025).
2. **Improved data collection on location of assets from clients can improve risk analysis:** More detailed information on the geographical location of assets and economic activities of

¹⁹ Current climate risk information is not yet sufficiently robust to be applied reliably at the level of individual houses in the Netherlands. Using such data at this scale can therefore lead to misclassification of risks and unintended outcomes, including maladaptation (Van Ginkel et al., 2024).

clients is essential to improve risk analysis. Without adequate insight into where exposures are actually located, financial institutions and supervisors cannot meaningfully assess climate risks or identify concentrations across portfolio.

3. **Broaden climate stress testing beyond single transmission channel approaches.** Stress testing should be continued and gradually expanded to cover a broader set of transmission channels beyond credit risk alone. This includes adding dimension such as business interruption and supply-chain disruptions, but also market risk, liquidity risk. Compounding these risks gives a more accurate indication of the systemic risk from physical hazards.
4. **Macroprudential policy for climate risk can be used to stimulate adaptation but can involve trade-offs with other policy objectives.** Measures such as capital requirements may reduce risk exposure, but can also restrict access to credit, affect housing affordability, and lead to uneven distributional outcomes.

7. Conclusion

Whether climate hazards pose a substantial threat to financial stability remains an open question, as current case studies are still in a developmental stage and show limited but uncertain impacts. In the European policy context, stakeholders such as the ECB, EBA, IMF, national banks, insurers, and governments are beginning to use climate stress testing to explore this issue. The second question, which transmission channels matter most, has so far been addressed mainly through credit risk, while market, liquidity, and macroeconomic channels remain underexplored. In this ADT, we identify financial adaptation measures that complement technical adaptation. Insurance arrangements and information tools are relatively well-developed, and in some countries already implemented in practice. In contrast, macroprudential policy options for climate risk remain largely untested and uncertain, as their effectiveness depends heavily on high-quality data, new methodologies, and potential changes to regulatory mandates. This contrast highlights that while some financial measures are ready for application, others require substantial research and institutional development before they can play a meaningful role. Overall, the potential of macroprudential policy to reduce climate risk is still unclear, calling for further stress testing, better data, and coordinated action across regulators, financial institutions, and governments.

ADT 6 – Transport and supply chains (Deltares)

1. Introduction

1.1 Problem definition and aim

Climate change affects the infrastructure sector, leading to delays and disruptions in supply chains, resulting in industry losses. According to the European Commission, the infrastructure sector is projected to require about €29 billion annually in adaptation investments, covering flood protection (€6.3 billion), building retrofits (€6.9 billion), and reinforcement of transport infrastructure (€4.5 billion). The estimated Net Present Value of all infrastructure sector adaptation and resilience investments is about €520 billion to 2050 (European Commission, 2026; Munday et al., 2026). This is a large sum, which requires a lot of strategic efforts to make and implement adaptation plans.

Although awareness of climate risks is increasing, the implementation of adaptation measures remains challenging. Adaptation decisions are shaped by complex interactions between different actors, organisations, decision-making criteria and priorities. These decisions are influenced by underlying value judgements, such as how risks are prioritised, how trade-offs are made, and what time horizons are considered.

This ADT aims to better understand and structure how climate adaptation decisions are made in the transport infrastructure sector, and to support more effective adaptation planning and application in transportation systems. It seeks to provide insight into how different actors, decision-making levels, and value judgements shape adaptation choices, and how these factors influence the implementation of measures in practice. By developing and applying a framework to European case studies, the study additionally mentions enabling and limiting factors.

1.2 Method

In this ADT, we studied the transportation sector from the infrastructure side, where we see supply chains as users of infrastructure systems. The chapter uses an analytical approach to explore adaptation decision-making in transport infrastructure.

To structure the analysis, we developed a framework that revolves around two main dimensions: 1) actors and levels (spatial & temporal), and 2) underlying value judgements in adaptation choices, often implicitly made. The elements of this framework are derived from a review of existing literature, national adaptation strategies, and insights from the ACCREU project case studies 6.1 and 6.2. These sections also draw lessons from a set of European case studies on transport adaptation, with a particular focus on extreme rainfall and flooding events. Section 2 sets out what adaptation in transport infrastructure consists of, distinguishing measures by the scale at which they intervene and by their position in the disaster risk cycle. Section 3 describes the actors and decision-making levels involved, and Section 4 the value judgements that shape which measures are chosen. Section 5 presents three illustrative European cases in which these elements come together, and section 6 draws conclusions and recommendations.

2. Adaptation options in transport infrastructure

Adaptation measures in transport infrastructure differ in where they intervene in the risk chain and in when they take effect. Both are important for decision-making as they determine which actor can act and what kind of benefits the strategies offer.

2.1 Measures across spatial scales

An approach to classifying infrastructure adaptation is proposed in the MIRACA project (Table 6.1). This framework distinguishes adaptation according to spatial scale, differentiating between hazard-, system-, network-, and asset-level adaptation (MIRACA, 2023a; Peregrina Gonzalez et al., 2026).

Table 6.1: Classification of infrastructure adaptation across spatial scales.

Scale	Aim	Example adaptation measure
Hazard	Measures that reduce the intensity, likelihood, or impact of the hazard itself	Constructing or enhancing dikes or levees in an area to prevent flooding.
Asset	Measures that modify the individual infrastructure asset exposed to climate hazards, increasing robustness or resistance to the hazard	Elevating roads or rail tracks, reinforcing embankments, upgrading drainage systems
Network	Measures that aim to maintain service continuity across the transport network	Identifying and strengthening alternative routes, adding redundancy to key connections
System	Measures that change the way the transport system operates, including performance expectations, governance arrangements, and long-term rules or standards	Redefining acceptable service levels during extreme events, updating design standards Users may also change their behavior

This classification is also used to distinguish between four different **strategic directions**: 1) Reducing the hazard around the network, 2) making assets robust, 3) keeping the network functioning and 4) changing how the system operates (service levels, standards), with recovery as a temporal dimension cutting across these (see Section 2.2).

The distinction between the roles of infrastructure operators and spatial authorities, as well as their relationship to different adaptation scales, becomes evident in the case [adaptation to the Copenhagen Metro network](#) (Section 5.2). The Metro operator applied numerous adaptation measures. However, they also concluded that the implemented adaptation measures may not be sufficient for full protection against extreme weather events, sea level rise and storm surges in the future. Full protection against all these risks, specifically for the metro only would also be too costly for the operator. They concluded that external protection of the whole capital region, Greater Copenhagen, is more appropriate in socioeconomic terms than protecting the metro installations alone, hinting at hazard-level adaptation rather than asset-level adaptation.

2.2 Measures across temporal scales

Furthermore, it is important to identify when in the disaster-risk cycle the measures are taken. In disaster risk management, generally, four main stages are distinguished (Table 6.2). Climate adaptation measures can be related to these phases, reflecting whether the measures aim to prepare for, respond to or recover from extreme events to enhance resilience. The World Road Association PIARC uses these classifications in distinguishing climate resilience strategies ([Disaster Management Cycle | Disaster Management Manual - PIARC](#)). Adaptation decisions do not always have to be preventative. Having well-established emergency and recovery plans can, for example, also ensure transport resilience.

Table 6.2: Classification of infrastructure adaptation across temporal scales.

Scale	Aim	Example adaptation measure
Prevention	Long-term actions aimed to reduce impact of future events by addressing underlying risk factors	Mainly physical measures, such as levee creation or water retention areas. Level of risk is determined by design standards of these measures
Preparedness (right before)	Measures taken in this phase are aimed to improve readiness and response capacity	Developing emergency plans, improving early warning systems
Response (during)	Protecting assets and infrastructure during a hazard	Temporary closures, back-up generators, emergency pumps
Recovery (after)	Restore or rebuild infrastructure. Can involve short-term repairs or long-term reconstruction choices determining whether infrastructure is built back as before or build back better.	Rapid repairs to reopen routes, rebuilding bridges to higher standards, applying build-back better principles

The term *residual risk*, can now be explained: it is the risk you decide to accept in your *design and maintenance standards* (see Figure 6.1). For example, in The Netherlands, roads are designed in a matter that a rainfall event that can happen 1:10 years, will lead to maximum 30cm water on the roads. This rainfall event of 1:10 years can be linked to a severity of roughly 30mm in one hour (Stowa, 2019) (RWS, 2014). The risk that there is a heavier rainfall, and consequently the roads will be flooded more than 30cm, is the residual risk. This risk is mitigated by preparedness, response and recovery strategies.

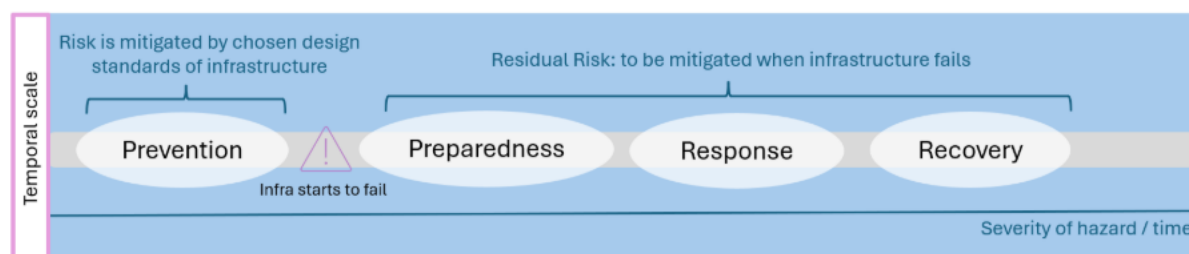


Figure 6.1: Residual risk linked to temporal scale.

2.2.1 Recovery: Build back better or build back the same

To understand resilience and infrastructure performance, Tierney & Bruneau (2007) developed the concept of the resilience triangle, where the resilience triangle represents the loss of functionality from damage and disruption, as well as the pattern of restoration and recovery over time. Figure 6.2 below builds upon this concept and adds the disaster risk management cycle in relation to this. Up to a certain level of hazard intensity, infrastructure performance remains stable. This corresponds to the prevention phase and is largely determined by the design standard of the asset or network. Design standards specify which hazard levels infrastructure is expected to withstand, such as a given flood return period. As long as hazards remain within these standards, performance does not significantly decline. However, when a hazard exceeds the design standard, infrastructure performance can no longer be fully maintained and it starts to fail.

Once hazards exceed design thresholds, preparedness and response measures become relevant. These include emergency planning, backup systems, temporary closures, or operational interventions during the event. In the figure, these measures influence how quickly infrastructure performance declines. Without such measures, performance may drop more steeply. Nevertheless, preparedness and response can only mitigate impacts up to a certain point.

The lowest point of the curve reflects the moment when damages occur and normal functioning is no longer possible. This leads into the recovery phase, during which infrastructure performance gradually improves as repairs are carried out and services are restored. The upward slope of the curve represents this recovery process over time. The faster the recovery process, the steeper the curve.

In the last phase, recovery, there are two pathways: build back better and build back the same. In a “build back the same” approach, infrastructure is restored to its previous condition, resulting in recovery to the same performance level as before the event. In a “build back better” approach, recovery is used as an opportunity to improve design standards and increase climate resilience. In the case of the Ahr Valey (see Section 5.1), an in depth analysis is carried out what type of built back better strategies are, and how they are applied. In this case study clear built back better application is lacking and it shows the importance of preparing beforehand.

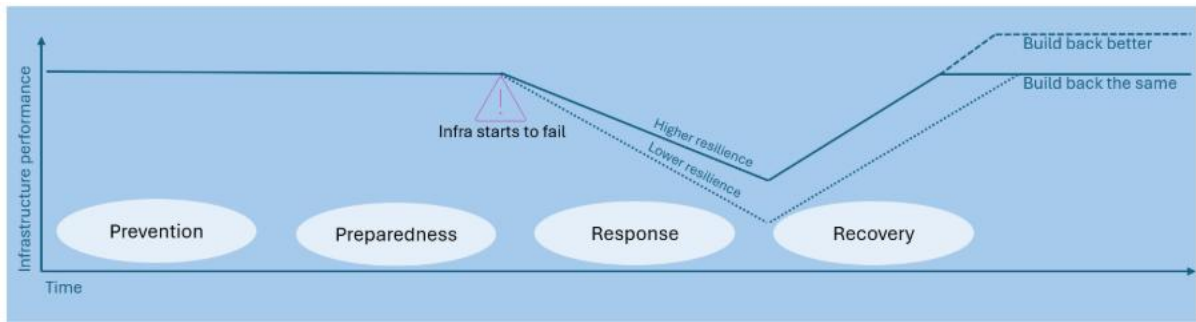


Figure 6.2: Linking the elements of the temporal scale to resilience and build back better

3. Who decides: Actors and decision-making levels

3.1 Introduction of elements

Which of the strategies will be chosen, depends to a large part on who holds the mandate for the budget and decisions. The next part of the framework introduces the key actors and decision-making scales involved in adaptation decisions for transport infrastructure (Figure 6.3). Climate adaptation can take many forms and occur at multiple levels: transport authorities obviously play a big part, but also spatial authorities and infrastructure users make adaptation decisions. Within transport authorities we specify the roles further to national, regional and local authorities, and strategic, tactical and operational scales.

Understanding who the different actors are and what they are responsible for helps to see what adaptation decisions can be made at each level of the infrastructure system. If this is not clear, together with the spatial and temporal scales of the infrastructure system, it becomes hard to know where adaptation decisions are actually made, where problems occur, and which actors need to work together to ensure that adaptation measures are implemented.

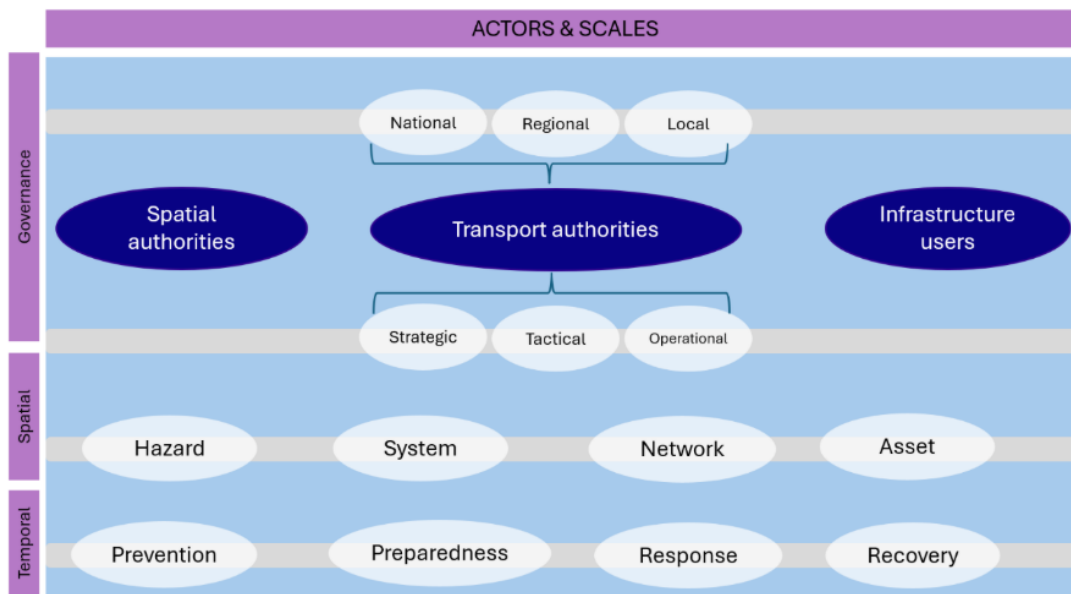


Figure 6.3: Framework of actors and scales (temporal and spatial)

3.2 Transport authorities

Transport authorities establish the regulatory framework for transport performance and make decisions regarding transport networks and assets within their institutional and business contexts. These authorities may be structured according to national, regional, and local spatial levels. Within transport authorities and operator organizations, three levels of decision-making can typically be distinguished: strategic, tactical, and operational (ICARUS, 2023).

- **Strategic level:** The strategic level defines long-term objectives and performance targets for transport infrastructure systems at the network or system scale. At this level, decisions are taken

by both government actors (such as national ministries, regional authorities, and municipalities) and/or operator leadership (boards, senior management, corporate strategy units). Strategic mandates include setting policy goals for infrastructure performance and resilience, defining acceptable risk levels, establishing regulatory frameworks (e.g. KPIs or risk standards), determining funding rules, and aligning infrastructure planning with spatial policy. Typical adaptation decisions at this level include setting flood-risk standards for transport networks or requiring climate-proof design standards. Decisions at the strategic level shape overall investment directions and determine the boundaries within which lower-level decisions are made.

- **Tactical level:** The tactical level connects strategic objectives to operational practice and typically operates at the network scale within operator organizations, such as national road authorities. Actors at this level are responsible for translating long-term goals and regulatory requirements into concrete plans and priorities. Mandates include drafting budget proposals across regions, assets, or corridors; developing design, maintenance, and investment programs; and prioritizing renovations, renewals, and expansions in line with strategic ambitions. Tactical adaptation decisions balance long-term resilience objectives with regional needs, technical feasibility, and organisational capacity, for example by embedding adaptation criteria into maintenance programmes.
- **Operational level:** The operational level focuses on the implementation of measures at the asset level. This includes day-to-day operations, inspections, maintenance, and targeted interventions for specific assets such as bridges, tunnels, or sections of track or roadway. Operational decisions ensure that infrastructure meets required performance and safety standards in practice.

3.3 Spatial authorities

Spatial authorities determine which locations are used for infrastructure and influence the way climate risks are managed in the natural system such as the water system. They also shape environmental and land-use regulations. Generally, hazard-level adaptation that is not specifically targeted for infrastructure but to protect areas from hazard influence is set at this spatial authorities-level.

3.4 Infrastructure users

Users of the transportation system are road and rail users which range from civilians to businesses and freight operators. These groups influence adaptation decisions through demand and service expectations. On the other hand, users and/or businesses may also change their behavior in response to a natural hazard influencing the service-levels of transport systems, such as creating larger stocks so they are less prone to be influenced by external shocks, for example as a result of affected transport. When users of infrastructure adapt their usage because of climatic events, it is seen as **system-level adaptation**, as explained in Section 2.1.

User adaptation is especially relevant for supply chains of industries. In the ACCREU case on supply chains (CS6.2), the stakeholders identified several adaptation options to enhance supply chain resilience against climate-related risks. These include:

- Localization, which involves sourcing from European suppliers or Europe-based distributors that produce in Asia, thereby reducing the direct sourcing risks
- Increased inventory levels, such as maintaining a safety stock to buffer against short-term supply shortages
- Improved operational flexibility, which entails adjusting production plans and resource allocation to minimize the impact of production shortfalls
- Supplier diversification, involving multi-sourcing to reduce switching times between suppliers.
- Near real-time monitoring systems, to be able to respond to climate-related events

Box 1: Lessons from ICARUS

The ICARUS project (acronym of: improving the uptake of climate change adaptation in the decision making processes of road authorities) was a European research initiative that addressed the gap between resilience research on road infrastructure and the implementation of adaptation within asset management processes. Research institutes and engineering firms around Europe worked together with national road authorities to research the bottlenecks around implementation of climate adaptation strategies into road asset management. Three outcomes are particularly interesting for the current study and are described below.

Tactical gap

As described, within the decision context, KPIs are often used to describe the required service level of the road or rail network. This decision context is often set at the *strategic-level* of the road or rail authority. On the other hand, climate adaptation measures are often taken at the *asset level* of the networks (e.g. improved drainage next to the roads) or through design guidelines that prescribe how resilient an asset should be. These measures are taken at the *operational level* of the road or rail authority. This presents a problem: a tactical gap between the different organizational levels that arises because it is often unclear how the design guidelines of measures taken at the *asset level*, will lead to better performance of the network (e.g. less disruption, less accidents) on the network level. To facilitate climate adaptation at the strategic level (where resources are allocated), an explicit connection should be made between the goals (KPIs) at the strategic level and the measures taken at the *asset level*.

Connecting resilience studies to decision-making context

Most road authorities in Europe have carried out resilience studies or stress tests, researching the vulnerable locations in the road (or rail) networks. This is carried out in various levels of detail. However, often the results of these resilience studies do not match the indicators used in the decision-making processes of operators. Operators usually have very specific KPIs to measure their service levels. When the KPIs and resilience-study results do not match, it is very challenging to make a good business case for adaptation. Besides that, KPIs can be vague, not clearly indicating a minimum service level of the roads or rail. It helps if these required service levels are clearly described, to be able to link the benefits of climate adaptation to the KPIs. In order to facilitate decision-making and implementation of adaptation strategies, the resilience study should therefore use those same indicators as the decision-making context. Hence, it is advised to road authorities to start with exploring the decision-making context, before carrying out a resilience study, in order to align the two.

Business case for climate adaptation

Oftentimes, road and rail authorities have different mechanisms that guide the decision-making on climate adaptation. There are four main mechanisms that guide most decisions. It is possible that there are mixes of these drivers.

- **Budget-driven:** A budget-driven approach aims to provide the highest service levels within a fixed budget, without formal minimum service levels. This means choices need to be made with a limited budget. In the case of climate adaptation, this may mean that not all necessary investments will be made, because of budget constraints.
- **Service-driven:** A service-driven approach aims to provide a minimal service level at all times. In this case, budget is not a limiting factor; if the minimum service levels are not met because of climate risks, additional budget can be released.
- **Optimum-service level-driven:** An optimum-service-level-approach seeks to balance costs and benefits, by identifying the economic optimum between net-benefits and costs. This requires extensive modelling of costs and benefits of climate adaptation strategies. So far, there are no examples of road authorities making decisions purely based on this mechanism.
- **Additional policy-driven decision criteria:** Next to steering on performance/service levels, other policy goals can also be taken into account while planning climate adaptation. Other goals can be for example biodiversity, carbon reduction or equity principles. These factors are then regarded as co-benefits.

To facilitate implementation of climate adaptation, it is important to understand the decision-making context at the road authority, and which mechanisms are used to make decisions.

4. Value judgements that shape adaptation choices

4.1 Introduction of elements in frame

Adaptation decisions for transport infrastructure are shaped not only by technical analyses or formal decision rules, mandates and actors, but also by underlying value judgments. In practice, these value judgments affect how business cases are constructed, which risks are prioritised, and how trade-offs are made between competing objectives such as cost, performance, resilience, and equity. While some of these judgments are made explicit through standards or policy objectives, many remain implicit and embedded in established planning practices. Value judgments for example influence whether adaptation measures are taken reactively or proactively, whether short-term performance is prioritised over long-term risk reduction, and whether adaptation focuses on maintaining existing systems or enabling more fundamental change. Therefore, they play a central role in determining the ambition of adaptation decisions.

In the context of climate adaptation, these choices are particularly important. Transport infrastructure investments are there for a long time and are often costly, meaning that decisions taken today can shape vulnerability and resilience for decades.

To support a more systematic understanding of adaptation decision-making, this framework distinguishes five categories of value judgments that are often found across adaptation decisions in transport infrastructure (Figure 6.4). Making these judgments explicit helps to clarify why adaptation decisions differ across actors and contexts, where tensions and trade-offs arise, and how adaptation outcomes are shaped by more than technical considerations alone.

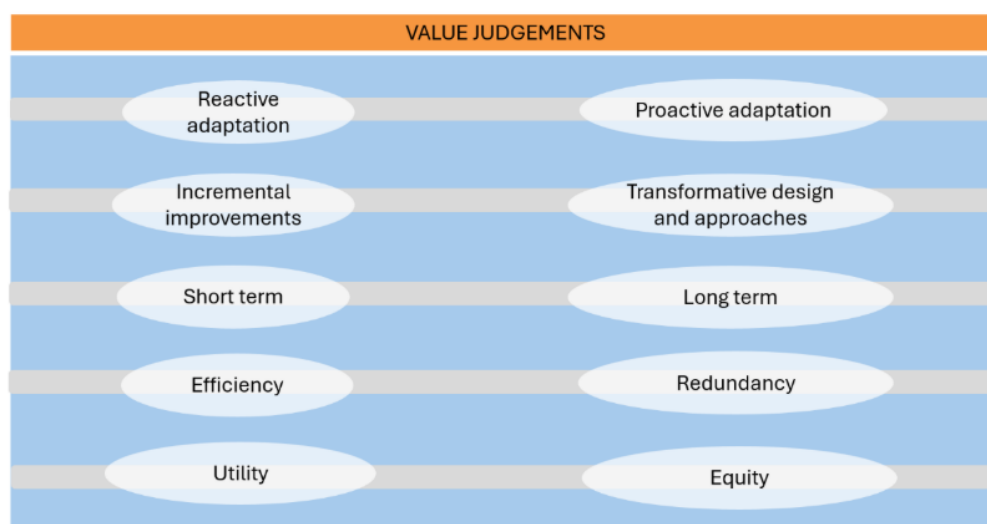


Figure 6.4: Framework of value judgements

4.2 Reactive vs proactive

A commonly used distinction in climate adaptation is between reactive and proactive adaptation. Reactive adaptation refers to measures taken after climate impacts occur, often in response to a crisis and under time pressure. Proactive adaptation, in contrast, aims to reduce risks before hazard impacts occur and is typically oriented towards long-term resilience and forward-looking investments (IPCC, 2001).

In practice, you see both strategies. Most European road- and rail authorities now have a climate adaptation plan. They update design standards and plan for hazardous events. However, it takes a long time to implement new design standards in infrastructure, because it is built for a long time. During a renovation, design standards can sometimes be updated to withstand more extreme weather.

In practise we see a lot of reactive behaviour, where actions are triggered by hazardous events. Ideally, the reactive behaviour leads to a ‘build back better’ strategy, where climate adaptation is incorporated

in the recovery (see Section 2.2.1). However, the extent to which this translates into adaptation measures remains limited in real-world cases. For example, after the severe floods in the Ahr Valley, built-back-better approaches were attempted, but most was built-back-the-same (Birkmann et al., 2023). In section 5.1 we discuss the enablers of built-back-better approaches and highlight this case.

At the same time, reactive contexts can sometimes enable build-back-better outcomes. After the 2024 DANA floods in Valencia, recovery efforts focused on quick restoration of rail services but also included selected adaptive measures. The Spanish railway operator ADIF highlighted the reinforcement of tunnel accesses to increase robustness against future climatic events, supported by regulatory instruments such as floodplain construction bans and mandatory risk assessments (ADIF, 2024). This suggests that reactive adaptation can incorporate proactive elements where governance structures and standards allow for it. Thus, in Valencia, recovery after the floods included both rapid repair and some targeted improvements, such as stronger tunnel entrances.

4.3 Incremental vs transformative

The differentiation between incremental and transformative adaptation strategies, was introduced by the Intergovernmental Panel on Climate Change:

“Some adaptation is incremental, which only modifies existing systems. Other actions are transformational, leading to changes in the fundamental characteristics of a system. For instance, building a seawall to protect a coastal community from flooding might exemplify incremental adaptation. Changing land use regulations in that community and establishing a program of managed retreat might exemplify transformational adaptation. There exists no bright line between incremental and transformational adaptation.” (IPCC Working Group II, Sixth Assessment Report, chapter 1 p. 75).

How these two approaches to adaptation translate to road and rail infrastructure, was explored, for example, in the Dutch National Adaptation Strategy 2026 (NAS’26) (*to be published*).

Incremental adaptation strategies NAS’26:

- Climate-proof maintenance practices, e.g. more regular cleansing of puddles
- Climate-proofing existing infrastructure e.g. updated design standards of water pumps
- Enforcing operational processes e.g. quicker response from emergency management after a flood

Transformational adaptation strategies NAS’26:

- Increasing network redundancy, e.g. increase of modal shift options
- Accepting reduced functionality during disasters, e.g. snow-schedules for train operators

In the transportation sector, the distinction between incremental and transformational is not so clear-cut. For example, increasing network redundancy can also be seen as an incremental strategy, if you keep using the transportation system in the same manner, just incrementally adding nodes. We cannot conclude that one approach should be preferred over the other. In some areas with large climate risks, a more transformative approach should be taken, whereas in areas with smaller risks incremental options are more effective.

Transformational approaches can, however, only be initiated from higher governance levels on the strategic level. Hazard, system and network levels should be considered. On the temporal scale the focus shifts from prevention to broadening adaptation options for preparedness, response and recovery.

In ACCREU case studies 6.1 and 6.2, we found that in transport infrastructure more incremental options were preferred over transformative strategies. In our stakeholder workshops we explored the topics. Reasons for preference for incremental adaptation were political reluctance, higher costs, and the complicated jurisdictional nature of transport infrastructure planning, where infrastructure authorities have to work together with spatial planning and water authorities. Similarly, in the context of increasing the climate resilience of supply chains, reactive and incremental options are rather employed than

transformative adaptation options, given established business models and structures. While our stakeholders generally expressed interest in the approach to talking about adaptation and found it helpful, it was difficult to find practical examples.

4.4 Short term vs long term

4.4.1 Time horizons

The time horizon that is taken for adaptation decisions influences the ambitions, design and business case for adaptation decisions. This is particularly the case because infrastructure investments and constructions are long-term investments. Markolf et al. (2022) describe how adaptation measures that mainly provide benefits in the long term are often difficult to justify within short planning and investment cycles. Existing decision-making and appraisal frameworks usually prioritise short-term efficiency, while infrastructure systems usually have a longer lifespan during which they are exposed to increasing climate risks (Markolf et al., 2022). Singh et al. (2023) show that the benefits of adaptive and resilient infrastructure investments often grow over time but are undervalued when decisions are based on short time horizons and limited consideration of future uncertainty, making it more difficult to build a convincing business case. Therefore, the choice of time horizon reflects an explicit value judgement about whether priority is given to short-term performance or long-term risk reduction. Several European infrastructure operators mention something about the time horizons that they apply into their strategic planning. For example, Deutsche Bahn applies IPCC climate scenarios (RCP 2.6 and RCP 8.5) and combines long-term climate projections with historical weather and disruption data to assess climate impacts and criticality for both new and existing assets (Deutsche Bahn, 2023; 2024). Spain's railway infrastructure manager ADIF similarly reports the use of short-, medium- and long-term horizons in vulnerability and risk assessments, indicating a forward-looking approach (ADIF, 2024). Network Rail in the United Kingdom primarily operates within five-year investment cycles, while acknowledging longer-term climate risks (Network Rail, 2024). In France, climate projections extending to 2100 are explicitly incorporated into transport infrastructure standards (Cerema, 2015). Beyond transport infrastructure, the Port of Rotterdam emphasises flexibility in adaptation measures as a response to long asset lifetimes and long-term climate uncertainty (Port of Rotterdam, 2022).

4.4.2 Existing assets or new assets

These time-horizon choices are closely linked to how adaptation is distributed between existing assets and new construction. Choices for time horizons are closely linked to whether adaptation focuses on upgrading existing assets or is embedded primarily in new construction.

Shorter planning horizons tend to favour incremental adaptation measures focused on maintaining or recovering the performance of existing infrastructure, such as operational adjustments, maintenance, and targeted upgrades. This is evident in Network Rail's approach, where climate adaptation is embedded in ongoing asset-management activities, such as drainage improvements, earthworks, and flood risk mitigation, within relatively short investment cycles (Network Rail, 2024).

Longer time horizons, by contrast, make it more feasible to incorporate future climate change into major renewals and new construction. France's transport infrastructure standards, for example, explicitly incorporate climate projections up to 2100 and apply them both to new construction and to the maintenance and upgrading of existing networks, reflecting the long lifespan of assets (Cerema, 2015). Deutsche Bahn similarly combines adaptation in new construction and expansion projects with measures to improve the resilience of the existing network (Deutsche Bahn, 2024).

4.5 Efficiency vs Redundancy (resilience)

Adaptation decisions often involve a tension between *efficiency* and *redundancy* (or, *resilience*), where greater redundancy often means less efficiency and vice versa. This tension becomes visible in how transport systems are designed and prioritised. Most infrastructure systems are designed based on *efficiency principles*: resources (e.g. number of roads, capacity of roads) are optimized, so the network functions well and is balanced to low delays of travel time (Markolf et al., 2022). Efficiency of a network is based on normal conditions without disruptions (e.g. an accident, or road closure because of flooding). The *resilience* of a network describes how a system performs when it is disrupted, or in other

words: the ability of infrastructure to continue functioning, to absorb disturbances, and to recover after failures.

Ganin et al. (2017) modelled the road networks of 40 cities in the US and compared how much travel delays there are under normal conditions versus when there are disruptions in the network. In their study they demonstrate that cities with efficient urban road networks (low delays compared to the capacity of the road network) are less able to cope with disruptions than cities with urban road networks that have more redundancy (e.g. spare capacity, alternative options). For example, Virginia Beach, VA, is an urban area where traffic operates well under ordinary circumstances but rapidly becomes clogged when parts of the network are disrupted. The resilience, so to say, is low. This is in line with the conclusions of Markolf et al. (2022), who state that measures such as spare capacity, alternative options, and system diversity often reduce performance under normal conditions, but are important for maintaining system function during extreme events.

Markolf et al. (2022) also note that decision-making and appraisal frameworks usually focus on efficiency under normal conditions, which makes it difficult to justify investments that mainly provide benefits during disruptions. When climate change will lead to more disruptions of roads, a focus of resilience instead of efficiency can reduce the overall delays in a network. A climate adaptation strategy can thus be to build in resilience, or redundancy, in the road network.

In the ACCREU case study 6.2 on supply chains, we also identified two types of strategies that increase redundancy. Firstly, *diversification of suppliers* or *transitioning for single- to multi-sourcing* was mentioned as an adaptation strategy that had limited exposure to disruptions because of climate related events. Secondly, a strategy that was mentioned was *increasing inventory levels* such as maintaining a safety stock to buffer against short-term supply shortages. Both were evaluated as successful strategies, however it was hard to monetize the exact benefits.

4.6 Equity vs utility

Research indicates that groups with lower societal status do not benefit equally from transport investments and services (Mu & Van De Walle, 2011; van Marle et al., 2023) and are more vulnerable to disruptions (Kilgarriff et al., 2019; van Marle et al., 2023). Traditional transportation planning often focuses on maximizing utility for the largest group, aiming to maximize aggregate benefits, resulting in an emphasis on areas with the highest transport demand (Jafino, 2021). However, this risks exacerbating existing inequalities or introducing new ones (van Marle et al., 2023; MIRACA, 2023b). Therefore, more recently, literature on transportation adaptation has given emphasis to including equity principles in determining investment priorities for infrastructure networks (MIRACA, 2023). Even when not explicitly acknowledged, prioritizing transport investments based on where demand is greatest constitutes an equity decision in itself. Therefore, making the equity outcomes of transportation investments explicit is necessary when considering adaptation measures.

ACCREU case study 6.1 studied how the use of three different equity principles will lead different investment strategies of the road network. The four different investment strategies, with three underlying equity principles were tested: GDP weighted strategy or maximize NPV (utilitarian principle), minimize deviation in investments per region (egalitarian), and per capita weighted strategy (prioritarian principle). The case shows that following these different equity principles will lead to spatially different investment patterns.

5. Adaptation decisions in practice: three cases

As we have laid out, successful climate adaptation takes place in complex field of actors, types of adaptation and value judgements on how to adapt. In this section we highlight three distinctive case studies, where the previously described elements come together. We zoom into success factors and limiting conditions, and it becomes clear that multiple factors that steer adaptation decisions come together in real-world cases. Using the proposed frames helps to understand the dynamics at play and be more aware at guiding future adaptation decision types.

5.1 Illustrative case 1: Floods in the Ahr Valley

The Western European floods of 2021 caused 180 deaths in Germany. Birkmann et al. (2023) examined the reconstruction process after this event, exploring challenges and opportunities to strengthen resilient recovery and build back better; including recovery of critical infrastructure and transport. Birkmann et al. (2023) found that **reconstruction processes after the 2021 floods suffered from fragmented planning and weak integration of resilience objectives, which challenged the ability to rebuild in a climate-resilient way**. The paper mentions the major role of **land-management and spatial planning choices as major determinants of exposure and resilience**.

Birkmann et al. (2023) show **that funding rules and administrative requirements often prioritise rapid restoration** of pre-disaster conditions over resilient redesign. The paper highlights that there were **no clear build-back-better principles**. Which, **under pressure to get the area up and running again as quickly as possible**, hindered opportunities to integrate higher climate-design standards or adaptation strategies.

Szymczak et al. (2022) show that the Ahr Valley floods caused extensive damage to the railway line, with bridges, tracks, embankments, and foundations severely affected by erosion. Railway bridges, like road bridges, also contributed to higher local water levels, worsening the overall damage. The authors stress the need for more flood-resilient bridge designs, with less flow obstruction and more erosion-resistant foundations. **When rebuilding, they recommend first assessing whether a bridge should return to its original location or be placed elsewhere**. Reconstruction is seen as an opportunity to improve the climate resilience of the entire railway system, for example by using slimmer bridge designs without central piers. They further argue that rail infrastructure must be designed for more extreme events, calling for **updated sizing standards based on appropriate magnitudes and return periods**. **This highlights that determining the level of acceptable risk guides the design standards and the resilience level of infrastructure**.

After the flood event, new flood hazard zones were introduced as well as new flood hazard maps, designated flood plain HQ100 and a high risk zone, including non-construction zones (Birkmann et al., 2023). These are legally binding and influence the way reconstruction is executed. However, there are tensions on the interpretation of these effects as the HQ100 event was based on historic data and disregarded factors like velocity and flood depth or climate change scenarios that modify return periods in the future. Therefore, the regulations were considered not sufficient for a risk-based adaptive planning process bridging hazard intensity and vulnerability (Birkmann et al. 2023). Szymczak et al. (2022) argue that infrastructure design should explicitly account for more extreme events by updating design standards and return periods. **This highlights the need for future-proof design standards and return periods in resiliency planning**.

5.2 Illustrative case 2: Enablers and barriers in *adaptation to the Copenhagen Metro*

Climate change impact assessment has been integrated in the design and planning of the Copenhagen metro since the start. The most important climate risk for the metro is flood risk, both from sea-level rise and precipitation.

A success factor in the adaptation of the Copenhagen Metro was the **early integration of climate change impact assessments** into the system's design and planning. Flood risk from extreme precipitation and sea-level rise was identified at an early stage. The metro was **designed using extreme flood scenarios**, including a 1/2000-year cloudburst event, corresponding to a 5% probability over the system's expected lifetime of 100 years. Adaptation measures included redesigning station entrances to divert surface water, improving drainage and pumping systems at transitions between above-ground tracks and tunnels, installing automatic pumping systems in underground stations, and adding floodgates at connections with other transport infrastructure. **These measures were aligned with the city's broader climate adaptation strategy**.

Limiting factors in this case were the fact that **decisions on station locations and routes are largely driven by economic and societal considerations rather than climate risk**, which limits the potential

to reduce exposure through design choices. The case shows that asset- and network-level adaptation have limits and that, **in some situations, climate risk reduction is more effective at the hazard level**, for example through regional flood-protection measures. **This also implies an important role for spatial planning authorities alongside infrastructure operators.**

5.3 Illustrative case 3: Enablers and barriers in [*adaptation to the UK railway network*](#)

The United Kingdom is projected to experience increased precipitation due to climate change. Therefore, there is a need to improve drainage management for railways. Network Rail, the national railway infrastructure manager in the UK set objectives for resilience of the railway, and also wider goals such as lower carbon footprint and more sustainable land management.

A success factor in adaptation to the UK railway is the **development of a strategic focus on climate resilience**, in relation to increased rainfall. Network Rail identified drainage capacity as a critical vulnerability and **linked climate adaptation to broader organisational objectives, such as asset performance and sustainable land management**. Weather-related delays and disruptions were recognised as a significant cost factor, which supported the **business case for adaptation**. This led to the implementation of drainage measures at vulnerable locations, including attenuation systems, additional pipework, and retention ponds. Further success factors include the **use of long-term planning cycles, collaboration with stakeholders across different levels of government, and the integration of adaptation into existing asset-management and compliance processes.**

At the same time, the case highlights limiting factors. Adaptation **decisions were strongly shaped by budget constraints**, requiring prioritisation between assets and routes. **High investment costs, without a direct return on investment further complicated the adaptation decisions.** Another limiting condition is the fact that changes to drainage or capacity at one location can affect water flows and performance elsewhere in the system, increasing the **complexity of decision-making.**

6. Conclusion and recommendations

This section examines adaptation decision types in transport infrastructure through a framework that combines two main dimensions: 1) actors and decision-making scales, and 2) (often implicit) value judgements that shape adaptation choices. Insights from European case studies demonstrate that adaptation outcomes depend on how these elements work together.

- **Governance scales:** Since actors tend to operate under different mandates and with different targets and goals to read, adaptation outcomes will depend on coordination between actors, both within operator organizations and outside infrastructure operators. From the ICARUS study we further learn that misalignments between decision-making levels, or unclear links between strategic objectives and operational measures for infrastructure operators, can limit the success of adaptation implementation decisions. **A practical recommendation is to involve spatial authorities where hazard-level adaptation is more effective than asset-level protection** (as learned from the Copenhagen case).
- **Spatial and temporal scales:** This ADT illustrated that Adaptation decision types can be categorized by spatial dimensions (hazard, system, network, asset) and temporal dimensions (prevention, preparedness, response, recovery). From the analysis, we learn that resilience cannot be achieved through prevention alone but depends on a combination of measures across spatial and temporal dimensions. **A practical recommendation is to make the connection between asset-level measures and network-level performance explicit to close the tactical gap.**
- **Value judgments:** value judgements often influence which risks are prioritised, which adaptation options are considered feasible, and how trade-offs are made in practice. Adaptation choices are therefore shaped by value judgements (e.g. reactive vs proactive, efficiency vs resilience, short vs long term). Case study findings suggest that these value judgements often remain implicit, although they determine the direction and possibilities of the adaptation

outcomes. **The corresponding recommendation is thus to make value judgements explicit in appraisal, particularly efficiency versus redundancy and the time horizon applied.**

- Adaptation decisions shaped by multiple dimensions: Hence, the framework shows that adaptation decision outcomes are shaped by the interaction between actors, scales and value judgements. Effective infrastructure adaptation approaches are observed where climate risks are considered early, where longer time horizons are applied, and where adaptation is embedded within existing organisational processes. At the same time, recovery after extreme events represents a critical moment, in which choices are made between restoring previous conditions and improving resilience for the future. In line with this, recommendations for adaptation would entail to **agree on build-back-better rules and funding conditions before an event rather than during recovery as well as to align resilience studies with the KPIs used in the decision-making context.**

ADT 7 – Cross-cutting decisions (PWA)

1. Decision context

At the global level, developing countries have prepared and submitted national adaptation plans (NAPs) to the United Nations Framework Convention on Climate Change²⁰ (UNFCCC). Most of these NAPs include estimates of the costs of adaptation (i.e., adaptation finance needs) (UNEP, 2025). However, while many European countries have also developed national adaptation plans and programmes (see ClimateAdapt²¹), most of their plans are not costed (World Bank, 2023).

This cost gap for Europe is a key omission, because cost estimates are needed to scale-up investment in adaptation. For public-focused adaptation, costs need to be known to allow the programming of actions in public spending and national budgeting. For non-public costs it is important to know the scale and affordability imposed on the real economy. For all actions, the analysis of costs is critical to allow comparison of costs to benefits, to help inform choices on alternative options, and to ensure effective and efficient adaptation.

However, it is stressed that the cost information required for these national adaptation plans are different to the cost information generated from sector integrated assessment models, e.g., from the sectoral models in ACCREU used in WP2. Instead, national plans are predominantly interested in short-term actions (and associated costs) that can be implemented over the next five years or so, as part of the next policy cycle, rather than cost estimates for the 2050s. This means that different, or at least complementary methods, are needed. National plans also have a much broader set of adaptation actions, that go beyond the normal focus of technical options in models, e.g., they will have important research, evidence, and process options, as well as soft options, and these need to also be costed.

Three ACCREU case studies were involved in addressing this research gap. CS 7.1 developed a framework and provided cost and benefit estimates for the English NAP (2023–2028), CS 7.2 built on CS7.1 and focused on the potential costs and benefits of adaptation for public finances in the UK, with a focus on the macroeconomics and fiscal costs and benefits of flooding (primarily reported in WP4). CS7.3 assessed the adaptation options in the National Strategy on Adaptation to Climate Change (NSACC) of the Republic of Cyprus and estimated the costs needed per sector in 2030 and 2050.

This adaptation decision type (ADT) builds on the work of these three case studies, and looks at current issues with assessing costs and benefits for national level adaptation. The ADT is therefore relevant for national governments across Europe.

It is also relevant for different types of stakeholders within government, which for adaptation include two main decision makers. First, adaptation leads, who are typically in the Ministry of Environment, and second, finance leads, who are typically in the Ministry of Finance. For example, in the UK, the case study stakeholders included Defra (Environment) and the Treasury (Finance). In Cyprus, the stakeholders were Ministry of Agriculture, Rural Development and Environment of Cyprus (Environment) and the Ministry of Finance of Cyprus (Finance).

The analysis, approaches and results from ACCREU here are also compared to other studies (outside of ACCREU) on costing adaptation, reflecting participation and discussion at the ADT workshop. This includes similar costing exercises for France (I4CE, 2024), Germany (Holscher et al., 2025), and at the European level (EC, 2026). This combined set of literature provides key policy insights.

2. Adaptation strategies

In 2025, EU Member States were mandated for the third time to report their national adaptation actions under the Regulation on the Governance of the Energy Union and Climate Action (2018/1999). The

²⁰ <https://napcentral.org/submitted-naps>

²¹ <https://climate-adapt.eea.europa.eu/en?activeTab=9631e688-acaf-47a5-b287-f83bbbf0d2f>

requirements for this reporting are further specified in Annex I of the first Commission Implementing Regulation (2020/1208).

In practice, the implementation of this requirement is varied, with different levels of details between individual Member States. This can range from quite high-level adaptation priorities down to specific actions (World Bank, 2024).

More information on the level of detail, and the types of adaptation that can be included, can be obtained by looking at the ACCREU case studies, as well as the non-ACCREU examples.

For England²², a high resolution of adaptation analysis was developed in the 3rd National Adaptation Plan (Defra, 2023a) with priority actions for the period 2023–2028). This followed from the 3rd National Climate Change Risk Assessment (CCRA3) which identified 61 national level risks and opportunities. These risks were aggregated into five thematic areas (infrastructure, natural environment, health and well-being, business and industry, and international) and this also was the structure used in NAP3. Within each of these thematic areas, a large number of actions were identified, arranged around individual risks. This led to a total of 389 unique adaptation actions. These varied considerably in their nature. They included i) evidence and research actions and ii) soft process based actions (e.g. meetings or capacity building). These are similar to the ACCREU adaptation typology and ‘soft’ options. They also included iii) specific investments and concrete actions (e.g. flood protection), which are similar to the ACCREU structural actions. However, they include an additional category of iv) mixed actions, where an action does not directly involve structural investment but would catalyze this following implementation (e.g., a commitment for new building codes that would lead to adaptation investment). There were green options included within the NAP3, but these were not separated out in the analysis, though they would fall into the investment category, e.g. nature-based flood protection. The short-term nature of the NAP3 meant there was less focus on transformational adaptation, though there were early soft options that were put in place to inform longer-term transformative change.

For Cyprus, the NAS report proposed 119 policies and measures in total. These covered 17 thematic areas: agriculture, ecosystems, cultural heritage, critical infrastructure, industry, energy, fisheries, forestry, health, water management, coastal areas, soil, spatial planning, tourism, transport, as well as cross-sectoral actions on governance and education. As in the English case study, actions varied considerably in their nature. They included i) evidence and research actions like specific studies and vulnerability assessments, as well as ii) soft process-based actions (e.g. capacity building, early warning systems), similar to the ACCREU adaptation typology’s ‘soft’ options. Actions also included iii) specific investments and concrete actions (e.g. flood protection, renovations of buildings), which are similar to the ACCREU structural actions. There were also iv) green options included in the Cyprus NSACC, such as nature-based solutions for coastline resilience, cultural heritage preservation and flood protection. As in the English case, there was little focus on transformational adaptation.

The other recent studies in Germany and at the EU level have similar levels of adaptation actions. In the analysis in Germany, for example (Holscher, et al 2025), the analysis considered 255 adaptation actions. The DG Clima study (EC, 2026) looked at five clusters: Infrastructure, Health, Ecosystems, Food, Economy and Finance, and worked with the 36 individual risk categories from the EUCRA, and clusters below this. It developed a shortlist of measures that totaled 155 unique adaptation measures.

All these studies therefore include a mix of actions (structural, soft, green), but this typology is not used in these assessments. Instead, all adopt a thematic-risk specific approach, where different option types can be considered as complements or alternatives, e.g. structural flood and nature-based flood would be considered as part of the flood risk theme.

²² In the UK, adaptation is devolved down to the individual countries, and thus the national adaptation plan is for England only.

The four studies above (England, Cyprus, Germany, EC) have between 119 and 389 individual actions, which indicates the general level that national adaptation works at. This moves beyond top-down costing at a high level, e.g. with one value for a sector, to a more disaggregated analysis. This in turn requires bottom-up costing, i.e., for several hundred individual actions. The methods to derive these costs do involve a mix of methods, as seen from the England and Cyprus studies. For example, where very detailed information is available it is possible to derive detailed activity-based budgets. In other areas, the results of models are used, especially for flooding and water sectors where there tends to be detailed modelling information available for most MS. However, in some cases there is little concrete information and indicative costing estimates need to be made, for example through expert elicitation. This is particularly the case for some of the process and soft options.

There is also an additional issue of attribution which is relevant for costs, i.e., over what actually counts as adaptation. This is particularly important because unlike mitigation, adaptation involves a broader set of activities that often involve the mainstreaming of climate adaptation into existing policies and actions, rather than as stand-alone. This makes it important to separate (attribute) the relevant adaptation costs.

This is not a new issue, and a lot of work has been undertaken in the developing country context to advance cost attribution typologies. These were also applied in the ACCREU case studies. In particular, a set of cost attribution typologies have been advanced and applied by the Multi-lateral Development Banks (the MDBs), specifically the Joint methodology for tracking climate change adaptation finance of the Multi-Lateral Development Banks (EIB, 2022). These identify three types of adaptation actions.

- Building climate resilience into programmes and investments (climate proofing, Type 1), where adaptation is a secondary objective. For example, the costs of addressing climate risks in the design standards for new road investments or new national rail projects. In this case only the additional (incremental) adaptation costs of making the investment resilient are counted (not the costs of the underlying investment).
- Investments where adaptation is one of a number of objectives (mixed adaptation, Type 2). For example, investing in peatland restoration delivers multiple benefits, including improved ecosystem services, water regulation, carbon sequestration, but also enhanced climate resilience (on-site and off-site). A proportion of these investments can therefore be counted as adaptation, but a judgement has to be made of the relevance of adaptation compared to other objectives (attribution).
- Targeted adaptation programmes and investments (pure adaptation, Type 3), where the primary objective is to reduce vulnerability to climate change. For example, investing in coastal flood protection to address sea-level rise. In this case the total spend is counted as adaptation.

This also affects the benefit calculation. For example, for climate proofing, only the benefits of the adaptation is considered, not the benefits of the underlying investment (e.g., only the benefits of reduced climate impacts on a road), whereas for a targeted adaptation investment all the benefits are relevant.

This typology has broad applicability for any European country and Member State, as well as at the European level.

3. Barriers to implementation and lessons on how these can be overcome

While a national adaptation plan or programme may be produced, with hundreds of costed priority actions, these will only have an impact if they are implemented with appropriate levels of financing. There is evidence that many national adaptation plans do not translate into implementation (Watkiss et al., 2026) and this is due to various barriers.

From a public policy perspective, the policy, investment and financing decisions for adaptation should follow the same approach as other public policy investments. It is therefore useful to look at the framework for these decisions and examine if these involve potential barriers.

There are a standard set of public policy frameworks in use across Europe, which are centred on welfare economics²³. These are the main approaches through which adaptation will be assessed and prioritized in national level planning. These approaches form the foundation of public policy intervention and public investment management in the European Commission and in most national governments. For example, at the EU level, new policies are subject to an EC [Impact Assessment](#) (EC, 2025), which examine whether there is a need for EU action and analyses the possible societal (welfare) impacts of available solutions. The same approaches are generally used at the country level, for example, in the UK, the Green Book on Central Government Guidance on Appraisal and Evaluation (HMT, 2022) sets out guidance on appraisal and the delivery of public value. The first step in this appraisal guidance is to provide the economic rationale for intervention, including consideration of market failures, and then the process progresses to economic appraisal (impact assessment) based around cost-benefit analysis. These public policy and welfare economic techniques are particularly used by Ministries of Finance, who also lead on public spending and budgeting.

However, the use of this conventional economic approach often acts as a barrier to adaptation, and can hinder the implementation of national adaptation plans, especially given the nature of adaptation.

Adaptation is generally considered to involve large numbers of market failures (economic barriers). These include information failures, positive externalities, and imperfect financial markets (Pauw et al., 2021) as well as policy failures and coordination failures (Frontier Economics and Paul Watkiss Associates 2022). Therefore, to fully implement adaptation often requires quite strong levels of policy intervention from a government. This is compounded by the nature of many traditional adaptation investments, which are either public goods, have strong distributional benefits, involve non-market sectors or have non-market benefits. This means they are more traditionally delivered and funded by the public sector. In effect, the economic (societal) benefits of adaptation are higher than the financial benefits, and these investments often do not generate revenue streams. This means, even though adaptation makes sense from a societal perspective, it will require public funding.

This leads to two important barriers. First, most national adaptation plans do not follow this standard public policy approach, and the initial ‘upstream’ case for adaptation. Instead, they jump straight to the science and lead with risk assessment then the identification of options. This is a missed opportunity because public policy frameworks and the use of welfare economics should, in theory, capture these issues and justify public policy intervention. Second, given the state of the public finances and fiscal pressures in most European countries, increasing public funding for adaptation is challenging. This is exacerbated as adaptation generally delivers benefits from avoiding impacts and can be considered as a defensive or non-productive investment, unlike other competing investment options which can generate economic growth. This is likely to mean countries underinvest in adaptation, even when there is a strong societal case.

More positively, the case studies do show some evidence that adaptation is being funded at scale already. The UK case study estimated NAP3 adaptation costs at around £9 billion/year (around Euro 10 billion) and most of these are actual budget lines and involve actual spending levels. Similarly the study in Germany (Holscher et al., 2025) looked at public budget and also found current adaptation expenditure. It is useful therefore to see what conditions and enabling factors supported the implementation and financing of adaptation in these cases.

There are some lessons from the UK on these enablers (Rising et al., 2025). First, there are some political economy influences. The requirement for continuous cycles and updated NAPs does create incentives for more advanced action over time. Further, as part of legislation, there is an independent body (the Climate Change Committee) which provides scrutiny of government progress on adaptation, publishing regular reports, and this also provides additional pressure for government action. Efforts

²³ This is concerned with social or public value and not simply market efficiency: it includes all relevant costs and benefits that affect wellbeing, not just market costs and benefits, and thus includes environmental, cultural, health, social, and justice effects.

have also been made to reduce policy and coordination failures. Each of the more than 61 priority climate risks identified in the CCRA3 has been formally assigned to a specific government department or ministry as a designated ‘risk owner’, ensuring accountability.

Second, the UK government has introduced a series of policy and regulatory reforms which enable adaptation. This includes climate adaptation updates to building codes for new residential developments, which incentivize passive ventilation to improve resilience to future heat risks. Similarly, economic regulators have been integrating adaptation within regulated sectors. For example, the water regulator, Ofwat, has authorized climate resilience investments by private water companies as part of its latest five-year price review (Ofwat, 2024: 2025), as well as introducing resilience standards for private water companies. There have also been economic policy levers, for example, agriculture subsidies have moved away from production to payment for public goods, and as part of this, on-farm natural flood management is supported (Defra, 2023b).

A further barrier may be the lack of information on the economic benefits of adaptation. There has been a lack of economic benefit analysis in all national adaptation plans, globally as well as in Europe (World Bank, 2024; Watkiss et al., 2026). This is due to the challenges associated with adaptation economic benefit analysis, such the site and context specificity, time and resources required, consideration of uncertainty. However, this lack of benefits information reduces the case for policy intervention and investment, and is a key research gap for future action. The England case study did undertake an initial analysis of the economic benefits of the main adaptation actions. This found most actions had positive economic benefit to cost ratios, ranging from 2:1 to as much as 10:1, and such information can be extremely useful in spending submissions for budget allocations, to argue for greater adaptation investment.

Experience in Cyprus points to similar policy challenges. Historically there has been an underinvestment in adaptation because financing such investments was not considered growth-enhancing. There has been considerable progress in measures that the country had to adopt in order to comply with EU legislation, but these related mainly to climate change mitigation which had also adaptation co-benefits such as the Energy Performance of Buildings Directive. Implementation of other adaptation measures has been slow, as also underlined in the relevant European [Council Recommendation](#) of 2024, which stressed that slow implementation was partly due to the lack of the proper institutional setting that would make implementation binding for public authorities (European Council, 2024). There are indications that, with deteriorating climate change impacts, more stringent EU policies and a recognized need for improved climate governance in the country, adaptation will become a more pronounced policy priority for the central government, which can also lead to proper public financing levels.

4. Policy insights

The ACCREU case studies, the ADT workshop, and the wider non-ACCREU studies, provide some valuable policy insights for national level adaptation.

First, **the results show that it is possible to cost national adaptation plans and programmes**, though this requires **mixed methods** and goes **beyond the typical analysis used in sector integrated assessment models**. It involves a greater level of resolution and consideration of a wider set of actions, including process actions. At the same time, it is challenging to include the more advanced decision-support tools (such as real options analysis, robust decision making, dynamic adaptation pathways) to these national assessments, as these methods are more aligned to individual project appraisal. This is identified as a key research gap, i.e., how to better integrate adaptive management into national adaptation plans and the associated economic analysis.

The ACCREU case studies, and the wider examples, also provide interesting results and findings on the costs of short-term adaptation in Europe. In England, annual adaptation costs are estimated at around £9 billion /year (~10 billion Euro). This is equivalent to around 0.4% of GDP. For Cyprus, the need for additional investment up to 2050 was estimated at 3.4 billion Euros (current prices), which is also

approximately 0.4% of GDP. The other non-ACCREDU case studies also generate similar numbers. For the German study, expenditure on adaptation was estimated between €2.07 billion and €3.41 billion, accounting for 0.42% to 0.69% of the total 2022 federal budget. At the EC level, the DG Clima study estimated adaptation investments needs in the EU up to 2050 at around €69 billion per year, which is equivalent to also around 0.4-0.5% of GDP. However, some caution is needed not to over-interpret these findings, and assume that short-term adaptation will have modest costs. The costs identified are still only a partial analysis of all adaptation costs, because not all climate risks are considered. Further, there are important differences between the studies: for example, the England analysis suggests that adaptation costs could rise very sharply after 2030, due to rising concerns around heat, but also the need to move from climate proofing new infrastructure to retrofitting existing infrastructure. Finally, these studies tend to focus on more public action: there will be additional costs to the real economy, including private sector infrastructure, that are not well captured. There is some evidence that these costs could be a similar order of magnitude to the identified costs above (see Aligishiev, Bellon and Massetti 2022).

However, there are also differences between the study results. In England and Cyprus, while the relative investment level is similar, the risk profile is very different, and thus the balance of adaptation investment varies. **The option mix reflects country hazard profiles.** Further, while most of the England estimates reflect actual budget expenditure, the costs for Cyprus are needs rather than flows, as less than 30% of the total adaptation investment is currently planned. There are also some interesting findings on the split between the public and private sectors. In England, the case study estimates that 55% of the adaptation costs fall to the public budget, while the rest will be borne by households and businesses. This reflects a high level of privatisation in the UK, which means costs are passed through in charges (e.g., water bills, electricity bills). In Cyprus, about 70% of adaptation costs are estimated to fall to public funds, in the form of infrastructure investments and financial support to households and businesses (e.g. to enable energy renovations of their buildings); this may be due to the fact that households and firms have already privately invested in recent years to adapt to the current semi-arid climate of Cyprus (e.g. for space cooling of residences and offices), so that the bulk of further costs falls to public funding e.g. for strengthening coastal infrastructure, investing in more water desalination and forest fire protection, etc. **This means the distribution of adaptation costs will vary with country and the underlying institutional landscape.**

Second, and more broadly, the case studies identify a number of important policy insights for national adaptation planning. **The analysis indicates there is a greater need to apply traditional public policy and welfare economic analysis to the early development of national adaptation plans and programmes.** This means adopting a policy-first approach rather than a science-first approach (see Deliverable 3.1). This includes an analysis of the justification for public intervention, and also means that adaptation options need to extend beyond technical options, to consider how to implement policy objectives, e.g., should the problem be addressed with regulation or market based instruments. **There is also a need to extend the analysis in national adaptation plans to consider the economic benefits of adaptation, as part of economic appraisal.** This is required to help make the intervention case. However, as highlighted in other ACCREDU work (Deliverable 3.2), this economic analysis should be comprehensive and include environmental and social benefits, as these are often required to fully build the case for adaptation, as they capture important co-benefits. It is also stressed that these economic appraisal techniques are designed for short-term, marginal decisions, they are not applicable for transformational adaptation. This is discussed in more depth in Deliverable 1.5. This means that alongside the use of these approaches, there also needs to be discussion on where and how they should be extended.

Further, and related to this, **there is a need to integrate adaptation into medium-term expenditure frameworks and spending decisions in government,** and through to budget allocations, as well following the approaches used for public investment management, i.e. aligning more closely to the processes used in government and led by Ministry of Finance. It is highlighted these adaptation spending needs will need to come from each individual ministry, not just the Ministry of Environment, because they have the responsibility and mandate for specific adaptation actions (e.g., transport related actions would need to come from the Ministry of Transport). This highlights important coordination

and political economy aspects will be critical for scaling up adaptation across government. Following from this, there is also a need to mainstream adaptation into the traditional medium term expenditure frameworks and budgeting processes, and the relevant criteria for government prioritisation with public investment management criteria and fiscal analysis.

Finally, as well as the economics of adaptation, **there will need to be a greater focus on the funding and financing of adaptation (UNEP, 2025)**. Financing relates to the source of finance and the financial instruments involved. This is different to the separate question regarding the funding of adaptation, i.e. how to pay for adaptation over the lifetime of the investment and how these costs (including the financing costs and the cost of capital) will be paid for. The difference between funding and financing is important because it influences who ultimately pays for adaptation. These issues are emerging for developing countries, which are using adaptation investment planning to try to convert national adaptation plans and programmes into finance (see Watkiss et al., 2026): similar initiatives will also be needed for European countries to do the same for their national plans, and this is an important research priority.

4. Synthesis

The seven Adaptation Decision Types cover different domains and sectors, and use different forms of evidence. ADT1 draws on a systematic review of 97 flood adaptation cost-benefit analyses, 27 policy CBAs and 27 multi-criteria analyses. ADT2 draws on a review of 48 case studies on wildfire adaptation. ADT3 combines two river basin case studies with sectoral modelling. ADT4 analyses four heat-health adaptation plans using the Just2Adapt tool, to assess the social justice of these plans. ADT5 reviews climate stress tests and financial adaptation instruments. ADT6 discusses different transport adaptation and develops an analytical value framework, which is applied to three illustrative European cases. ADT7 builds on national adaptation costs in England and Cyprus alongside comparable studies for Germany, France and the EU.

As a result, we cannot compare measurements or quantitative findings across them. At the same time, there are some key findings and patterns that are present across these sectors/domains.

4.1 Key findings

1. Each ADT classifies adaptation strategies differently

Each ADT used its own way of grouping adaptation measures into strategies, which reflect how adaptation decisions are framed in that domain. To synthesise across them, we first examined whether the distinction between grey, green and soft measures could work as a common classification.

This distinction works well where adaptation consists of physical measures. In ADT1, 65 of the 97 reviewed cases assessed a grey measure, 31 a green measure and 20 a soft measure, with 30 combining grey and green. In ADT2, this classification works well and is applied to the thirteen strategies, of which three are grey, three are green and seven are considered soft. They also added whether strategies were more incremental or more transformative, which is sometimes both, depending on location and scale (for instance building fire-resilient structures, see Table 2.1). In ADT3, the efficiency and supply directions consist predominantly of grey and green measures, while demand-side and reallocation measures are almost entirely soft. In other ADTs this classification is less relevant. In ADT 5 the categories do not apply, as financial instrument are not physical measures. In ADT6 there is a mixture of grey/green/soft, however the ADT's framework is about governance, scales and value judgements, where this distinction is less useful. ADT7 shows that national adaptation plans contain a mix of structural, soft and green actions, but that this typology is not used in national assessments, which work thematically by risk. In ADT4 this distinction is also less relevant, as it focuses more on the assessment of social justice.

A single classification therefore does not describe all seven ADTs, as what works for flood risk does not describe adaptation in the financial sector or what works for water allocation does not describe heat-health adaptation planning. We therefore summarize each ADT by its own strategic directions (Table 2). Each strategic direction shows potential different visions for directions that can be taken, under which different measures fall. The strategic directions also differ in implementation phase: some are more incremental (connected to the current practices/status quo), while others are more transformational.

Table 2. Strategic directions per ADT.

ADT	Strategic Directions
1. Flood Risk	Keeping the water out; making space for water; reducing what is exposed; limiting impacts of flooding - see Table 1.4
2. Forestry and ecosystems	Suppressing fires; fire prevention management in existing landscapes; transforming the landscape; reducing what is exposed (enabled by financing, incentives and capacity building strategies) – See Table 2.2
3. Water-food-biodiversity	Increasing water-use efficiency; increasing or buffering supply; reducing or reshaping demand; reallocating between users – see Table 3.1
4. Health and justice	Cooling the environment; reducing exposure of people and buildings; strengthening coping capacity; addressing structural drivers of vulnerability – see Table 4.1
5. Finance and private sector	Rely on government-led physical adaptation; use existing macroprudential options for climate risk management; give the private sector a key role in spatial planning and insurance– see Table 5.5
6. Transport and supply chains	Reducing the hazard around the network; making assets robust; keeping the network functioning; changing how the system operates (service levels, standards), with recovery as a temporal dimension across all – see Table 6.1
7. Cross-cutting decisions	National planning groups actions by their nature (evidence and research, soft process-based, investment, mixed, green) and by attribution type (climate proofing, mixed adaptation, pure adaptation across all sectors and hazards).

2. Economic appraisal influences which strategies are preferred

Clearest common finding across the ADTs is that the way adaptation is appraised influences which strategies appear most attractive, and this systematically favours incremental, hazard-focused, physical measures.

ADT1 (floods) provides the most direct evidence of this. Benefits in flood adaptation CBA are often focused solely as flood risk reduction. Around half the reviewed cases included co-effects, and only 12 included co-costs. Several of the reviewed cases showed that including co-effects changed the conclusions or the ranking of measures, with nature-based solutions performing better once co-effects were counted. As benefits of green and soft measures more often include effects outside flood damage metrics, the observed dominance of grey prevention measures is partly reinforced by a narrow economic appraisal practice.

In ADT2 (wildfires) there is a very unbalanced financial structure, as around 90% of the wildfire budget goes to the suppression, and only 10% goes to prevention. They found that in general, when the economic assessment is more narrow, many strategies are financially unviable. For instance, the benefits of fuel treatment only exceed costs when wider societal benefits such as wildlife habitat and avoided loss of life are counted. Also capacity building has benefits that are hard to quantify because they appear as knowledge and awareness over the long term. This is similar to the findings in ADT1 regarding co-effects.

ADT3 (water-food nexus) also shows this asymmetry in the water scarcity domain. Conventional appraisals quantify infrastructure investments, agricultural production and water productivity, while environmental flows, biodiversity and cross-sectoral effects are harder to express in a single economic metric. In the Ebro assessment, local storage improved agricultural water-use efficiency while crop switching generated substantial water savings, but performed poorly on agricultural revenue, and environmental flows were assessed separately (and not monetized). Currently, efficiency and supply/irrigation expansion are well captured in appraisals, and also the directions that European policy has supported mostly.

In ADT6 (transport) the same mechanism is apparent, as it shows that appraisal frameworks focus on efficiency under normal conditions, which makes it difficult to justify redundancy, as its benefits only appear during disruptions. ADT7 identifies the limitations at national level, as standard public policy appraisal is designed for short-term, marginal decisions and is not applicable to transformational adaptation, while most national adaptation plans do not analyse benefits at all.

3. Scale: strategies that work at one level might not work at another level

Several ADTs find that adaptation measures which perform well at the level at which they are assessed produce different, sometimes opposite, effects at a wider scale, or the other way around.

The clearest example is the irrigation efficiency paradox in ADT3. Transitioning from gravity-based to drip irrigation raises yields and water-use efficiency at field scale, but at basin scale the savings are frequently offset by increased consumptive use and reduced return flows, as irrigated areas expand or shift to more water-intensive crops. Efficiency gains at one level can therefore increase net consumption at another, which is why the ADT recommends that they be accompanied by abstraction limits or allocation rules.

ADT2 also shows this scale mismatch through their cost and benefits across actors. Forest owners and managers bear the cost of fuel management, while the benefits extend broadly to society, which gives them limited incentives to invest.

ADT5 also finds a scale mismatch in the assessment of financial risk, as the reviewed stress tests report limited impacts on financial stability, while the same events may cause severe losses for individual households and for specific regions and sectors.

We also see examples of this in ADT4, that looks at the social distribution of heat measures. Urban greening reduces heat exposure at city level, but the distribution of effects often favours wealthier neighbourhoods. Thus, although the aggregated outcome is positive, the distribution of the risk might not change or even worsen.

4. Distributional effects are consequential, but they are rarely assessed

Distributional effects are recognised as important across the ADTs, but they are seldomly assessed explicitly.

ADT1 provides the quantitative evidence. Of the 97 academic flood CBAs, three applied equity weights and none applied multiple social welfare functions. None of the 27 policy CBAs presented outcomes for different social groups, and none applied equity weights. In the multi-criteria analyses, equity was the only component not included in a majority of cases. When equity weights are applied, it can affect the desirability of adaptation overall or choices for where to prioritize adaptation (Markanday et al., 2021; Lockwood et al., 2024).

ADT2 shows distributional effects as well. Firebreaks are concentrated in high-value forest areas and rarely extend to more marginal areas, which reduces the protection for the people living there. Zoning that restricts housing density can raise property values, which reduces affordability. In wildfire-prone areas, wealthier residents can invest in protection while less affluent neighbours remain more exposed. The California fee was withdrawn in 2017 after opposition raised fairness concerns, showing a distributional case where policy failed.

ADT6 shows that using the standard utilitarian principle for appraisal, is already a policy choice. In CS6.1, applying utilitarian, egalitarian and prioritarian principles to road network investment produced different spatial investment patterns and preferences. Prioritizing investment where transport demand

is greatest (and thus greatest overall potential asset loss) is already an equity decision. Making this explicit by showing other ways of doing this can help to increase transparency of adaptation decisions and highlighting trade-offs.

ADT5 shows how distributional effects can arise from the way measures or instruments are designed. It shows that risk-based insurance premiums provide a risk signal but can become unaffordable in high-risk areas, potentially locking in households that cannot move out and cannot insure themselves. Macroprudential measures may restrict credit access and affect housing affordability, with distributional consequences.

Several ADTs give a similar recommendation, which is that distributional questions should be considered early on, when options are still being defined, and not at the appraisal stage, as early consideration of equity may also broaden the range of measures that are being considered.

5. Barriers: common across the ADT domains, but differ systematically by type of strategy

The ADTs identify a recurring set of barriers: limited financial resources, gaps in data and knowledge, limited awareness, fragmented or misaligned mandates, political reluctance. Financial constraints are mentioned as key barrier in ADT2, ADT4 and ADT7, while data limitations are most consistently reported in ADT5 and appear in ADT2, 4 and 6 as well.

Besides this shared list of barriers, many differ significantly by type of strategy. Measures focusing on the hazard or on assets are mainly constrained by cost and technical feasibility: capital and maintenance costs in ADT3, retrofit costs in ADT4, budget-driven prioritization in ADT6. Measures focused on demand, behaviour or the structural drivers of vulnerability are mainly constrained by mandate and political feasibility. Water managers have no regulatory authority over agricultural development or trade policies (ADT3), while climate adaptation lies outside the mandate of central banks (ADT5). In ADT2, fragmented ownership is a barrier to landscape-scale strategies as nobody has the mandate over the landscape as a whole. The most effective adaptation for a transport operator may be hazard-level protection that falls under the responsibility of spatial authorities (ADT6). Adaptation spending must come from individual line ministries rather than from the environment ministry alone (ADT7). The second set of barriers are not resolved by making more funding available.

Also, barriers to transform are often linked with long-term cycles that come with high uncertainties, thus decisions made today can impact outcomes decades into the future, which makes experimenting with new practices, such as replanting different tree species for wildfire resilience (ADT2) less appealing. This also holds for most other sectors, such as flood risk management (ADT1), water scarcity (ADT3) and heat (ADT4).

6. Lock-in and windows of opportunity

Adaptation decisions often concentrate around specific moments in time, such as crises or large infrastructural maintenance or upgrade programmes. How well these ‘windows of opportunity’ moments are anticipated and prepared for determines whether they lead to more resilient outcomes or to a rebuilding of what was there before. Recurring planning cycles offer a more predictable kind of opportunity. ADT7 shows that statutory cycles of adaptation plans, combined with independent scrutiny and clearly assigned responsibilities for each priority risk, create regular moments at which the prevailing direction can be reconsidered, and help ensure that decision-makers are prepared when less predictable windows arise.

There are also risks of lock-ins, for instance when protection reduces risks, which encourages development in areas that are now considered safe. Over time the economic value concentrated behind the dikes/defences makes alternative strategies politically and financially unviable (ADT1, ADT5).

Lock-ins and its self-reinforcing mechanisms are a key reason why grey measures have long been the preferred options in flood adaptation (ADT1). In the transport sector (ADT6), long asset lifetimes cause that decisions taken today will shape the vulnerability for decades, while short investment cycles favour measures with short-term benefits.

Post-disaster recovery is a very clear ‘window of opportunity’. After the 2021 Ahr Valley floods, funding rules and administrative requirements prioritized rapid restoration over resilient design, and in the absence of clear build-back-better principles most reconstruction was done similar to pre-flood conditions. Recovery after the 2024 DANA floods in Valencia included selected adaptive measures, supported by existing regulatory instruments such as floodplain construction bans and mandatory risk assessments (ADT6). The key difference was caused by whether rules and standards were already in place before the event. These windows of opportunity also open and close, for instance awareness of heat risk rises immediately after a heatwave and declines over time, which makes it difficult to keep the issue on political agendas (ADT4). In theory, wildfires would also offer a post-disaster window of opportunity, however post-fire recovery was not examined in the reviewed wildfire cases.

7. Transformative options: identified in theory but rare in practice

Transformative strategies are identified across the ADTs but are seldom implemented and still less frequently appraised. In ADT2, re-thinking land-use patterns (such as mosaic landscapes, agroforestry), adaptive ecosystem management and relocation are all classified as transformative, and are all less common or not yet implemented., with key barriers mentioned: coordination across fragmented stakeholders, long time horizons, lower direct revenues and public resistance. At the same time, it is acknowledged in ADT2 that effective wildfire adaptation will require transformative and landscape-level changes. In ADT3, structural changes to demand, including trade modification and dietary shifts, are identified as necessary for basin-level water savings but have not been implemented. In ADT6, case studies 6.1 and 6.2 found that incremental options are preferred over transformative ones, due to political reluctance (according to stakeholders) and the higher costs and complexity of coordinating across different domains. In ADT7, the short-term focus of national adaptation plans results in less attention to transformational adaptation in both England and Cyprus.

This connects to our appraisal finding, that current economic appraisals are less suitable for transformational adaptation, as these are often the strategies that have values that are out of the scope of conventional/standard appraisals. As a result, these options are also less likely to be selected.

8. The role of sectoral models

Sectoral models play a substantial role in the ADTs where adaptation consists of physical measures whose effects can be modelled. In ADT1 they are used across the reviewed flood cases. In ADT2, several models are listed, with different use cases. Some models are more suitable for modelling short fire events or for large areas, whereas others are suitable for longer events or for smaller areas, hence applicable for a range of stakeholders from forest managers to insurers. Moreover, modelling-based approaches could help identify the areas with the highest return on investments for fuel management, which could help overcome the barrier of high upfront and maintenance costs related to it. In ADT3, GLOBIOM, EPIC-IIASA and CWatM are combined to assess agricultural production, water availability and environmental flows in the Thaya and Ebro basins. The role of models is more limited when adaptation is concerned with plans, mandates and budgets. As discussed in ADT7, models are valuable for framing risks and for high-level messages about the effectiveness of adaptation in the longer term, but they do not tell a policy maker what to do in the next five years, and they are of little use for costing of the soft and process-based options that are often a large part of a national adaptation plan. Models can also play an important role in assumptions and scenarios they run. For instance, in ADT5, central banks report difficulty in operationalising physical risk data for stress testing, mainly

because of limited spatial resolution and the need to translate generic impact indicators into asset-level risks.

4.2 Towards generic adaptation pathways

For each ADT, we translated the key strategies into different strategic directions as outlined in Table 2. These represent the key alternative courses of action within the sector/domain. In many ADTs one (or two) directions dominate the current adaptation landscape, while other (often more transformational) strategic directions are known but are rarely assessed or implemented. In ADT1 the reviewed cases concentrate on keeping the water out, with 82 of 97 cases including prevention measures and only six assessing preparedness, response or recovery. In ADT2, wildfire management has concentrated on suppressing fires, which receives around 90% of the EU wildfire budget against 10% for prevention; fire prevention management in existing landscapes is widely implemented, particularly in Southern Europe, while transforming the landscape and reducing what is exposed remain less commonly or not yet implemented. In ADT3, European policy has supported efficiency and supply most strongly, while demand-side change and reallocation remain largely unimplemented. In ADT4, warning and communication measures are the most common in heat-health plans, while measures acting on the built environment and on the structural drivers of vulnerability are the least developed. In ADT5, collective protection and insurance arrangements are established, while macroprudential steering has not been implemented or tested for climate risk. In ADT6, asset-level measures and design standards dominate, while redundancy and prepared recovery receive less attention.

The findings above identify what sustains these dominant directions. Most straightforwardly, they are the established practice: grey flood protection, fire suppression, irrigation efficiency, design standards for infrastructure and collectively financed flood protection have been the prevailing approach for decades, and are embedded in institutions, budgets and regulations built around them. Economic appraisal reinforces this, as it captures the benefits of some directions more readily than others. Where an alternative direction is considered, its benefits often fall outside the appraisal frame, which makes it harder to justify even where it performs well on other grounds. And mandates limit which directions an actor can choose at all, so that domains tend to adapt where their dominant actors have authority to act. Sunk investments and established practice reinforce existing choices over time, as in the development that follows successful flood protection, or the long asset lifetimes and short investment cycles in transport infrastructure. In forestry, long rotation cycles combined with uncertainty about future climate conditions make experimenting with new practices risky, which makes traditional practices appear more appealing (ADT2). Funding rules and time pressure after an event favour restoring what was there before. The directions that are least pursued are, in several ADTs, also those that would require the largest shift from current practice, such as transforming the landscape in ADT2, reducing demand in ADT3, market-led allocation of risk in ADT5 and accepting reduced service levels in ADT6.

The findings also identify where these choices may open, where there are ‘windows of opportunities’: recovery moments, recurring planning cycles, regulatory review points and EU frameworks that require sectors to be assessed jointly (see also finding 6).

These patterns are summarized in Figure 2, which bring the strategic directions of the ADTs together along two dimensions: to what extent each direction is more transformational or more established practice, and how well conventional economic appraisal captures its benefits. The positions are qualitative and reflect our interpretation of the ADT chapters rather than a systematic assessment. The pattern that emerges is that directions which are well established also tend to be those whose benefits appraisal captures most readily, while directions requiring a larger shift from current practice cluster where appraisal captures their benefits least. Part of this relationship is inherent, as strategies that are more transformational more often produce broader and non-market benefits. It nevertheless illustrates

why the dominant directions are self-reinforcing: the strategic directions that would require the largest shift are also those whose case is hardest to make within current appraisal practice.



Figure 2. Strategic directions per ADT, positioned established practice versus more transformational changes and by how well their benefits are captured in conventional economic appraisal. Positions are relative and based on the authors' interpretation of the ADT chapters. ADT7 is not plotted, as it concerns the appraisal and budgeting layer represented by the vertical axis.

All of these describe the **starting conditions** for generic adaptation pathways. A pathway describes a sequence of decisions over time, including the conditions under which one course of action is shifted to another. The ADTs identify the available adaptation directions and the dominant one's (the status quo), and what reinforces or alters them, but they do not yet indicate when a switch between directions becomes necessary or advisable. ADT2 is the only ADT that explicitly points to an adaptation pathways approach, noting that wildfire adaptation would lend itself well to dynamic adaptive policy pathways given the deep uncertainties and the limits of individual strategies, but that no case studies have yet tested such an approach. Defining such switching conditions, whether in terms of climate thresholds, societal thresholds, adaptation limits or changes in the decision context, requires a further analysis at the level of specific decisions and locations. This would be a priority for further work.

4.3 Future directions

The findings reported in the ADT and synthesis point towards several directions for future research and adaptation planning. First of all, the results highlight the importance of broadening the scope of economic appraisal. Across the different domains, the benefits of some strategic directions are captured more clearly than for others, and the directions that appraisal represents well are largely those that are pursued. Further work is needed on the barriers to more comprehensive appraisal, on improved and better tailored guidance, and on the enabling conditions for broader appraisal, including how co-effects, distributional effects and benefits that only materialise under disruption can be given weight alongside directly quantifiable ones.

A second direction concerns distributional effects, which several ADTs identify as consequential but rarely assessed. The recurring recommendation is to consider these effects early in adaptation planning, when options are still being defined, rather than at the appraisal stage, since doing so may broaden the range of measures that is considered.

A third direction concerns fragmented governance, which was among the most frequently reported barriers across ADTs. Where the most effective strategy falls outside the mandate of the actor bearing the risk, more funding alone will not resolve the barrier, and further work is needed to better align policy instruments, institutional mandates and budgets with where risks and responsibilities actually lie.

Finally, defining the conditions under which a shift between strategic directions becomes necessary would be the logical next step towards generic adaptation pathways and effective adaptation planning (see Section 4.2).

5. References

- It.org U.S. Chapter. (2022, April). Technology and MRV in forest carbon finance [White paper].
<https://us.it.org/wp-content/uploads/2022/05/It.org-US-Technology-and-MRV-in-Forest-Carbon-Finance.pdf>
- Abunyewah, M., Gajendran, T., Erdiaw-Kwasie, M. O., Baah, C., Okyere, S. A., & Kankanamge, A. K. S. U. (2025). The multidimensional impacts of heatwaves on human ecosystems: A systematic literature review and future research direction. *Environmental Science & Policy*, 165, 104024.
<https://doi.org/10.1016/j.envsci.2025.104024>
- Adamson, M. (2018). Flood risk management in Europe: The EU ‘Floods’ directive and a case study of Ireland. *International Journal of River Basin Management*, 16(3), 261–272.
<https://doi.org/10.1080/15715124.2018.1437744>
- ADIF. (2024). *2024 sustainability report* (English version). Administrador de Infraestructuras Ferroviarias.
https://www.adif.es/documents/34745/10774271/2024_ESTADO_SOSTENIB_ADIF_AV_ENG.pdf.
- Adobes Golfe, V., & Dalmau Rovira, F. (2022, May 12). Building fire resilience using recycled water in Riba-Roja de Túria, Spain. Climate-ADAPT. <https://climate-adapt.eea.europa.eu/en/metadata/case-studies/building-fire-resilience-using-recycled-water-in-riba-roja-de-turia-spain>
- Alcasena, F. J., Ager, A. A., Bailey, J. D., Pineda, N., & Vega-García, C. (2019). Towards a comprehensive wildfire management strategy for Mediterranean areas: Framework development and implementation in Catalonia, Spain. *Journal of Environmental Management*, 231, 303–320.
<https://doi.org/10.1016/j.jenvman.2018.10.027>
- Alcasena, F., et al. (2021). Fostering carbon credits to finance wildfire risk reduction forest management in Mediterranean landscapes. *Land*, 10(10), 1104. <https://doi.org/10.3390/land10101104>
- Aligishiev, Z., Bellon, M. and Massetti, E. (2022). Macro-fiscal implications of adaptation to climate change. IMF Staff Climate Note 2022/002. Washington D.C.: International Monetary Fund.
<https://www.imf.org/en/Publications/staff-climate-notes/Issues/2022/03/16/Macro-Fiscal-Implications-of-Adaptation-to-Climate-Change-512769>
- Alves, A., Gersonius, B., Kapelan, Z., Vojinovic, Z., & Sanchez, A. (2019). Assessing the co-Benefits of green-blue-grey infrastructure for sustainable urban flood risk management. *Journal of Environmental Management*, 239, 244–254. <https://doi.org/10.1016/j.jenvman.2019.03.036>
- Amorim-Maia, A.T., Anguelovski, I., Connolly, J.J., Chu, E. (2023). Seeking refuge? The potential of urban climate shelters to address intersecting vulnerabilities. *Landsc. Urban Plan.*, 238 (2023), Article 104836, [10.1016/j.landurbplan.2023.104836](https://doi.org/10.1016/j.landurbplan.2023.104836)
- Antonova, M., & Critchley, M. (2023, December). Using carbon markets to break down barriers to ecosystem restoration in Europe. UNEP-WCMC. <https://www.unep-wcmc.org/en/news/using-carbon-markets-to-break-down-barriers-to-ecosystem-restoration-in-europe>
- Aparício, B. A., Pereira, J. M. C., Santos, F. C., Bruni, C., & Sá, A. C. L. (2022). Combining wildfire behaviour simulations and network analysis to support wildfire management: A Mediterranean landscape case study. *Ecological Indicators*, 137, 108726. <https://doi.org/10.1016/j.ecolind.2022.108726>
- Arifin, J., Aziz, A., & Akhter, S. (2025). Artificial intelligence and meteorological forecasting: A synthesis of precision and computational advancement. *Journal of Computational Science & Technology Studies*.
<https://doi.org/10.32996/jcsts>
- Atoba, K. O., Brody, S. D., Highfield, W. E., Shepard, C. C., & Verdone, L. N. (2021). Strategic property buyouts to enhance flood resilience: A multi-criteria spatial approach for incorporating ecological values into the selection process. *Environmental Hazards*, 20(3), 229–247.
<https://doi.org/10.1080/17477891.2020.1771251>
- Australian Prudential Regulation Authority (APRA). (2022). *Information Paper – Climate Vulnerability Assessment Results*. Canberra: APRA. Published November 2022
- Azhar, M., Kane, B., Vahedifard, F., & AghaKouchak, A. (2025). Comprehensive portfolio of adaptation measures to safeguard against evolving flood risks in a changing climate. *Communications Earth & Environment*, 6(1), 824. <https://doi.org/10.1038/s43247-025-02779-z>
- Baack, F., Halman, J., Vinke-de Kruijf, J., Özerol, G., & Kuks, S. (2024). Dutch municipalities tackling climate change adaptation to heat stress through mainstreaming across sectors. *Environmental Science & Policy*, 160, 103845. <https://doi.org/10.1016/j.envsci.2024.103845>
- Baccour, S., Tilmant, A., Albiac, J., Espanmanesh, V., & Kahil, T. (2025). Probabilistic trade-offs analysis for sustainable and equitable management of climate-induced water risks. *Water Resources Research*, 61(2), e2024WR038514. <https://doi.org/10.1029/2024WR038514>
- Bal, F., & Vleugel, J. M. (2014). Climate change adaptation: Use and value of a climate buffer area. *International Journal of Safety and Security Engineering*, 4(3), 193–206.
<https://doi.org/10.2495/SAFE-V4-N3-193-206>

- Balkovič, J., van der Velde, M., Schmid, E., Skalský, R., Khabarov, N., Obersteiner, M., Stürmer, B., & Xiong, W. (2014). Pan-European crop modelling with EPIC: Implementation, up-scaling and regional crop yield validation. *Agricultural Systems*, 120, 61–75. <https://doi.org/10.1016/j.agsy.2013.05.008>
- Bank of Canada. (2023). *Climate-related flood risk to residential lending portfolios in Canada* (Staff Discussion Paper 2023-33). Bank of Canada. <https://www.bankofcanada.ca/2023/12/staff-discussion-paper-2023-33/>
- Bank of England. (2021). *Key elements of the 2021 Biennial Exploratory Scenario: Financial risks from climate change*. <https://www.bankofengland.co.uk/stress-testing/2021/key-elements-2021-biennial-exploratory-scenario-financial-risks-climate-change>
- Bank Negara Malaysia. (2024). *Climate Risk Stress Testing (CRST) Exercise and Climate Risk Assessment Framework*. Bank Negara Malaysia. <https://www.bnm.gov.my/-/climate-risk-stress-testing>
- Banwell, N., Michel, S., & Senn, N. (2024). Greenspaces and Health: Scoping Review of studies in Europe. *Public health reviews*, 45, 1606863. <https://doi.org/10.3389/phrs.2024.1606863>
- Barnes, A. P., Soto, I., Eory, V., Beck, B., Balafoutis, A., Sánchez, B., Vangeyte, J., Fountas, S., van der Wal, T., & Gómez-Barbero, M. (2019). Exploring the adoption of precision agricultural technologies: A cross regional study of EU farmers. *Land Use Policy*, 80, 163–174. <https://doi.org/10.1016/j.landusepol.2018.10.004>
- Baró, F., Calderón-Argelich, A., Langemeyer, J & Connolly, J.J.T. (2019). Under one canopy? Assessing the distributional environmental justice implications of street tree benefits in Barcelona. *Environ. Sci. & Policy*, 102, pp. 54-64
- Battiston, S., Fragkiadakis, K., Hackstock, P., Mandel, A., Mazzocchi, A., Monasterolo, I., Naumann-Woleske, K., Paroussos, L., Ju, Y., van Ruijven, B., & Tsiaras, S. (2025). *NGFS Phase 5 Short Term Scenarios*. [10.5281/zenodo.15790097](https://doi.org/10.5281/zenodo.15790097).
- Bertassello, L. E., Van Der Velde, M., Maes, J., Liu, S., Brandt, M., & Feyen, L. (2026). Assessing European cities with the 3-30-300 rule underscores the need for enhanced urban greening efforts. *Nature Communications*, 17(1), 4846. <https://doi.org/10.1038/s41467-026-71523-8>
- Bertomeu, M., Pineda, J., & Pulido, F. (2022). Managing wildfire risk in mosaic landscapes: A case study of the Upper Gata River catchment in Sierra de Gata, Spain. *Land*, 11(4), 465. <https://doi.org/10.3390/land11040465>
- Birkmann, J., Schütttrumpf, H., Handmer, J., Thieken, A., Kuhlicke, C., Truedinger, A., Sauter, H., Klopries, E.-M., Greiving, S., Jamshed, A., Merz, B., Solecki, W., & Kirschbauer, L. (2023). *Strengthening resilience in reconstruction after extreme events: Insights from flood-affected communities in Germany*. *International Journal of Disaster Risk Reduction*, 96, 103965. <https://doi.org/10.1016/j.ijdrr.2023.103965>.
- Bognar, J., & Van Dijk, R. (2023, October 17). Wildfires in the EU: From response to resilience. Institute for European Environmental Policy. <https://ieep.eu/news/wildfires-in-the-eu-from-response-to-resilience/>
- Bottazzi, P., Wiik, E., Crespo, D., & Jones, J. P. G. (2018). Payment for environmental ‘self-service’: Exploring the links between farmers’ motivation and additionality in a conservation incentive programme in the Bolivian Andes. *Ecological Economics*, 150, 11–23. <https://doi.org/10.1016/j.ecolecon.2018.03.032>
- Botzen, W. J. W., Monteiro, É., Estrada, F., Pesaro, G., & Menoni, S. (2017). Economic Assessment of Mitigating Damage of Flood Events: Cost–Benefit Analysis of Flood-Proofing Commercial Buildings in Umbria, Italy. *The Geneva Papers on Risk and Insurance - Issues and Practice*, 42(4), 585–608. <https://doi.org/10.1057/s41288-017-0065-0>
- Bowman, D. M. J. S., Williamson, G. J., Abatzoglou, J. T., Kolden, C. A., Cochrane, M. A., & Smith, A. M. S. (2017). Human exposure and sensitivity to globally extreme wildfire events. *Nature Ecology & Evolution*, 1(3), 0058. <https://doi.org/10.1038/s41559-016-0058>
- Brady, M., Höjgård, S., Kaspersson, E., & Rabinowicz, E. (n.d.). European policy analysis: The CAP and future challenges. <https://www.agrifood.se/IDEMA>
- Bragg, M. A., Poudel, A., & Vasconcelos, J. G. (2025). Comparing SWMM and HEC-RAS hydrological modeling performance in semi-urbanized watershed. *Water*, 17(9), 1331. <https://doi.org/10.3390/w17091331>
- Broekx, S., Smets, S., Liekens, I., Bulckaen, D., & De Nocker, L. (2011). Designing a long-term flood risk management plan for the Scheldt estuary using a risk-based approach. *Natural Hazards*, 57(2), 245–266. <https://doi.org/10.1007/s11069-010-9610-x>
- Brouwer, R., & van Ek, R. (2004). Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands. *Ecological Economics*, 50(1–2), 1–21. <https://doi.org/10.1016/j.ecolecon.2004.01.020>
- Brunette, M., & Couture, S. (2023). Forest insurance for natural events: An overview by economists. *Forests*, 14(2), 289. <https://doi.org/10.3390/f14020289>

- Brunette, M., Couture, S., & Pannequin, F. (2017). Is forest insurance a relevant vector to induce adaptation efforts to climate change? *Annals of Forest Science*, 74(2). <https://doi.org/10.1007/s13595-017-0639-9>
- Burek, P., Satoh, Y., Kahil, T., Tang, T., Greve, P., Smilovic, M., Guillaumot, L., Zhao, F., & Wada, Y. (2020). Development of the Community Water Model (CWatM v1.04) – a high-resolution hydrological model for global and regional assessment of integrated water resources management. *Geoscientific Model Development*, 13, 3267–3298. <https://doi.org/10.5194/gmd-13-3267-2020>
- Byerly, H., et al. (2020). Developing behavioral and evidence-based programs for wildfire risk mitigation. *Fire*, 3(4), 1–9. <https://doi.org/10.3390/fire3040066>
- Caloia, F. G., van Ginkel, K. C., & Jansen, D. J. (2023). *Floods and financial stability: Scenario-based evidence from below sea level* (No. TI 2023-083/IV). Tinbergen Institute Discussion Paper.
- Camare, H. M., & Lane, D. E. (2015). Adaptation analysis for environmental change in coastal communities. *Socio-Economic Planning Sciences*, 51, 34–45. <https://doi.org/10.1016/j.seps.2015.06.003>
- Camerer, C. F., & Kunreuther, H. (1989). Decision Processes for Low Probability Events: Policy Implications. *Journal of Policy Analysis and Management*, 8(4), 565. <https://doi.org/10.2307/3325045>
- Casanueva, A., Burgstall, A., Kotlarski, S., Messeri, A., Morabito, M., Flouris, A. D., Nybo, L., Spirig, C., & Schwierz, C. (2019). Overview of Existing Heat-Health Warning Systems in Europe. *International Journal of Environmental Research and Public Health*, 16(15), 2657. <https://doi.org/10.3390/ijerph16152657>
- Cerema. (2015). *Adaptation of French standards for design, maintenance and operation of transport infrastructures* (National Adaptation Plan – Transport). European Climate Adaptation Platform (Climate-ADAPT). <https://climate-adapt.eea.europa.eu/en/metadata/case-studies/adaptation-of-french-standards-for-design-maintenance-and-operation-of-transport-infrastructure/nap-2015-transport.pdf>
- Chong, Z., Zhang, M., Wen, J., Wang, L., Mi, J., Bricker, J., Nmor, S., & Dai, Z. (2021). Coastal protection using building with nature concept: A case study from Chongming Dongtan Shoal, China. *Acta Oceanologica Sinica*, 40(10), 152–166. <https://doi.org/10.1007/s13131-021-1761-y>
- City of Barcelona (2025). Strategy to Combat the Heat: Heat Plan 2025-2035. <https://bcnroc.ajuntament.barcelona.cat/bitstreams/c65e81c2-f9f7-4762-addd-91deb9aaaa2d/download>
- City of Tucson (2024). Heat Action Roadmap. An action roadmap to prepare for extreme heat. https://heathealth.info/wp-content/uploads/ATTACHMENT_A_-_CITY_OF_TUCSON_HEAT_ACTION_ROADMAP-compressed.pdf
- City of Vienna (2022). Vienna Heat Action Plan For a cool Vienna. <https://www.digital.wienbibliothek.at/wbrup/content/pageview/5536206>
- Climate-ADAPT. (2016, June 7). CALCHAS – An integrated analysis system for the effective fire conservancy of forests. European Environment Agency. <https://climate-adapt.eea.europa.eu/en/metadata/case-studies/calchas-an-integrated-analysis-system-for-the-effective-fire-conservancy-of-forests>
- Cogos, S., Roturier, S., & Östlund, L. (2020). The origins of prescribed burning in Scandinavian forestry: The seminal role of Joel Wretling in the management of fire-dependent forests. *European Journal of Forest Research*, 139(3), 393–406. <https://doi.org/10.1007/s10342-019-01247-6>
- Cole, H; Lamarca, M; Connolly, J., & Anguelovski, I. (2017). Are green cities healthy and equitable? Unpacking the relationship between health, green space and gentrification. *Environ. Int.*, 158 (2017), Article 106959
- Corderi-Novoa, D., Hori, T., & Yamin, L. E. (2021). The economics of investment and prioritization of flood risk reduction measures in a watershed. *Risk Analysis*, 41(8), 1345–1361. <https://doi.org/10.1111/risa.13642>
- Crespo, D., Albiac, J., Dinar, A., Esteban, E., & Kahil, T. (2022). Integrating ecosystem benefits for sustainable water allocation in hydroeconomic modeling. *PLOS ONE*, 17(5), e0267439. <https://doi.org/10.1371/journal.pone.0267439>
- Cuchi, T., Bobrowski, R., Wężyk, P, Breunig, F.M. & Pesck, V.A. (2024). Contributions to a global understanding of socioenvironmental justice related to urban forest: trends from Brazilian cities in the southeastern Paraná State. *Urban For. & Urban Green.*, 95. Article 128322
- Daigneault, A., Brown, P., & Gawith, D. (2016). Dredging versus hedging: Comparing hard infrastructure to ecosystem-based adaptation to flooding. *Ecological Economics*, 122, 25–35. <https://doi.org/10.1016/j.ecolecon.2015.11.023>
- Dale, L., & Barrett, K. (2023). Missing the mark: Effectiveness and funding in community wildfire risk reduction. *Headwaters Economics*. https://headwaterseconomics.org/wp-content/uploads/HE_2023_Missing-the-Mark-Wildfire.pdf
- Damianidis, C., et al. (2021). Agroforestry as a sustainable land use option to reduce wildfires risk in European Mediterranean areas. *Agroforestry Systems*, 95(5), 919–929. <https://doi.org/10.1007/s10457-020-00482-w>

- Dandy, N. (2012). Understanding private land-manager decision-making: A framework for forestry. Forest Research. https://cdn.forestresearch.gov.uk/2012/02/understanding_land-manager_decision-making_dandy2012.pdf
- das Neves, L., Bolle, A., & De Nocker, L. (2023). Cost-benefit-analysis of coastal adaptation strategies and pathways. A case study in West Africa. *Ocean & Coastal Management*, 239, 106576. <https://doi.org/10.1016/j.ocecoaman.2023.106576>
- de Bandt, O., Kuntz, L. C., Pankratz, N., Pegoraro, F., Solheim, H., Sutton, G., ... & Xia, F. D. (2025). The effects of climate change-related risks on banks: A literature review. *Journal of Economic Surveys*, 39(4), 1553-1594. <https://doi.org/10.1111/joes.12665>
- Defra (2023a). The Third National Adaptation Programme (NAP3) and the Fourth Strategy for Climate Adaptation Reporting. Published by the Department for Environment, Food & Rural Affairs. Available at https://assets.publishing.service.gov.uk/media/64ba74102059dc00125d27a7/The_Third_National_Adaptation_Programme.pdf
- Defra (2023b) Environmental Land Management (ELM) update: how government will pay for land-based environment and climate goods and services. London: Department for Environment, Food and Rural Affairs.
- de Paula Netto, M. O., Coimbra, V. S., Lagarez Junior, M. L., Ferreira, A. A., & Barra Rocha, C. H. (2024). Comparative Analysis of SWAT and HEC-HMS Models for Efficient Watershed Management. *Revista de Gestão Social e Ambiental*, 18(11), e09931. <https://doi.org/10.24857/rgsa.v18n11-185>
- Depietri, Y., Renaud, F. G., & Kallis, G. (2012). Heat waves and floods in urban areas: A policy-oriented review of ecosystem services. *Sustainability Science* 7(1):95-107, <https://doi.org/10.1007/s11625-011-0142-4>
- Deutsche Bahn AG. (2023). *Adaptation to climate change*. In *Integrated report 2023*. <https://ibir.deutschebahn.com/2023/en/combined-management-report/green-transformation/climate-protection/adaptation-to-climate-change/>.
- Deutsche Bahn AG. (2024). *Adaptation to climate change*. In *Interim group management report 2024 (unaudited)*. <https://zbir.deutschebahn.com/2024/en/interim-group-management-report-unaudited/green-transformation/climate-protection/>.
- Dittrich, R., Ball, T., Wreford, A., Moran, D., & Spray, C. J. (2019). A cost-benefit analysis of afforestation as a climate change adaptation measure to reduce flood risk. *Journal of Flood Risk Management*, 12(4), e12482. <https://doi.org/10.1111/jfr3.12482>
- Dobbs, T. L., & Pretty, J. (2008). Case study of agri-environmental payments: The United Kingdom. *Ecological Economics*, 65(4), 765–775. <https://doi.org/10.1016/j.ecolecon.2007.07.030>
- Dottori, F., Mentaschi, L., Bianchi, A., Alfieri, L., Feyen, L. (2020). *Adapting to rising river flood risk in the EU under climate change*. EUR 29955 EN. Publications Office of the European Union, Luxembourg. <https://doi.org/10.2760/14505>
- EASAC. (2025). Changing wildfires: Policy options for a fire-literate and fire-adapted Europe (EASAC Policy Report 48). https://doi.org/10.1553/EASAC_Report_Changing-Wildfires_2025
- European Banking Authority. (2023). *2023 EU-wide stress test: Results*. European Banking Authority
- European Central Bank (2022). *ECB economy-wide climate stress test*.
- European Central Bank. (2023, May 12). *Climate risks: The macroprudential view*. ECB Blog. <https://www.ecb.europa.eu/press/blog/date/2023/html/ecb.blog231212~368bddd2b.en.html>
- European Central Bank. (2025). *Integrating climate risk into the 2025 EU-wide stress test: the effects of climate risks for firms*. ECB Macropudential Bulletin.
- European Central Bank (ECB), & European Insurance and Occupational Pensions Authority (EIOPA). (2024). *Towards a European system for natural catastrophe risk management: The possible role of European solutions in reducing the impact of natural catastrophes stemming from climate change*.
- European Central Bank (ECB), & European Systemic Risk Board (ESRB). (2022). *The macroprudential challenge of climate change*
- European Commission. (2014). Guide to cost-benefit analysis of investment projects. Economic appraisal tool for cohesion policy 2014–2020. <https://dx.doi.org/10.2776/97516>
- European Commission. (2021). Economic appraisal vademecum 2021–2027; General principles and sector applications. <https://dx.doi.org/10.2776/182302>
- European Commission (2021). Structured approaches for forest fire emergencies in resilient societies. CORDIS – EU Research Results. <https://doi.org/10.3030/869353>
- European Commission. (2025). Impact assessments. https://commission.europa.eu/law/law-making-process/planning-and-proposing-law/impact-assessments_en
- European Commission. (2026). Directorate-General for Climate Action, Monteleone, L., Roberti, G., Fossati, F., Davies, W. et al., Assessment of EU and Member States adaptation investment needs – Study on the

- macro-economic impacts of the climate transition, 2026, <https://data.europa.eu/doi/10.2834/2895769>. Available at <https://op.europa.eu/en/publication-detail/-/publication/d2039eac-f742-11f0-b9bc-01aa75ed71a1/language-en>
- European Council (2024). Council Recommendation of 21 October 2024 on economic, budgetary, employment and structural policies of Cyprus. https://eur-lex.europa.eu/legal-content/En/TXT/PDF/?uri=OJ:C_202406820&qid=1736517110096
- EIB (2022). *Joint methodology for tracking climate change adaptation finance*. EIB. Available at: https://www.eib.org/attachments/lucalli/20220242_mdbs_joint_methodology_climate_finance_en.pdf
- European Environment Agency (EEA). (2017). Relocation as adaptation to flooding in the Eferdinger Becken, Austria. Climate-ADAPT. <https://climate-adapt.eea.europa.eu/en/metadata/case-studies/relocation-as-adaptation-to-flooding-in-the-eferdinger-becken-austria>
- European Environment Agency (EEA). (2019). Climate change adaptation in the agriculture sector in Europe (EEA Report No. 04/2019). Publications Office of the European Union. <https://doi.org/10.2800/537176>
- European Environment Agency (EEA). (2020). *Urban adaptation in Europe: How cities and towns respond to climate change*.
- European Environment Agency (EEA). (2021). *Who benefits from nature in cities?: Social inequalities in access to urban green and blue spaces across Europe*. Publications Office. <https://doi.org/10.2800/041176>
- European Environment Agency (EEA). (2022). *Cooling buildings sustainably in Europe: Exploring the links between climate change mitigation and adaptation, and their social impacts*. Publications Office. <https://doi.org/10.2800/36810>
- European Environment Agency (EEA). (2024). The impacts of heat on health: surveillance and preparedness in Europe.
- European Environment Agency (EEA). (2025). Europe's environment and climate: Knowledge for resilience, prosperity and sustainability (EEA Report 11/2025). <https://doi.org/10.2800/3817344>
- European Parliament and Council of the European Union. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities, L 327, 1–73.
- European Parliament and Council of the European Union. (2021). Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021 establishing rules on support for strategic plans to be drawn up by Member States under the Common Agricultural Policy (CAP Strategic Plans). Official Journal of the European Union, L 435, 1–186.
- European Parliament and Council of the European Union. (2024). Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869. Official Journal of the European Union, L 2024/1991, 29 July 2024.
- Elia, M., Lovreglio, R., Ranieri, N., Sanesi, G., & Laforteza, R. (2016). Cost-effectiveness of fuel removals in Mediterranean wildland-urban interfaces threatened by wildfires. *Forests*, 7(7), 149. <https://doi.org/10.3390/f7070149>
- Endendijk, T., van Ederen, D., de Moel, H., van Ginkel, K., Aerts, J. C. J. H., & Botzen, W. W. (2024). *Physical climate risk assessment framework for real estate investments and mortgages* Available at <https://ssrn.com/abstract=4902445>
- ENW (2023). Verzekeren van overstromingen vanuit het primaire systeem aantrekkelijk? . Bijlage bij ENW-advies 23-06. ENW Expertise Netwerk Waterveiligheid. 13 juli 2023.
- Essenfelder, A. H., Bagli, S., Mysiak, J., Pal, J. S., Mercogliano, P., Reder, A., Rianna, G., Mazzoli, P., Broccoli, D., & Luzzi, V. (2022). Probabilistic Assessment of Pluvial Flood Risk Across 20 European Cities: A Demonstrator of the Copernicus Disaster Risk Reduction Service for Pluvial Flood Risk in Urban Areas. *Water Economics and Policy*, 08(03), 2240007. <https://doi.org/10.1142/S2382624X22400070>
- Facing Fire. (n.d.). Service-Learning to improve wildfire management in Southern Europe. Facing Fire. <https://facingfire.eu/>
- Farahmand, H., Yin, K., Hsu, C.-W., Savadogo, I., Espinet Alegre, X., & Mostafavi, A. (2024). Integrating climate projections and probabilistic network analysis into regional transport resilience planning. *Transportation Research Part D: Transport and Environment*, 133, 104229. <https://doi.org/10.1016/j.trd.2024.104229>
- Federal state of Bremen (2024). Heat Action Plan Bremen. Bremerhaven. <https://hitzeportal.bremen.de/sixcms/media.php/13/Hitzeaktionsplan.pdf>
- Fernandes, P., & Botelho, H. (2004). Analysis of the prescribed burning practice in the pine forest of northwestern Portugal. *Journal of Environmental Management*, 70(1), 15–26. <https://doi.org/10.1016/j.jenvman.2003.10.001>
- Fernandez-Anez, N., et al. (2021). Current wildland fire patterns and challenges in Europe: A synthesis of national perspectives. *SAGE Open*, 11, 1–15. <https://doi.org/10.1177/11786221211028185>

- Fernández-García, V., Beltrán-Marcos, D., Fernández-Guisuraga, J. M., Marcos, E., & Calvo, L. (2022). Predicting potential wildfire severity across Southern Europe with global data sources. *Science of the Total Environment*, 829, 154729. <https://doi.org/10.1016/j.scitotenv.2022.154729>
- Filippi, J.-B., Bosseur, F., Mari, C., & Lac, C. (2018). Simulation of a Large Wildfire in a Coupled Fire-Atmosphere Model. *Atmosphere*, 9(6), 218. <https://doi.org/10.3390/atmos9060218>
- Finney, M. A. (2002). Fire growth using minimum travel time methods. *Canadian Journal of Forest Research*, 32(8), 1420–1424. <https://doi.org/10.1139/x02-068>
- Finney, M. A., & Andrews, P. L. (1999). FARSITE: A program for fire growth simulation. <http://fire.org>
- Finney, M. A., Seli, R. C., McHugh, C. W., Ager, A. A., Bahro, B., & Agee, J. K. (2007). Simulation of long-term landscape-level fuel treatment effects on large wildfires. <https://www.publish.csiro.au/journals/ijwf>
- FIRE-RES. (n.d.). Living labs. <https://fire-res.eu/living-labs/>
- FirEURisk Project. (n.d.). FirEURisk: Dissecting risk to prevent extreme wildfires. FirEURisk Project. <https://fireurisk.eu/>
- Fleming, M., & Brauer, T. (2016). HEC-HMS Quick Start Guide, Version 4.2 (No. CPD-74D). U.S. Army Corps of Engineers.
- Floreac, D. V., Chalak, D. M., & Hailu, A. (2017). Integrating intangible values in economic analyses of flood mitigation: A case study of the Brown Hill and Keswick creeks catchment in Adelaide. *The Australian Journal of Emergency Management*, 32(4), 30–36.
- Financial Services Agency (FSA) & Bank of Japan (BoJ) (2022). Pilot Scenario Analysis Exercise on Climate-Related Risks Based on Common Scenarios. fsa.go.jp/en/news/2022/20220826/03.pdf
- Financial Stability Board (FSB). (2025). *Assessment of climate-related vulnerabilities: Analytical framework and toolkit*.
- Freedman, B., Stinson, G., & Lacoul, P. (2009). Carbon credits and the conservation of natural areas. *Environmental Reviews*, 17, 1–19. <https://doi.org/10.1139/A08-007>
- French, K., & Kousky, C. (2023). The effect of disaster insurance on community resilience: A research agenda for local policy. *Climate Policy*, 23(5), 662–670. <https://doi.org/10.1080/14693062.2023.2170313>
- Fridman, D., Biran, N., & Kissinger, M. (2021). Beyond blue: An extended framework of blue water footprint accounting. *Science of the Total Environment*, 777, 146010. <https://doi.org/10.1016/j.scitotenv.2021.146010>
- Frontier Economics (2021). Barriers to financing adaptation actions in the UK. Report by Frontier Economics & Paul Watkiss Associates to the Climate Change Committee. Available at <https://www.theccc.org.uk/publication/barriers-to-financing-adaptation-actions-in-the-uk-frontier-economics-paul-watkiss-associates/>
- Gallo, E., Quijal-Zamorano, M., Méndez Turrubiates, R.F. et al. (2024). Heat-related mortality in Europe during 2023 and the role of adaptation in protecting health. *Nat Med* 30, 3101–3105. <https://doi.org/10.1038/s41591-024-03186-1>
- Galluccio, G., Hinkel, J., Fiorini Beckhauser, E., Bisaro, A., Biancardi Aleu, R., Campostrini, P., Casas, M. F., Espin, O., & Vafeidis, A. T.: Sea Level Rise in Europe: Adaptation measures and decision-making principles, in: Sea Level Rise in Europe: 1st Assessment Report of the Knowledge Hub on Sea Level Rise (SLRE1), edited by: van den Hurk, B., Pinardi, N., Kiefer, T., Larkin, K., Manderscheid, P., and Richter, K., Copernicus Publications, State Planet, 3-slre1, 6, <https://doi.org/10.5194/sp-3-slre1-6-2024>, 2024.
- Ganin, A. A., Kitsak, M., Marchese, D., Keisler, J. M., Seager, T., & Linkov, I. (2017). Resilience and efficiency in transportation networks. *Science Advances*, 3(12), e1701079. <https://doi.org/10.1126/sciadv.1701079>
- Geffert, K., Voss, S., Rehfuess, E., & Rechel, B. (2024). The role of the public health service in the implementation of heat health action plans for climate change adaptation in Germany: A qualitative study. *Health Research Policy and Systems*, 22(1), 161. <https://doi.org/10.1186/s12961-024-01231-6>
- Gibbs, M. T. (2015). Pitfalls in developing coastal climate adaptation responses. *Climate Risk Management*, 8, 1–8. <https://doi.org/10.1016/j.crm.2015.05.001>
- Gibson, M. J., Savic, D. A., Djordjevic, S., Chen, A. S., Fraser, S., & Watson, T. (2016). Accuracy and computational efficiency of 2D urban surface flood modelling based on cellular automata. *Procedia Engineering*, 154, 801–810. <https://doi.org/10.1016/j.proeng.2016.07.409>
- van Ginkel, K., Endendijk, T., van Veggel, W., & Schasfoort, F. (2024). *Kansen en gevaren van klimaatinformatie op huisniveau*. Deltares.
- van Ginkel, K. C. H., Rijken, B., Hoogvliet, M., van Veggel, W., Botzen, W. J. W., & Filatova, T. (2025). How an economic and financial perspective could guide transformational adaptation to sea level rise. *npj Climate Action*, 4(1), 89. <https://doi.org/10.1038/s44168-025-00297-4>

- Godschalk, D. R., Rose, A., Mittler, E., Porter, K., & West, C. T. (2009). Estimating the value of foresight: Aggregate analysis of natural hazard mitigation benefits and costs. *Journal of Environmental Planning and Management*, 52(6), 739–756. <https://doi.org/10.1080/09640560903083715>
- Gokcekus, H., Kassem, Y., & Alijl, N. (2024). Enhancing Co-Benefits and reducing Flood Risks through Nature-based Solutions and Assessments: A Case Study in the Dead Sea Region of Jordan. *Engineering, Technology & Applied Science Research*, 14(5), 16450–16459. <https://doi.org/10.48084/etasr.7944>
- Gonçalves, A. M., Brandão, T., & Ferreira, J. C. (2023). Wildfire detection with deep learning: A case study for the CICLOPE Project. IEEE Access. <https://doi.org/10.1109/ACCESS.2023.0322000>
- Goniewicz, K., Burkle, F. M., & Khorram-Manesh, A. (2025). Transforming global public health: Climate collaboration, political challenges, and systemic change. *Journal of Infection and Public Health*, 18(1), 102615. <https://doi.org/10.1016/j.jiph.2024.102615>
- Grafton, R. Q., Williams, J., Perry, C. J., Molle, F., Ringler, C., Steduto, P., Udall, B., Wheeler, S. A., Wang, Y., Garrick, D., & Allen, R. G. (2018). The paradox of irrigation efficiency. *Science*, 361(6404), 748–750. <https://doi.org/10.1126/science.aat9314>
- Gribble, M., Aamodt, E., Skilbred, E. S., & Mikalsen, R. F. (2025). WUI guideline for Norway: Veileder for å beskytte bebyggelse mot skogbrann i Norge (RISE Report 2025:23). RISE Fire Research, RISE Research Institutes of Sweden AB. <https://risefr.no/media/publikasjoner/upload/2025/rise-report-2025-23-wui-guideline-norway-treecads.pdf>
- Groen, L., Alexander, M., King, J. P., Jager, N. W., & Huitema, D. (2023). Re-examining policy stability in climate adaptation through a lock-in perspective. *Journal of European Public Policy*, 30(3), 488–512. <https://doi.org/10.1080/13501763.2022.2064535>
- Gupta, A., De, B., Das, S., & Mukherjee, M. (2025). Thermal hazards in urban spaces: A review of climate-resilient planning and design to reduce the heat stress. *Urban Climate*, 59, 102296. <https://doi.org/10.1016/j.uclim.2025.102296>
- Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, 23(2), 485–498. <https://doi.org/10.1016/j.gloenvcha.2012.12.006>
- Haer, T., Botzen, W. J. W., van, V., Connor, H., Zavala-Hidalgo, J., Eilander, D. M., & Ward, P. J. (2018). Coastal and river flood risk analyses for guiding economically optimal flood adaptation policies: A country-scale study for Mexico. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, A376(20170329), 1–17. <https://doi.org/10.1098/rsta.2017.0329>
- Haer, T., Botzen, W. J. W., Zavala-Hidalgo, J., Cusell, C., & J. Ward, P. (2017). Economic evaluation of climate risk adaptation strategies: Cost-benefit analysis of flood protection in Tabasco, Mexico. *Atmósfera*, 30(2), 101–120. <https://doi.org/10.20937/ATM.2017.30.02.03>
- Havlík, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M. C., Mosnier, A., Thornton, P. K., Böttcher, H., Conant, R. T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., & Notenbaert, A. (2014). Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences*, 111(10), 3709–3714.
- Hayes, B. D. (2004). Interdisciplinary planning of nonstructural flood hazard mitigation. *Journal of Water Resources Planning and Management*, 130(1), 15–25. [https://doi.org/10.1061/\(ASCE\)0733-9496\(2004\)130:1\(15\)](https://doi.org/10.1061/(ASCE)0733-9496(2004)130:1(15))
- Hengst-Ehrhart, Y. (2019). Knowing is not enough: Exploring the missing link between climate change knowledge and action of German forest owners and managers. *Annals of Forest Science*, 76(4). <https://doi.org/10.1007/s13595-019-0878-z>
- HMG (2022). *UK Climate Change Risk Assessment 2022*. HMG, London. Available at: <https://assets.publishing.service.gov.uk/media/61e54d8f8fa8f505985ef3c7/climate-change-risk-assessment-2022.pdf>
- HMT (2022). *Green Book. The Green Book: appraisal and evaluation in central government*. HMT, London. Available at: <https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-government/the-green-book-2020>
- HMT (2024). *Business case guidance for projects and programmes*. <https://www.gov.uk/government/publications/business-case-guidance-for-projects-and-programmes>
- HMT (2025). *Accounting for the effects of climate change Supplementary Green Book guidance*. Available at: https://assets.publishing.service.gov.uk/media/6830434ce9440506ee953a33/Accounting_for_the_effects_of_climate_change_Green_Book_supplementary_guidance.pdf
- Hochrainer-Stigler, S., van der Velde, M., Fritz, S., & Pflug, G. (2014). Remote sensing data for managing climate risks: Index-based insurance and growth-related applications for smallholder farmers in Ethiopia. *Climate Risk Management*, 6, 27–38. <https://doi.org/10.1016/j.crm.2014.09.002>

- Holscher, L. et al (2025). Ausgaben des Bundes für die Anpassung an den Klimawandel Entwicklung und Pilotierung einer Analysemethodik. https://www.infras.ch/media/filer_public/78/a8/78a8f645-d853-44b6-9c7c-b213666bf043/3514a-klimaanpassung-ausgaben-deutschland.pdf
- Houghton, A., & Castillo-Salgado, C. (2019). Associations between Green Building Design Strategies and Community Health Resilience to Extreme Heat Events: A Systematic Review of the Evidence. *International Journal of Environmental Research and Public Health*, 16(4), 663. <https://doi.org/10.3390/ijerph16040663>
- Huber, K. (2018). Resilience strategies for wildfire. Center for Climate and Energy Solutions. <https://www.c2es.org/wp-content/uploads/2018/11/resilience-strategies-for-wildfire.pdf>
- Hudson, P., Botzen, W. W., & Aerts, J. C. (2019). Flood insurance arrangements in the European Union for future flood risk under climate and socioeconomic change. *Global environmental change*, 58, 101966.
- Hudson, P., Raška, P., Macháč, J., & Slavíková, L. (2022). Balancing the interaction between urban regeneration and flood risk management – a cost benefit approach in Ústí nad Labem. *Land Use Policy*, 120, 106276. <https://doi.org/10.1016/j.landusepol.2022.106276>
- Hunter, M. E., & Taylor, M. H. (2022). The economic value of fuel treatments: A review of the recent literature for fuel treatment planning. *Forests*, 13(12), 2042. <https://doi.org/10.3390/f13122042>
- ICARUS. (2023). D2.2: *Guidelines on using performance metrics to make the case for adaptation* (Deliverable No. D2.2). ICARUS – Improving Climate Resilience of Road Infrastructure. <https://icarus.project.cedr.eu/wp-content/uploads/2023/09/D2.2-ICARUS-Guidelines-on-using-performance-metrics-to-make-the-case-for-adaptation.pdf>
- I4CE (2024). Anticipating the impacts of a 4°C warming: what is the cost of adaptation? https://www.i4ce.org/wp-content/uploads/2024/09/Anticipating-impacts-4-degrees-warming-cost-of-adaptation_Sept2024.pdf
- IEA (2026), Share of households equipped with air conditioner by region, 2015-2025, IEA, Paris. <https://www.iea.org/data-and-statistics/charts/share-of-households-equipped-with-air-conditioner-by-region-2015-2025>, Licence: CC BY 4.0
- International Monetary Fund (2024). Monetary and Capital Markets Department "Kingdom of the Netherlands-The Netherlands: Financial Sector Assessment Program- Technical Note on Climate Risk Analysis", *IMF Staff Country Reports* 2024, 169, accessed October 6, 2025, <https://doi.org/10.5089/9798400279690.002>
- International Monetary Fund. (2025). Monetary and Capital Markets Department. Canada: Financial Sector Assessment Program-Technical Note on Climate Risks Analysis. *IMF Staff Country Reports*, 2025(234), Article A001, A001. Retrieved May 4, 2026, from <https://doi.org/10.5089/9798229021920.002.A001>
- IPCC. (2001). *Climate change 2001: Impacts, adaptation, and vulnerability* (Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Annex B Glossary of Terms). Cambridge University Press. <https://archive.ipcc.ch/ipccreports/tar/wg2/index.php?idp=689>
- IPCC. (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.
- Jactel, H., et al. (2017). Tree diversity drives forest stand resistance to natural disturbances. *Current Forestry Reports*. <https://doi.org/10.1007/s40725-017-0064-1>
- Jandl, R., Spathelf, P., Bolte, A., & Prescott, C. E. (2019). Forest adaptation to climate change—is non-management an option? *Annals of Forest Science*, 76(2). <https://doi.org/10.1007/s13595-019-0827-x>
- Jiffry, A. F., & Al-Mohannadi, D. M. (2024). Developing a systematic framework to assess climate change impacts on Qatar's power systems: A transition of adaptation and mitigation. *Chemical Engineering Transactions*, 114, 289–294. <https://doi.org/10.3303/CET24114049>
- Johnson, L. E., Cifelli, R., & White, A. (2020). Benefits of an advanced quantitative precipitation information system. *Journal of Flood Risk Management*, 13(S1), e12573. <https://doi.org/10.1111/jfr3.12573>
- Jug, D., Jug, I., Brozović, B., Šeremešić, S., Dolijanović, Ž., Zsembeli, J., Ujj, A., Marjanovic, J., Smutny, V., Dušková, S., Neudert, L., Macák, M., Wilczewski, E., & Đurđević, B. (2025). Conservation soil tillage: Bridging science and farmer expectations—An overview from Southern to Northern Europe. *Agriculture*, 15(3), 260. <https://doi.org/10.3390/agriculture15030260>
- Kahil, T., Baccour, S., Joseph, J., Sahu, R. K., Burek, P., Ng, J., Asad, S., Fridman, D., Albiac, J., Ward, F. A., & Wada, Y. (2025). Development of the global hydro-economic model (ECHO-Global version 1.0) for assessing the performance of water management options. *Geoscientific Model Development*, 18, 7987–8015. <https://doi.org/10.5194/gmd-18-7987-2025>
- Kalabokidis, K., Palaiologou, P., & Finney, M. (2013). Fire behavior simulation in Mediterranean forests using the minimum travel time algorithm. http://www.firemodels.org/downloads/flammapp/5.0/ReleaseNotes_FMP5.pdf

- Kalfin, Sukono, Supian, S., & Mamat, M. (2022). Insurance as an Alternative for Sustainable Economic Recovery after Natural Disasters: A Systematic Literature Review. *Sustainability*, 14(7), 4349. <https://doi.org/10.3390/su14074349>
- Käyhkö, J., Malmström (Nee Jurgilevich), A., Räsänen, A., Pörsti, S., & Juhola, S. (2024). Policy impact pathways of climate-related urban health vulnerability – A retrospective analysis. *Health & Place*, 88, 103266. <https://doi.org/10.1016/j.healthplace.2024.103266>
- Kates, R. W., Travis, W. R., & Wilbanks, T. J. (2012). Transformational adaptation when incremental adaptations to climate change are insufficient. *Proceedings of the National Academy of Sciences of the United States of America*, 109(19), 7156–7161. <https://doi.org/10.1073/pnas.1115521109>
- Keenan, N. J., & Oldfield, S. G. (2012). The Urban Impacts Toolbox: An initial assessment of climate change flood adaptation options for Westport. *Weather and Climate*, 32(2), 40–61. <https://doi.org/10.2307/26169732>
- Kirschner, J. A., Ascoli, D., Moore, P., Clark, J., Calvani, S., & Boustras, G. (2024). Governance drivers hinder and support a paradigm shift in wildfire risk management in Italy. *Regional Environmental Change*, 24(1), 1–16. <https://doi.org/10.1007/s10113-023-02174-4>
- Kjellstrom, T., & McMichael, A. J. (2013). Climate change threats to population health and well-being: the imperative of protective solutions that will last. *Global Health Action*, 6(1). <https://doi.org/10.3402/gha.v6i0.20816>
- Klinsky, S., Roberts, T., Huq, S., Okereke, C., Newell, P., Dauvergne, P., O'Brien, K., Schroeder, H., Tschakert, P., Clapp, J., 2017. Why equity is fundamental in climate change policy research. *Glob. Environ. Change* 44, 170–173.
- Knittel, N., Tesselaar, M., Wouter Botzen, W. J., Bachner, G., & Tiggeloven, T. (2023). Who bears the indirect costs of flood risk? An economy-wide assessment of different insurance systems in Europe under climate change. *Economic Systems Research*, 1–30. <https://doi.org/10.1080/09535314.2023.2272211>
- Korfmacher, M., Hartwell, C., Hill, K., Matthews-Trigg, N., Hess, J., Nori-Sarma, A., Wellenius, G., & Errett, N. (2025). Lessons learnt from the 2021 Pacific Northwest heat dome: A qualitative study of western Washington's healthcare community response. *BMJ Open*, 15(4), e089093. <https://doi.org/10.1136/bmjopen-2024-089093>
- Kotsila P and Anguelovski I. (2023). Justice should be at the centre of assessments of climate change impacts on health. *The Lancet Public Health*, 8, e11–e12
- Kousky, C., Olmstead, S. M., Walls, M. A., & Macauley, M. (2013). Strategically placing green infrastructure: Cost-effective land conservation in the floodplain. *Environmental Science & Technology*, 47(8), 3563–3570. <https://doi.org/10.1021/es303938c>
- Kousky, C., & Walls, M. (2014). Floodplain conservation as a flood mitigation strategy: Examining costs and benefits. *Ecological Economics*, 104, 119–128. <https://doi.org/10.1016/j.ecolecon.2014.05.001>
- Kull, D., Mechler, R., & Hochrainer-Stigler, S. (2013). Probabilistic cost-benefit analysis of disaster risk management in a development context. *Disasters*, 37(3), 374–400. <https://doi.org/10.1111/disa.12002>
- Kunreuther, H. (2008). Reducing Losses from Catastrophic Risks through Long-Term Insurance and Mitigation. *Social Research: An International Quarterly*, 75(3), 905–930. <https://doi.org/10.1353/sor.2008.0009>
- Lai, X., Wen, J., Shan, X., Shen, L., Wan, C., Shao, L., Wu, Y., Chen, B., & Li, W. (2023). Cost-benefit analysis of local knowledge-based flood adaptation measures: A case study of Datian community in Zhejiang Province, China. *International Journal of Disaster Risk Reduction*, 87, 103573. <https://doi.org/10.1016/j.ijdrr.2023.103573>
- Lasage, R., Veldkamp, T. I. E., de Moel, H., Van, T. C., Phi, H. L., Vellinga, P., & Aerts, J. C. J. H. (2014). Assessment of the effectiveness of flood adaptation strategies for HCMC. *Natural Hazards and Earth System Sciences*, 14(6), 1441–1457. <https://doi.org/10.5194/nhess-14-1441-2014>
- Lasanta, T., Khorchani, M., Pérez-Cabello, F., Errea, P., Sáenz-Blanco, R., & Nadal-Romero, E. (2018). Clearing shrubland and extensive livestock farming: Active prevention to control wildfires in the Mediterranean mountains. *Journal of Environmental Management*, 227, 256–266. <https://doi.org/10.1016/j.jenvman.2018.08.104>
- Lepore, C., Mok, J. (2024). *Beyond the dikes: flood scenarios for financial stability risk analysis*. International Monetary Fund. Working Paper No. 2024/197. <https://doi.org/10.5089/9798400289545.001>
- Lidestav, G., & Westin, K. (2023). The impact of Swedish forest owners' values and objectives on management practices and forest policy accomplishment. *Small-scale Forestry*, 22(3), 435–456. <https://doi.org/10.1007/s11842-022-09538-4>
- Liu, J., Li, Z., Shao, W., Yan, D., & Mei, C. (2020). Urban flood modelling in Qiqihar city based on MIKE flood. *Proceedings of the International Association of Hydrological Sciences*, 383, 185–192. <https://doi.org/10.5194/piahs-383-185-2020>

- Locatelli, L., Guerrero, M., Russo, B., Martínez-Gomariz, E., Sunyer, D., & Martínez, M. (2020). Socio-economic assessment of green infrastructure for climate change adaptation in the context of urban drainage planning. *Sustainability*, 12(9), 3792. <https://doi.org/10.3390/su12093792>
- Lockwood, J. W., Oppenheimer, M., Lin, N., & Gourevitch, J. (2024). Socioeconomic distributional impacts of evaluating flood mitigation activities using equity-weighted benefit-cost analysis. *Environmental Research Letters*, 19(7), 074024. <https://doi.org/10.1088/1748-9326/ad4ef8>
- Lyra, A.M.G.C., Bressane, A., Silva, M.B. et al. (2026). Urban heatscapes and environmental injustice: Structural drivers and governance pathways for equitable climate adaptation – A scoping review. *Environmental Science & Policy* 180 (June): 104399. <https://doi.org/10.1016/j.envsci.2026.104399>.
- Ma, C., Van Coile, R., & Gernay, T. (2024). Fire protection costs in composite buildings for cost-benefit analysis of fire designs. *Journal of Constructional Steel Research*, 215, 108517. <https://doi.org/10.1016/j.jcsr.2024.108517>
- Macassa, G., Ribeiro, A. I., Marttila, A., Stål, F., Silva, J. P., Rydback, M., Rashid, M., & Barros, H. (2022). Public Health Aspects of Climate Change Adaptation in Three Cities: A Qualitative Study. *International Journal of Environmental Research and Public Health*, 19(16), 10292. <https://doi.org/10.3390/ijerph191610292>
- Mallen, E., Joseph, H. A., McLaughlin, M., English, D. Q., Olmedo, C., Roach, M., Tirdea, C., Vargo, J., Wolff, M., & York, E. (2022). Overcoming Barriers to Successful Climate and Health Adaptation Practice: Notes from the Field. *International Journal of Environmental Research and Public Health*, 19(12), 7169. <https://doi.org/10.3390/ijerph19127169>
- Mancilla-Leytón, J. M., Hernando, C., Cambrollé, J., Muñoz-Vallés, S., Pino-Mejías, R., & Vicente, Á. M. (2021). Can shrub flammability be affected by goat grazing? Flammability parameters of Mediterranean shrub species under grazing. *Sustainability*, 13(3), 1555. <https://doi.org/10.3390/su13031555>
- Mancilla-Leytón, J. M., & Martín Vicente, A. (2012). Un método natural para la prevención de incendio: Evaluación del efecto del pastoreo sobre el biocombustible acumulado. *Forests Systems*, 21(2), 199–204. <https://doi.org/10.5424/fs/2012212-02289>
- Manville, M., Lens, M., & Monkkonen, P. (2019). Zoning and affordability: A reply to Storper and Rodríguez-Pose. <http://econ.geo.uu.nl/peeg/peeg1914.pdf>
- Marino, E., Hernando, C., Planelles, R., Madrigal, J., Guijarro, M., & Sebastián, A. (2014). Forest fuel management for wildfire prevention in Spain: A quantitative SWOT analysis. *International Journal of Wildland Fire*, 23(3), 373–384. <https://doi.org/10.1071/WF12203>
- Markanday, A., Markandya, A., De Murieta, E. S., & Galarraga, I. (2021). Accounting for the effects of employment, equity, and risk aversion in cost-benefit analysis: An application to an adaptation project. *Journal of Benefit-Cost Analysis*, 12(2), 313–334. <https://doi.org/10.1017/bca.2020.32>
- Markolf, S. A., Helmrich, A., Kim, Y., Hoff, R., & Chester, M. (2022). Balancing efficiency and resilience objectives in pursuit of sustainable infrastructure transformations. *Current Opinion in Environmental Sustainability*, 56, 101181. <https://doi.org/10.1016/j.cosust.2022.101181>.
- Martinez, G. S., Kendrovski, V., Salazar, M. A., de'Donato, F., & Boeckmann, M. (2022). Heat-health action planning in the WHO European Region: Status and policy implications. *Environmental Research*, 214, 113709. <https://doi.org/10.1016/j.envres.2022.113709>
- Martinez, G. S., Linares, C., Ayuso, A., Kendrovski, V., Boeckmann, M., & Diaz, J. (2019). Heat-health action plans in Europe: Challenges ahead and how to tackle them. *Environmental Research*, 176, 108548. <https://doi.org/10.1016/j.envres.2019.108548>
- Mayrhuber, E. A.-S., Dückers, M. L. A., Wallner, P., Arnberger, A., Alex, B., Wiesböck, L., Wanka, A., Kolland, F., Eder, R., Hutter, H.-P., & Kutalek, R. (2018). Vulnerability to heatwaves and implications for public health interventions – A scoping review. *Environmental Research*, 166, 42–54. <https://doi.org/10.1016/j.envres.2018.05.021>
- McConnell, K., & Koslov, L. (2024). Critically assessing the idea of wildfire managed retreat. *Environmental Research Letters*. <https://doi.org/10.1088/1748-9326/ad31d9>
- Meldrum, J. R., et al. (2024). Rethinking cost-share programs in consideration of economic equity: A case study of wildfire risk mitigation assistance for private landowners. *Ecological Economics*, 216, 108041. <https://doi.org/10.1016/j.ecolecon.2023.108041>
- Milad, M., Schaich, H., & Konold, W. (2013). How is adaptation to climate change reflected in current practice of forest management and conservation? A case study from Germany. *Biodiversity and Conservation*, 22(5), 1181–1202. <https://doi.org/10.1007/s10531-012-0337-8>
- MIRACA Consortium. (2023a). *Review of adaptation options for critical infrastructure (CI) reducing hazard intensity* (Deliverable D4.1). <https://miraca-project.eu/wp-content/uploads/2023/04/D4.1-MIRACA.pdf>.
- MIRACA Consortium. (2023b). *D4.2: Building system-of-systems methodologies for multi-hazard infrastructure risk assessment* (Deliverable No. D4.2). Horizon Europe Project MIRACA – Multi-hazard Infrastructure

- Risk Assessment for Climate Adaptation. https://miraca-project.eu/wp-content/uploads/2023/04/D4_2_MIRACA_nosig.pdf
- Moraes, R. P., Reguero, B. G., Mazarrasa, I., Ricker, M., & Juanes, J. A. (2022). Nature-based solutions in coastal and estuarine areas of Europe. *Frontiers in Environmental Science*, 10, 829526. <https://doi.org/10.3389/fenvs.2022.829526>
- Moritz, M. A., et al. (2014). Learning to coexist with wildfire. *Nature*. <https://doi.org/10.1038/nature13946>
- Munday, P., Parker, Z. and Panichi, R. (2026). Sustainability Insights I Research: Mercury Rising: European entities show some adaptation gains as physical risks mount. S&P Global Ratings. 24 March 2026.
- Nabuurs, G.-J., Verkerk, P. J., Schelhaas, M.-J., González Olabarria, J. R., Trasobares, A., & Cienciala, E. (2018). Climate-Smart Forestry: Mitigation impacts in three European regions (From Science to Policy 6). European Forest Institute. <https://doi.org/10.36333/fs06>
- Nardini, A., & Pavan, S. (2012). River restoration: Not only for the sake of nature but also for saving money while addressing flood risk. A decision-making framework applied to the Chiese River (Po basin, Italy). *Journal of Flood Risk Management*, 5(2), 111–133. <https://doi.org/10.1111/j.1753-318X.2011.01132.x>
- Neidermeier, A. N., Zagaria, C., Pampanoni, V., West, T. A. P., & Verburg, P. H. (2023). Mapping opportunities for the use of land management strategies to address fire risk in Europe. *Journal of Environmental Management*, 346, 118941. <https://doi.org/10.1016/j.jenvman.2023.118941>
- Network Rail. (2024). *Control Period 7 weather resilience and climate change adaptation plans: Combined summary of all regions*. <https://www.networkrail.co.uk/wp-content/uploads/2024/04/CP7-WRCCA-Plans-combined-summary-of-all-regions-April-2024.pdf>
- Noss, R. F. (2002). Beyond Kyoto: Forest management in a time of rapid climate change [Después de Kyoto: Manejo forestal en tiempos de cambio climático acelerado]. *Conservation Biology*, 16(2), 578–590. <https://doi.org/10.1046/j.1523-1739.2001.015003578.x>
- Ocio, D., Stocker, C., Eraso, Á., Martínez, A., & de Galdeano, J. M. S. (2016). Towards a reliable and cost-efficient flood risk management: The case of the Basque Country (Spain). *Natural Hazards*, 81(1), 617–639. <https://doi.org/10.1007/s11069-015-2099-6>
- Ofwat (2025) Ofwat's Fourth Climate Adaptation Report. <https://www.ofwat.gov.uk/wp-content/uploads/2025/02/Ofwats-4th-Climate-Adaptation-Report.pdf>
- Ofwat (2024) Our final determinations for the 2024 price review Sector summary. <https://www.ofwat.gov.uk/wp-content/uploads/2025/04/PR24-FD-sector-summary-revised.pdf>
- Oláh, A. M. (2016, October 3). Tatabánya, Hungary, addressing the impacts of urban heatwaves and forest fires with alert measures. Climate-ADAPT. <https://climate-adapt.eea.europa.eu/en/metadata/case-studies/tatabanya-hungary-addressing-the-impacts-of-urban-heat-waves-and-forest-fires-with-alert-measures>
- Oliveira, T. M., Barros, A. M. G., Ager, A. A., & Fernandes, P. M. (2016). Assessing the effect of a fuel break network to reduce burnt area and wildfire risk transmission. *International Journal of Wildland Fire*, 25(6), 619–632. <https://doi.org/10.1071/WF15146>
- Olofsson, E., & Jakobsson, R. (2024). Private forest owners' climate adaptation measures and the motivations behind them in a south Swedish county. *Scandinavian Journal of Forest Research*, 39(5), 263–276. <https://doi.org/10.1080/02827581.2024.2380685>
- Orlik, A. Rohrböck, P. Müller, A.-M. (2024). Klimarückblick Wien 2023 (Climate Review for Vienna). Vienna: CCCA, 2024 (German). https://ccca.ac.at/fileadmin/00_DokumenteHauptmenue/02_Klimawissen/Klimastatusbericht/KSB_2023/KRB_2023/Klimarueckblick_Wien_2023.pdf
- Palaiologou, P., Kalabokidis, K., Ager, A. A., & Day, M. A. (2020). Development of comprehensive fuel management strategies for reducing wildfire risk in Greece. *Forests*, 11(8), 789. <https://doi.org/10.3390/F11080789>
- Palazzo, A., Valin, H., Batka, M., & Havlík, P. (2019). Investment needs for irrigation infrastructure along different socioeconomic pathways. World Bank Policy Research Working Paper No. 8744. World Bank, Washington, DC.
- Palazzo, A., Kahil, T., Willaarts, B. A., Burek, P., van Dijk, M., Tang, T., Magnuszewski, P., Havlík, P., Langan, S., & Wada, Y. (2024a). Assessing sustainable development pathways for water, food, and energy security in a transboundary river basin. *Environmental Development*, 51, 101030. <https://doi.org/10.1016/j.envdev.2024.101030>
- Palazzo, A., Arbelaez-Gaviria, J., Burek, P., Frank, S., Fridman, D., Havlík, P., Augustynczyk, A. L., Wögerer, M., De Cian, E., Colelli, F., & Falchetta, G. (2024b). *Impacts on food, energy, and water*. ACCREU Deliverable D2.2, Assessing Climate Change Risk in Europe (ACCREU), Horizon Europe Grant Agreement No. 101081358. IIASA.

- Pan, C., et al. (2022). Key challenges and approaches to addressing barriers in forest carbon offset projects. Northeast Forestry University. <https://doi.org/10.1007/s11676-022-01488-z>
- Pareja, J., Baraza, E., Ibáñez, M., Domenech, O., & Bartolomé, J. (2020). The role of feral goats in maintaining firebreaks by using attractants. *Sustainability*, 12(17), 7144. <https://doi.org/10.3390/su12177144>
- Pauw, W. P., Kempa, L., Moslener, U., Grüning, C., & Çevik, C. (2021). A focus on market imperfections can help governments to mobilize private investments in adaptation. *Climate and Development*, 14(1), 91–97. <https://doi.org/10.1080/17565529.2021.1885337>
- Penning-Rowsell, E. C., Haigh, N., Lavery, S., & McFadden, L. (2013). A threatened world city: The benefits of protecting London from the sea. *Natural Hazards*, 66(3), 1383–1404. <https://doi.org/10.1007/s11069-011-0075-3>
- Pent, G. J. (2020). Over-yielding in temperate silvopastures: A meta-analysis. *Agroforestry Systems*. <https://doi.org/10.1007/s10457-020-00494-6>
- Peregrina Gonzalez, E. D., Van Ginkel, K. C. H., Van Marle, M. J. E., Asgarpour, S., & Koks, E. E. (2026). A multi-level framework for climate adaptation of critical infrastructure: Flood risk in railway networks. *Environmental Research: Infrastructure and Sustainability*, 6(3), 035003. <https://doi.org/10.1088/2634-4505/ae7fb5>
- Perrot-Maître, D. (2006). The Vittel payments for ecosystem services: A “perfect” PES case? International Institute for Environment and Development. <https://www.iied.org/sites/default/files/pdfs/migrate/G00388.pdf>
- Von Peter, G., von Dahlen, S., & Saxena, S. (2024). Unmitigated disasters? Risk sharing and macroeconomic recovery in a large international panel. *Journal of International Economics*, 149, 103920. <https://doi.org/10.1016/j.jinteco.2024.103920>
- Petrović, B., Bumbálek, R., Zoubek, T., Kuneš, R., Smutný, L., & Bartoš, P. (2024). Application of precision agriculture technologies in Central Europe—Review. *Journal of Agriculture and Food Research*, 15, 101048. <https://doi.org/10.1016/j.jafr.2024.101048>
- Petrovic, B., & Csambalik, L. (2025). Enhancing precision agriculture for climate change mitigation in Visegrad countries: Factors shaping adaptation. *Land*, 14(2), 399. <https://doi.org/10.3390/land14020399>
- Piñol, J., Beven, K., & Viegas, D. X. (2005). Modelling the effect of fire-exclusion and prescribed fire on wildfire size in Mediterranean ecosystems. *Ecological Modelling*, 183(4), 397–409. <https://doi.org/10.1016/j.ecolmodel.2004.09.001>
- Planas-Carbonell, A., Anguelovski, I., Oscilowicz, E., Pérez-del-Pulgar, C., & Shokry, G. (2023). From greening the climate-adaptive city to green climate gentrification? Civic perceptions of short-lived benefits and exclusionary protection in Boston, Philadelphia, Amsterdam and Barcelona. *Urban Climate*, 48, 101295. <https://doi.org/10.1016/j.uclim.2022.101295>
- Port of Rotterdam Authority. (2022). *Climate adaptation strategy and implementation*. <https://www.portofrotterdam.com>.
- Porthin, M., Rosqvist, T., Perrels, A., & Molarius, R. (2013). Multi-criteria decision analysis in adaptation decision-making: A flood case study in Finland. *Regional Environmental Change*, 13(6), 1171–1180. <https://doi.org/10.1007/s10113-013-0423-9>
- Pörtner, H.-O., Roberts, D. C., Tignor, M. M. B., Poloczanska, E., Mintenbeck, K., Alegría, A., Craig, M., Langsdorf, S., Löschke, S., Möller, V., Okem, A., & Rama, B. (Eds.). (2022). *Climate change 2022: Impacts, adaptation and vulnerability. Working Group II contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.
- Price, S. J., & Germino, M. J. (2022). Modeling of fire spread in sagebrush steppe using FARSITE: An approach to improving input data and simulation accuracy. *Fire Ecology*, 18(1). <https://doi.org/10.1186/s42408-022-00147-2>
- Pyrenean Climate Change Observatory. (n.d.). MEDACC: Adapting the Mediterranean to climate change. <https://www.opcc-ctp.org/en/bp/medacc-adapting-mediterranean-climate-change>
- Quintarelli, V., Radicetti, E., Allevato, E., Stazi, S. R., Haider, G., Abideen, Z., Bibi, S., Jamal, A., & Mancinelli, R. (2022). Cover crops for sustainable cropping systems: A review. *Agriculture*, 12(12), 2076. <https://doi.org/10.3390/agriculture12122076>
- Reckien, D., Creutzig, F., Fernandez, B., Lwasa, S., Tovar-Restrepo, M., Mcevoy, D., Satterthwaite, D., 2017. Climate change, equity and the Sustainable Development Goals: an urban perspective. *Environ. Urban*. 29 (1), 159–182.
- Reinders, H. J., Schoenmaker, D., & Van Dijk, M. (2023). A finance approach to climate stress testing. *Journal of International Money and Finance*, 131, 102797. <https://doi.org/10.1016/j.jimonfin.2022.102797>
- Regelink, M., Reinders, H. J., Vleeschhouwer, M., & van de Wiel, I. (2015). *Waterproof? An exploration of climate-related risks for the Dutch financial sector*. De Nederlandsche Bank. <https://www.dnb.nl/en/news/news-and-archive/publiek-2015/dnb323406.jsp>

- Regos, A., Aquilué, N., Retana, J., De Cáceres, M., & Brotons, L. (2014). Using unplanned fires to help suppressing future large fires in Mediterranean forests. *PLoS ONE*, 9(4), e94906. <https://doi.org/10.1371/journal.pone.0094906>
- Revell, D., King, P., Giliam, J., Calil, J., Jenkins, S., Helmer, C., Nakagawa, J., Snyder, A., Ellis, J., & Jamieson, M. (2021). A holistic framework for evaluating adaptation approaches to coastal hazards and sea level rise: A case study from Imperial Beach, California. *Water*, 13(9), 1324. <https://doi.org/10.3390/w13091324>
- Richters, O., Kriegler, E., Anz, J., Bertram, C., Cui, R., Edmonds, J., ... & Zwerling, M. (2024). NGFS Climate Scenarios Technical Documentation: V5. 0.
- Rijkswaterstaat (2014). Richtlijn Ontwerp Autosnelwegen ROA 2014.
- Rising, J. et al. (2026) The macroeconomic case for investing in climate adaptation. London: Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science.
- Roberge, J.-M., Fries, C., Normark, E., Mårald, E., Sténs, A., Sandström, C., Sonesson, J., Appelqvist, C., & Lundmark, T. (2020). Forest management in Sweden: Current practice and historical background (Rapport 2020/4). Skogsstyrelsen. <https://www.skogsstyrelsen.se/globalassets/om-oss/rapporter/rapporter-20222021202020192018/rapport-2020-4-forest-management-in-sweden.pdf>
- Romijn, G., & Renes, G. (2013). *Algemene leidraad voor maatschappelijke kosten-baten analyse*. Centraal Planbureau & Planbureau voor de Leefomgeving.
- Ruangpan, L., Vojinovic, Z., Plavšić, J., Curran, A., Rosic, N., Pudar, R., Savic, D., & Brdjanovic, D. (2024). Economic assessment of nature-based solutions to reduce flood risk and enhance co-benefits. *Journal of Environmental Management*, 352, 119985. <https://doi.org/10.1016/j.jenvman.2023.119985>
- Runhaar, H., Wilk, B., Persson, Å., Uittenbroek, C., & Wamsler, C. (2018). Mainstreaming climate adaptation: Taking stock about “what works” from empirical research worldwide. *Regional Environmental Change*, 18(4), 1201–1210
- Sabri, S. S. S. B., Hussain, M. R. M., Sani, J. A., Hamed, S. A., & Rusli, N. (2024). Five phases cycles in Emergency Preparedness and Response Plan (EPRP) as an emergency management for campus environment. *Journal of Advanced Research in Technology and Innovation Management*, 11(1), 12–20.
- Sacchelli, S., Cipollaro, M., & Fabbri, S. (2018). A GIS-based model for multiscale forest insurance analysis: The Italian case study. *Forest Policy and Economics*, 92, 106–118. <https://doi.org/10.1016/j.forpol.2018.04.011>
- Salis, M., et al. (2016). Evaluating alternative fuel treatment strategies to reduce wildfire losses in a Mediterranean area. *Forest Ecology and Management*, 368, 207–221. <https://doi.org/10.1016/j.foreco.2016.03.009>
- Salis, M., et al. (2018). Modeling the effects of different fuel treatment mosaics on wildfire spread and behavior in a Mediterranean agro-pastoral area. *Journal of Environmental Management*, 212, 490–505. <https://doi.org/10.1016/j.jenvman.2018.02.020>
- Sánchez, J. J., Holmes, T. P., Loomis, J., & González-Cabán, A. (2022). Homeowners willingness to pay to reduce wildfire risk in wildland urban interface areas: Implications for targeting financial incentives. *International Journal of Disaster Risk Reduction*, 68, 102696. <https://doi.org/10.1016/j.ijdrr.2021.102696>
- Santini, A., Masiero, M., Amato, G., & Pettenella, D. M. (2025). From flood to drip irrigation: A review of irrigation modernization trade-offs. *Water*, 17(20), 3018. <https://doi.org/10.3390/w17203018>
- Santuopoli, G. (2024, July 30). A community of practice for the sustainable management of forests surrounding the Occhito Lake in Puglia, Italy. Climate-ADAPT. <https://climate-adapt.eea.europa.eu/en/metadatas/case-studies/a-community-of-practice-for-the-sustainable-management-of-forests-surrounding-the-occhito-lake-in-puglia-italy>
- Scussolini, P., Tran, T. V. T., Koks, E., Diaz-Loaiza, A., Ho, P. L., & Lasage, R. (2017). Adaptation to sea level rise: A multidisciplinary analysis for Ho Chi Minh City, Vietnam. *Water Resources Research*, 53(12), 10841–10857. <https://doi.org/10.1002/2017WR021344>
- Seebauer, S., Thaler, T., Hanger-Kopp, S., & Schinko, T. (2023). How path dependency manifests in flood risk management: Observations from four decades in the Ennstal and Aist catchments in Austria. *Regional Environmental Change*, 23(1). <https://doi.org/10.1007/s10113-023-02029-y>
- Seidl, R., Rammer, W., & Lexer, M. J. (2011). Adaptation options to reduce climate change vulnerability of sustainable forest management in the Austrian Alps. *Canadian Journal of Forest Research*, 41(4), 694–706. <https://doi.org/10.1139/x10-235>
- Shala, I., & Schumacher, B. (2024). *The impact of natural disasters on banks' impairment flow, Evidence from Germany*. *Journal of Climate Finance*, 6, 100031.
- SILVANUS Project. (n.d.). Pilots. SILVANUS Project. <https://silvanus-project.eu/results/pilots/>
- Skogsstyrelsen. (2025, April 2). Skogsbrand – förebyggande åtgärder. <https://www.skogsstyrelsen.se/bruka-skog/skogsskador/skogsbrander>

- Skougaard Kaspersen, P., Høegh Ravn, N., Arnbjerg-Nielsen, K., Madsen, H., & Drews, M. (2017). Comparison of the impacts of urban development and climate change on exposing European cities to pluvial flooding. *Hydrology and Earth System Sciences*, 21(8), 4131–4147. <https://doi.org/10.5194/hess-21-4131-2017>
- Sousa-Silva, R., Ponette, Q., Verheyen, K., Van Herzele, A., & Muys, B. (2016). Adaptation of forest management to climate change as perceived by forest owners and managers in Belgium. *Forest Ecosystems*, 3(1). <https://doi.org/10.1186/s40663-016-0082-7>
- Social Security and Administration Management. (2023). A study on social housing and housing affordability in Australia based on zoning regulations. *Social Security and Administration Management*, 4(8). <https://doi.org/10.23977/socsam.2023.040812>
- Stegeman, H., de Wilde, J. & Hobma, E. (2026). Hot Summer Economics. Economic effects of the hot European summer of 2026. Triodos Bank.
- STOWA (2019). Neerslagstatistiek en -reeksen voor het waterbeheer 2019. <https://www.stowa.nl/publicaties/neerslagstatistiek-en-reeksen-voor-het-waterbeheer-2019>
- Szymczak, S., Backendorf, F., Bott, F., Fricke, K., Junghänel, T., & Walawender, E. (2022). *Impacts of heavy and persistent precipitation on railroad infrastructure in July 2021: A case study from the Ahr Valley, Rhineland-Palatinate, Germany*. *Atmosphere*, 13(7), 1118. <https://doi.org/10.3390/atmos13071118>
- Tàbara, D., Saurí, D., & Cerdan, R. (2003). Forest fire risk management and public participation in changing socioenvironmental conditions: A case study in a Mediterranean region. *Risk Analysis*, 23(2), 249–260. <https://doi.org/10.1111/1539-6924.00305>
- Tansar, H., Babur, M., & Karnchanapaiboon, S. L. (2020). Flood inundation modeling and hazard assessment in Lower Ping River Basin using MIKE FLOOD. *Arabian Journal of Geosciences*, 13(18), 934. <https://doi.org/10.1007/s12517-020-05891-w>
- Tesselaar, M., Botzen, W. W., Haer, T., Hudson, P., Tiggeoven, T., & Aerts, J. C. (2020). Regional inequalities in flood insurance affordability and uptake under climate change. *Sustainability*, 12(20), 8734.
- Tesselaar, M., Botzen, W. W., Robinson, P. J., Aerts, J. C., & Zhou, F. (2022). Charity hazard and the flood insurance protection gap: An EU scale assessment under climate change. *Ecological Economics*, 193, 107289.
- Tesselaar, M., Botzen, W. W., Tiggeoven, T., & Aerts, J. C. (2023). Flood insurance is a driver of population growth in European floodplains. *Nature Communications*, 14(1), 7483.
- Tesselaar, M., & Botzen, W. J. W. (2026). Inequality in flood insurance arrangements to finance flood recovery under climate change. *Climate Risk Management*, 53, 100850. <https://doi.org/10.1016/j.crm.2026.100850>
- Thacker, S., Kelly, S., Pant, R., & Hall, J. W. (2018). Evaluating the benefits of adaptation of critical infrastructures to hydrometeorological risks. *Risk Analysis*, 38(1), 134–150. <https://doi.org/10.1111/risa.12839>
- Tierney & Bruneau (2007). *Conceptualizing and measuring resilience. A key to disaster loss reduction*. TR News 2050. May-june 20227. https://onlinepubs.trb.org/onlinepubs/trnews/trnews250_p14-17.pdf
- Tinoco, N. (2023). Post-disaster (im)mobility aspiration and capability formation: Case study of Southern California wildfire. *Population and Environment*, 45(2). <https://doi.org/10.1007/s11111-023-00416-5>
- Tőzsér, D., Gutiérrez Pérez, D. I., Karmakar, R., Boros, A., & Magura, T. (2026). Climate-resilient agriculture in Central Europe: Crop diversification, food safety, and integrated adaptation pathways. *Agriculture*, 16(17), 1841. <https://doi.org/10.3390/agriculture16171841>
- TREEADS Project. (n.d.). Pilot campaigns. TREEADS Project. https://treeads-project.eu/portfolio_category/pilot-campaigns/
- Tschakert, P., Ogra, A., Sharma, U., Karthikeyan, K., Singh, A., & Bhowmik, A. (2025). Intersecting inequalities and urban heat adaptation. *Global Environmental Change*, 92, 103003. <https://doi.org/10.1016/j.gloenvcha.2025.103003>
- Turner, G. A., de'Donato, F., Hoeben, A. D., Nordeng, Z., Coleman, S., Otto, I. M., Hajat, S., & Kovats, S. (2024). Implementation of climate adaptation in the public health sector in Europe: Qualitative thematic analysis. *European Journal of Public Health*, 34(3), 544–549. <https://doi.org/10.1093/eurpub/ckad218>
- Tyburski, Ł., & Szczygieł, R. (2023). Rules for the construction of firebreaks along public roads in selected European countries. *Forests, Forest Policy and Economics*. <https://doi.org/10.2478/ffp-2023-0020>
- United Nations Environment Programme (2023). *Adaptation Gap Report 2023: Underfinanced. Underprepared. Inadequate investment and planning on climate adaptation leaves world exposed*. United Nations Environment Programme. <https://doi.org/10.59117/20.500.11822/43796>
- United Nations Environment Programme (2024). *A Comprehensive Review of Global Supervisory Climate Stress Tests*. Geneva.

- United Nations Environment Programme (2025). *Adaptation Gap Report 2025: Running on empty. The world is gearing up for climate resilience — without the money to get there* [Neufeldt, H., Hammill, A., Leiter, T., Magnan, A., Watkiss, P., Bakhtiari, F., Bueno Rubial, P., Butera, B., Canales, N., Chapagain, D., Christiansen, L., Dale, T., Milford, F., Niles, K., Njuguna, L., Pauw, P., Singh, C. and Yang, G.]. Nairobi. <https://wedocs.unep.org/20.500.11822/48798>.
- Ulpiani, G., Treville, A., Bertoldi, P., Veters, N., Barbosa, P., Feyen, L., Naumann, G., & Santamouris, M. (2024). Are cities taking action against urban overheating? Insights from over 7,500 local climate actions. *One Earth*, 7(5), 848–866. <https://doi.org/10.1016/j.oneear.2024.04.010>
- Uyttewaal, K., Stoof, C. R., Canaleta, G., Cifre-Sabater, M., Langer, L., & Ludwig, F. (2024). Uplifting local ecological knowledge as part of adaptation pathways to wildfire risk reduction: A case study in Montseny, Catalonia (Spain). *Ambio*. <https://doi.org/10.1007/s13280>
- Vanderkimpfen, P., Melger, E., & Peeters, P. (2009). Flood modeling for risk evaluation – a MIKE FLOOD vs. SOBEK 1D2D benchmark study. *Flood Risk Management: Research and Practice*.
- Vanderplanken, K., Van Den Hazel, P., Marx, M., Shams, A. Z., Guha-Sapir, D., & Van Loenhout, J. A. F. (2021). Governing heatwaves in Europe: Comparing health policy and practices to better understand roles, responsibilities and collaboration. *Health Research Policy and Systems*, 19(1), 20. <https://doi.org/10.1186/s12961-020-00645-2>
- Varela, E., Górriz-Mifsud, E., Ruiz-Mirazo, J., & López-i-Gelats, F. (2018). Payment for targeted grazing: Integrating local shepherds into wildfire prevention. *Forests*, 9(8), 464. <https://doi.org/10.3390/f9080464>
- Vico, G., Tamburino, L., & Rigby, J. R. (2020). Designing on-farm irrigation ponds for high and stable yield for different climates and risk-coping attitudes. *Journal of Hydrology*, 584, 124634. <https://doi.org/10.1016/j.jhydrol.2020.124634>
- Vousdoukas, M.I., Mentashi, L., Mongelli, I., Ciscar, J.C., Hinkel, J., Ward, P., Gosling, S., Feyen, L. (2020). *Adapting to rising coastal flood risk in the EU under climate change*. EUR 29969 EN. Publications Office of the European Union, Luxembourg. <https://doi.org/10.2760/456870>
- Watkiss, P., et al (2026). Climate adaptation investment planning: insights from applications in developing countries, *Climate and Development*. <https://doi.org/10.1080/17565529.2026.2689995>
- Wei, H., Wu, H., Zhang, L., & Liu, J. (2024). Urban flooding simulation and flood risk assessment based on the InfoWorks ICM model: A case study of the urban inland rivers in Zhengzhou, China. *Water Science & Technology*, 90(4), 1338–1358. <https://doi.org/10.2166/wst.2024.280>
- Weiss, G., et al. (2019). Forest ownership changes in Europe: State of knowledge and conceptual foundations. *Forest Policy and Economics*, 102, 1–13. <https://doi.org/10.1016/j.forpol.2018.03.003>
- Wesseling, A., Warner, J. F., Syed, M. A., Chan, F., Duc Tran, D., Huq, H., Huthoff, F., Le Thuy, N., Pinter, N., Van Staveren, M., Wester, P., & Zegwaard, A. (2015). Trends in flood risk management in deltas around the world: Are we going ‘soft’? *International Journal of Water Governance*, 4, 25–46. <https://doi.org/10.7564/15-IJWG90>
- Winsemius, H. C., Van Beek, L. P. H., Jongman, B., Ward, P. J., & Bouwman, A. (2013). A framework for global river flood risk assessments. *Hydrology and Earth System Sciences*, 17(5), 1871–1892. <https://doi.org/10.5194/hess-17-1871-2013>
- Wojciechowska, K. A., & Kok, M. (2013). First insight into the probabilistic evacuation criteria in the Netherlands. *Journal of Flood Risk Management*, 6(2), 99–111. <https://doi.org/10.1111/j.1753-318X.2012.01159.x>
- Wong, N. H., Tan, C. L., Kolokotsa, D. D., & Takebayashi, H. (2021). Greenery as a mitigation and adaptation strategy to urban heat. *Nature Reviews Earth & Environment*, 2(3), 166–181.
- World Bank. (2021). Economics for disaster prevention and preparedness: Investment in disaster risk management in Europe makes economic sense (Summary report). <https://civil-protection-knowledge-network.europa.eu/system/files/2024-04/Investment%20in%20Disaster%20Risk%20Management%20-%20Summary.pdf>
- World Bank (2024). *Climate Adaptation Costing in a Changing World*. World Bank Group, 2024. Available at: <https://documents1.worldbank.org/curated/en/099050224072021662/pdf/P179070140a07209a1b5d012d978862b4ff.pdf>
- Yamagami, C., & Kawasaki, A. (2024). Reevaluating the benefit of flood risk management for flood-prone livelihoods. *International Journal of Disaster Risk Reduction*, 106, 104416. <https://doi.org/10.1016/j.ijdrr.2024.104416>
- Yaron, G., & Wilson, D. (2020). Estimating the economic returns to community-level interventions that build resilience to flooding. *Journal of Flood Risk Management*, 13(4), e12662. <https://doi.org/10.1111/jfr3.12662>
- Yau, Y. (2015). The value of building safety: A hedonic price approach. *Urbani Izziv*, 26(1), 92–104. <https://doi.org/10.5379/urbani-izziv-en-2015-26-01-003>

- Yohe, G., Knee, K., & Kirshen, P. (2011). On the economics of coastal adaptation solutions in an uncertain world. *Climatic Change*, 106(1), 71–92. <https://doi.org/10.1007/s10584-010-9997-0>
- Yusof, Z., Saad, N. A., Abd Rahim, M. S., Kalimuthu, P., & Wan Abdul Majid, W. H. A. (2023). Assessment on the efficiency of flood mitigation measures. *Jurnal Kejuruteraan*, 35(4), 831–841. [https://doi.org/10.17576/jkukm-2023-35\(4\)-05](https://doi.org/10.17576/jkukm-2023-35(4)-05)
- Zainal, N. N., & Abu Talib, S. H. (2024). Review paper on applications of the HEC-RAS model for flooding, agriculture, and water quality simulation. *Water Practice & Technology*, 19(7), 2883–2900. <https://doi.org/10.2166/wpt.2024.173>
- Zeferino, J. A. (2020). Optimizing the location of aerial resources to combat wildfires: A case study of Portugal. *Natural Hazards*, 100(3), 1195–1213. <https://doi.org/10.1007/s11069-020-03856-6>
- Zeng, P., Fang, W., Zhang, H., & Liang, Z. (2023). Cost-benefit analysis of the Wuxikou Integrated Flood Management Project considering the effects of flood risk reduction and resettlement. *International Journal of Disaster Risk Science*, 14(5), 795–812. <https://doi.org/10.1007/s13753-023-00520-y>
- Zhang, J., Zheng, H., Zhang, X., Lin, Z., VanLooy, J., & Kennedy, A. (2023). Strategic land acquisition for efficient and equitable flood risk reduction in the United States. *Climate Risk Management*, 42, 100554. <https://doi.org/10.1016/j.crm.2023.100554>
- Zhou, Q., Halsnæs, K., & Arnbjerg-Nielsen, K. (2012). Economic assessment of climate adaptation options for urban drainage design in Odense, Denmark. *Water Science and Technology*, 66(8), 1812–1820. <https://doi.org/10.2166/wst.2012.386>
- Zhou, Q., Mikkelsen, P. S., Halsnæs, K., & Arnbjerg-Nielsen, K. (2012). Framework for economic pluvial flood risk assessment considering climate change effects and adaptation benefits. *Journal of Hydrology*, 414–415, 539–549. <https://doi.org/10.1016/j.jhydrol.2011.11.031>

Annex

Appendix A: Generic ADT format

1. Decision context

Short description of the decision context. Answer to the following questions: For which key stakeholder group(s) is the information relevant: i.e. who are the main stakeholders that would implement and/or evaluate the adaptation strategies you are looking at within your adaptation decision type. Clearly define at which spatial or governance scale these stakeholders operate and their role in the climate adaptation process. What is/are the challenges for adaptation policy this typology of stakeholders is typically facing in the broader European context? What are the challenges for adaptation policy faced by your stakeholders that can be generalized as “typical” for similar stakeholders’ types in the broader European context?

2. Adaptation strategies

Here, we envision: (1) list the possible strategies the stakeholder group(s) could take to address the adaptation challenges, and (2) select those more widely implemented, less commonly implemented and not yet implemented.

If there are any differences in the prevalence of implementation of specific strategies across EU member states or for instance across small/medium/large cities or companies, these observations could be described here. When those patterns are not noticeable or hard to find for all EU member states, an alternative could be to check whether there are differences in the implementation across different pillars they address: hazard, vulnerability, exposure or adaptive capacity for instance, but other classifications such as green/grey/soft/incremental/transformational are also possible.

The main aim of this section is to provide an (concise) overview of adaptation efforts in Europe for each ADT theme.

3. Assessment of strategies – barriers to implementation

This is one of the longest sections of the document. It includes an assessment of the strategies characterizing the ADT. Why are some strategies very prevalent and others not? Which strategies have hardly been assessed or implemented? What are key limits or barriers for their implementation? What can we learn from ACCREU case studies or other case studies in Europe on enabling conditions or success stories?

Other questions that could be answered here: What are the main costs and benefits of the strategies involved? What are the distributional effects of the strategies? Who would finance the strategy? Does the strategy come with many co-benefits and co-costs? Do the strategies have a long lead time? Are the strategies robust or only suitable for short-term climate impacts?

4. Lessons learned for implementation of strategies

This section goes into more depth into one or more of the barriers mentioned above, that is key to the policy question and/or stakeholders. Are there case studies either within the same theme, or on a different hazard, where this type of barrier was overcome? These barriers can be linked to implementation of a measure, but could also be linked to barriers in the economic appraisal of adaptation strategies that limit the application etc. This section may also include reflections on the output of the ADT workshops.

5. Role of sectoral models for implementation of strategies

This section provides some information on the relevance of sectoral models for the generic stakeholders in your ADT. For the different sectoral models relevant to the adaptation decision type, please describe i) what the model can be used for that is relevant to the identified stakeholders for decision-making/adaptation planning/adaptation appraisal; ii) what the model can sometimes be used for; iii) what the model cannot be used for.

6. Conclusion

Finally, it ends with a conclusion on the main lessons learned and advise for the stakeholders on the policy question.

Appendix B: ADT1

Table B.1: Sectoral models for flood risk assessment.

Model name	Description	Can typically be used for ... (advantages)	Can typically not be used for ... (disadvantages)	Applications
DIVA	Global coastal impact and adaptation model with NUTS2 or smaller coastal unit resolution for the EU; Modelling of direct damages to physical assets and infrastructure, loss of agricultural dry-land, loss and change of coastal ecosystems (wetlands); time horizon, 2030, 2050, 2100.	Rapid assessment of vulnerability to coastal flooding, including rapid assessment of expected economic and ecologic damages	Locally specific assessments and decision making	Mexico (R) (Haer et al., 2017) ACCREU: WP2; CS1.2
GLOFRIS	Global flood risk assessment model (river and coastal floods); 1x1km2 or EU- NUTS3 resolution; Climate change impacts and adaptation policy assessment in 2030, 2050, 2100; Assessments of direct damage across sectors (Rural, Urban, Agriculture, Industry, Infrastructure, Nature). Indirect economic damage via scaling factor.	Assessment of vulnerability to coastal and riverine flooding	Locally specific assessments and decision making; Less useful in areas where “impact of tidal backwater play a dominant role” (Winsemius et al., 2013, p.1881)	Mexico (R) (Haer et al., 2017); Mexico (N) (Haer et al., 2018); Italy (R) (Botzen et al., 2017) ACCREU: WP2; CS5.2
HEC-HMS	“simulate the precipitation-runoff processes of dendritic watershed systems” (Fleming & Brauer, 2016, p.1)	“Hydrographs produced by the program can be used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, wetlands hydrology, and systems operation.” (Fleming & Brauer, 2016, p.1)	HEC-HMS has “slight difficulty in predicting peak flows” (de Paula Netto et al., 2024, p.14)	UK (L) (Dittrich et al., 2019); China (L) (Lai et al., 2023); Serbia (R) (Ruangpan et al., 2024); Bolivia (R) (Corderi-Novoa et al., 2021); Jordan (R) (Gokcekus et al., 2024)
HEC-RAS	“perform one-dimensional steady flow, one and two-dimensional unsteady flow calculations, sediment transport/mobile bed computations, and water temperature/water quality modelling” (HEC-RAS)	“It is frequently used to compute the primary 1D flow parameters for steady and erratic river flow regimes, [...useful for] determining the impact of hydraulic structures on upstream and downstream channels, estimating flood plains, analyzing river capacity,	Longer-term assessments (Bragg et al., 2025)	Fiji (R) (Daigneault et al., 2016); Spain (R) (Ocio et al., 2016); Serbia (R) (Ruangpan et al., 2024); Bolivia (R) (Corderi-Novoa et al., 2021); Jordan (R) (Gokcekus et al., 2024)

		checking the depth at any point in rivers, and choosing the locations of hydraulic structure installations based on the analysis of water demand and supply for agriculture” (Zainal & Abu Talib, 2024, p.2897)		
MIKE	MIKE 11 is 1D, MIKE 21 2D model, can be coupled through MIKE FLOOD (Tansar et al., 2020).	“[MIKE FLOOD] is developed to integrate the best modeling features of MIKE 11 and MIKE 21 for inland, coastal, and urban flooding and also to avoid the limitations of resolutions and accuracy” (Tansar et al., 2020, p.6)	Accurate calculation of maximum velocity (Vanderkimpfen et al., 2009) “some problems, such as computational stability and the simulation of water inflow in buildings.” (Liu et al., 2020, p.190)	Aotearoa (L) (Keenan & Oldfield, 2012); Belgium (R) (Broekx et al., 2011); China (L) (Chong et al., 2021); China (R) (Zeng et al., 2023); Denmark (L) (Zhou, Mikkelsen, et al., 2012); Italy (R) (Nardini & Pavan, 2012); Vietnam (L) (Lasage et al., 2014)
InfoWorks ICM	“modeling simple to complex hydraulic and hydrologic network elements quickly and accurately in a collaborative environment.” (Autodesk InfoWorks ICM 2026 Get Prices & Buy Official InfoWorks ICM)	“Its key feature lies in its ability to realistically simulate the interaction between surface water bodies and underground drainage pipe systems” (Wei et al., 2024, p.1341)	“InfoWorks does not appear to be able to perform full double precision (8 bytes) runs on the GPU, but only single precision (4 bytes)” Gibson et al., 2016, p.805); complexity in setting up the model (Gibson et al., 2016)	Spain (L, 2x) (Locatelli et al., 2020) Malaysia (R) (Yusof et al., 2023)

Note: L/R/N refers to the case study levels: Local, Regional, National respectively. Further, only the models that were applied in three or more case studies, at least one of which in Europe, are shown in this table. Further, the cases listed in italics combined HEC-HMS and HEC-RAS.

Appendix C: ADT2

This appendix is included as separate document (Excel file). It provides more detailed information on all 48 reviewed cases.

Appendix D: ADT2

Table A1. Sectoral models

Sectoral model name and description	Can typically be used for ...	Can sometimes be used for ...	Can typically not be used for ...
<i>ForeFire</i> Integrated wildfire risk and adaptation model. Combines ignition probability, climate projections (SSP-RCP, EURO-CORDEX), wind downscaling, land cover (CORINE, GLOBIOM), high-resolution spread modelling (ForeFire).	Visualize wildfire spread and the area affected based on weather, terrain and vegetation, especially for larger fires	Testing adaptation measures to inform stakeholders about the effect of fire management strategies	Real-time fire forecasting, highly detailed operational decision-making
<i>Treatment Optimization Model (TOM)</i> Modeling the effect of different fuel treatment placements on wildfire behavior to identify and disrupt fastest fire pathways. Requires static weather and vegetation inputs.	Identifying optimal treatment zones to slow or stop fire spread	Insurance companies to provide risk insights or information about risk reduction incentives	Modeling the effect of adaptation strategies other than fuel treatment, real-time fire forecasting
<i>FARSITE</i> Wildfire model using changing weather and landscape features to predict fire spread.	Support fire suppression decisions for specific fire events, for example decide if fires should be suppressed or allowed to burn under supervision	Evaluate economic consequences of fires with or without fuel treatment strategies	Large-scale, long-term strategic planning
<i>Minimum Travel Time (MTT)</i> Model simulating fire spread and intensity from various ignition points. Requires static weather and vegetation inputs.	Small-scale wildfire risk assessment, strategic fuel management planning		Long-duration fires where environmental conditions change, modelling wildfire suppression efforts

Appendix E: ADT5

Source	Climate hazard	Transmission channel	Assets and method	Results	Limitations
Dutch Central Bank (DNB), Caloia et al. (2026)	High-resolution coastal and river flood data. Event-based data	Credit Risk	Property damage of residential and commercial real estate	CET-1 impacts: 30–50 basis points for most scenarios, 50–110 basis points for worst credible floods.	No macro-financial considerations. Possible underestimation in damage curve. Limited forward-looking
IMF, FSAP (2024)	High-resolution coastal and river flood data. Event-based data.	Credit Risk	Flood damage is aggregated at a country level, then: i) direct destruction of physical capital, ii) impact on total factor productivity, iii) shock to house prices Financial stability model and global macro-financial model	Smaller CET-1 impacts than Caloia et al. Very high GDP impacts, up till 15%	Same as Caloia et al. The very high GDP impacts seem at odds with the limited CET-1 impacts.
Endendijk et al. (2024)	High-resolution flood data. Event-based and risk-based data.	Credit Risk	Flood damage at asset level, then: Credit risk model + ASRF model for capital requirements + interruption duration for lost rent cash flows	- Mortgage lenders are resilient to a sudden capitalization of flood risk on the housing market. - Portfolio diversification and financial adaptation are strategies to mitigate the impact of flooding on the portfolio level.	Hypothetical portfolio's
Bank of England (2021)	Physical risk (Inland flood, coastal flood, cyclones, wind, wildfires), transition risk, scenario based	Credit risk	Test builds upon NGFS scenarios 2050: an Early, late and no action that impact transition and physical risk. Insurers: climate risk impact on	- Severe physical risk scenario projects around 60 billion pounds cumulative loss for bank lending (and 340 billion total including insurance) for No action scenario. - Insurer losses concentrated in areas prone to coastal and inland flooding.	Bottom-up stress test based upon participating submissions, large variability in frameworks banks used, data constraints (location of corporate assets), climate risk only

			insurance claims.		partially measured.
ECB (2022)	Physical climate scenarios (drought & heat risk and flood risk). Event based.	Credit risk	Drought & heat based upon NGFS estimates for labour productivity shocks Flood risk: LISFLOOD-model as a basis for the NUTS-3 regions in Europe were classified into 4 categories.	- Susceptible countries to heat stress (Mainly southern Europe) were shocked with 1–4% for labour productivity. - Less vulnerable countries had net positive value-added impact. -the cumulative losses on loans for the flood scenario, ranges up to 100 basis points - An important conclusion is that banks have relatively little exposure to the areas with high flood risk -The medium flood zone shows the highest LTV increase, of some 18%.	- Low data availability was perceived as a main barrier in bank stress tests (causing a underestimation of mainly transition risk) - The stress-test does not incorporate an adverse widespread market-specific stress scenario which is used in traditional banking stress tests. -Only 60% of ECB banks participated -Estimates do not account for insurance and public natural disaster relief, these numbers likely are an overestimation.
Deutsche Bundesbank (2024)	Physical risk, regional flood data, historical event based	Credit risk	Difference-in-difference estimation. 191 banks using 451 banks as control group. Tests the impact of severe flood event (2013) on impairment flows²⁴ for regional banks in Germany.	- Impairment flows are around 3% higher compared to unaffected banks (also years after flood). Mainly driven by agriculture, manufacturing and mortgage loans. - Profitability of banks significantly lower years after flood event ($p<0,01$)	- Regionally less diversified banks. - Profitability does not directly indicate anything about stability. - Relationship between hazards and impacts on banking sector is in developing stage (and still inconclusive)
Federal Reserve System (FED, 2024),	Physical risk, hurricane, other hazard based upon participant	Credit risk	Participatory process with 6 large banks, FED sets parameters on	- A 1/100-year event increases the probability of default by around 50 basis point for commercial real estate	-Pilot exercise where participants use different methodologies in

²⁴ Definition: *Net valuation adjustments on domestic loans over total assets in %*, Shala (2022)

United states of America	modelling capacity		physical hazards (SSP/RCP based) and impact of probability of default. For baseline, 1/100 and 1/200 event (2023). Some participants included indirect impact ²⁵ that can affect credit risk.	(for physical risk hurricane module) -A 1/100-year event increases the probability of default by around 100 basis point for commercial real estate (for other impacts, idiosyncratic shock)	estimating credit risk due to climate change. -Differences based upon risk interpretation, data availability and prior knowledge -Data limitations, dependent on external parties to solve data gaps
Bank of Canada (2023)	(Granular) flood data, Two scenarios, average annual loss (AAL) and severe 1/100-year event.	Credit Risk	Residential real estate secured lending portfolio with focus on loss given default. Based upon JBA risk management and KatRisk. 1/100 event.	“Modest” impact on loss given default (0,24% increase on average) -Mainly due to housing prices increases over last decade. Weaker housing market combined with longer settlement time of default can strongly increase the effect. - Urban development in flood prone areas can increase risk.	- Granular flood data may cause underestimation of actual risk (mainly for specific locations) - Uncertainty of flood-related defaults. -Does not consider simultaneous macroeconomic shocks.
IMF (2025)	Physical risk; wildfires. Risk-based	Credit risk	Risk-based, Impacts linked to fire severity based upon RCP 4.5 and 8.5 with focus on loss given default (LGD)	-By 2041–2070, around 65 % of mortgage loans are exposed to very high or extreme wildfire risk under both RCP4.5 and RCP8.5, compared to 38 % in the historical baseline. - LGD increases range from about 1.6 percentage points under RCP4.5 to 6.4 percentage in points under RCP8.5 in West-Canada. -Up to 17.5 percentage points most affected area (Saskatchewan)	- does not take into account other macro-economic activity (business interruption, employment effects etc.) - strong reliance on current insurance assumptions -sensitive to geographic concentration -single hazard and transmission channel -granular data may result in under or overestimation of risks

²⁵ Such as pricing, infrastructure and supply chain impacts.

Financial Services Agency (FSA) & Bank of Japan (2022)	Floods and typhoons	Credit Risk	NGSF: Net zero 2050, Current policies. Damage to assets and collateral due to floods, suspension of business activities	-No quantitative results presented, only directional/indicative. -Physical risk leads to measurable increases in expected credit costs, but these remain well below banks' annual net income levels. Impact grows over time: average annual physical-risk credit costs by 2100 are several times larger than those to 2050	- Outcomes highly dependent based on model and selection of indicators for individual banks. - Limited data availability on business unit locations of borrowers (officers and plants)
Australian Prudential Regulation Authority (APRA, 2022)	Tropical cyclone, precipitation stress, river flood, fire weather stress, drought stress and heat stress. Risk-based	Credit Risk	Scenarios based on NGSF, Delayed Transition, Current policies scenario for 2050. Hazard data obtained from insurance company MunichRe. Increase in lending loss rates bps,	Increase in loss rates of 5-35% depending on region. Higher increases in loss rates for areas North/Queensland), 20% of postcodes account for 75% of losses. ~Aggregate annualized loss rates agriculture from 10 to 25 bps	- Hazard data is mainly on postcode or regional level - Risk towards non-agricultural business activity is not included. - Future research is suggested to include tail risk (event based); improve asset level data; exercise still framed as exploratory
Bank of Malaysia (2024)	Floods	Credit Risk	Exercise considers both long- and short-term risk scenario. Short physical scenario considers event-based 1/200-year event on 1 st of January 2024, similar to RCP8.5 in 2050. Climate variables are downscaled to Malaysia based upon NGFS	Results pending, banks are expected to create an assessment on impact of flood on collateral value and repayment capacity on a postcode-level.	- Limitations in data and modelling therefore only credit risk is considered quantitatively. Other risks such as market, liquidity and operational risk are examined qualitatively. - Exercise is made to identify knowledge and research gaps.