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Climate change adaptation options and their associated costs and benefits in Ireland

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Abstract

Climate change poses a significant threat to Ireland, with far-reaching implications for its environment, people, and economy. Consequently, proactive measures are important to mitigate and adapt to these impacts. This paper analyses potential adaptation options and their associated costs and benefits, building upon previous research on the economic implications of climate change in Ireland. We examine the current state of climate change in Ireland, highlighting the various impacts on different sectors. Subsequently, we present an overview of various adaptation measures and their current implementation status. We describe the methodologies used to estimate the costs and benefits of adaptation options, including cost-benefit analysis, cost-effectiveness analysis and multi-criteria analysis. We then estimate the costs and benefits of various adaptation measures in Ireland. Finally, we discuss the barriers to implementing adaptation measures, including financial constraints, policy gaps, and institutional limitations.

1 Introduction

Despite international efforts to limit global warming to below two degrees Celsius compared to pre-industrial[1] temperatures, greenhouse gas (GHG) emissions are still increasing worldwide. This increase has resulted in several adverse consequences, including rising temperatures and sea levels and more frequent and intense extreme weather events like storms, floods, and heat waves (Calvin et al., 2023; United Nations Environment Programme, 2023). These extreme weather events can cause significant damage to infrastructure, disrupt agricultural activities, and destroy ecosystems, leading to economic losses and displacement of communities.

Ireland is already experiencing the impacts of climate change, affecting various sectors such as infrastructure and human health (Climate Change Advisory Council, 2022; Desmond et al., 2017). Climate change is causing altered precipitation patterns, leading to riverine flooding, and threatening low-lying areas along rivers (Lincke et al., 2019; IPCC, 2022). This has significant implications for urban and rural communities and infrastructure. Also, the increased frequency and intensity of storms and storm surges are contributing to the heightened risk of coastal flooding, which can impact coastal ecosystems (such as salt marshes, mangroves, and dunes) and human settlements (Devoy, 2008; Flood et al., 2020). This is particularly concerning given Ireland's extensive coastline and the fact that many major cities and towns are located close to the coast (Flood & Sweeney, 2012). Over the last seven years, Ireland has experienced five large-scale storms that disrupted the economy and social life and destroyed properties. These storms include Storm Ophelia in 2017, Storm Eleanor in 2018, and in 2021 storms Darcy, Arwen, and Barra.

Climate change directly impacts Ireland's agricultural sector, which is a crucial part of the country's economy and culture (Emmet-Booth et al., 2019). The changing temperature, precipitation patterns, and extreme weather events affect crop yields and livestock management, increasing farmers' costs. This, in turn, has implications for food security and rural livelihoods. However, some crops like barley and wheat may benefit from climatic changes due to the positive effects of CO_2 fertilisation (Boere et al., 2019). Furthermore, outdoor workers may face occupational heat stress challenges as temperatures continue to rise. This could lead to reduced productivity, increased health risks for workers, and implications for overall economic output (Kjellstrom et al., 2014; Dasgupta et al., 2021).

Moreover, climate change impacts human health in Ireland, including the spread of infectious diseases and heat-related illnesses. Vulnerable populations, such as the elderly and those with pre-existing health conditions, are at higher risk (Pascal et al., 2013). The changing climate also affects air and water quality, leading to respiratory and other health problems (Mirsaeidi et al., 2016; Rocklöv & Dubrow, 2020). Besides these, climate change affects the quality and availability of ecosystem services, impacts tourism, and influences mental health. Therefore,

[1] The term "pre-industrial" refers to the period prior to significant industrialisation. It typically refers to the era before the late 18th century, when industrial activities significantly impacted the Earth's climate.

it is imperative to implement adaptive measures to mitigate these impacts and safeguard the health, security, and prosperity of Ireland's people and ecosystems.

Climate change adaptation refers to the adjustments made to cope with the actual and expected climate changes and their effects. The goal is to minimise harm or take advantage of beneficial opportunities (IPCC, 2007, 2014). These adjustments can take various forms, ranging from policies, infrastructure, and behaviour modifications to address the effects of climate change on economies, ecosystems, and societies (Agrawala et al., 2008). Several adaptation options are available, from simple solutions like early warning systems for floods and storms to more complex solutions such as sustainable agricultural practices, improving infrastructure, and enhancing coastal protection. These options can be broadly grouped into soft, grey, and green measures (European Environment Agency (EEA), 2013; Bachner et al., 2019; Flood et al., 2020). Soft measures comprise information measures such as early warning systems. Grey measures are comprised of structural protection, such as flood protection dams. Green measures are ecosystem-based measures such as natural flood retention areas or forest management.

Adapting to climate change can bring multiple co-benefits, such as increased food security, improved public health, and enhanced ecosystem services (IPCC, 2014; Zusman et al., 2021). It can also create new economic opportunities by developing green technologies and new jobs that can help build a more resilient and equitable society. In addition, adaptation contributes to social justice and equity by ensuring that the consequences of climate change do not disproportionately burden the most vulnerable populations.

Furthermore, adaptation is a critical component of climate change mitigation. While mitigation efforts aim to reduce greenhouse gas emissions to minimise the extent of climate change, some level of warming is already locked in due to past emissions (Watkiss, 2007; Matthews & Caldeira, 2008; Agrawala et al., 2011). Therefore, adapting to the changing climate is necessary to cope with unavoidable impacts. At the same time, efforts must continue to mitigate emissions to prevent further warming and reduce the severity of the future effects.

This paper provides an overview of Ireland's climate change adaptation options and their associated costs and benefits. The aim is to provide cost estimates that can support economic analysis of adaptation research and decision-making in Ireland. The paper builds on previous research by de Bruin et al. (2024) on the economic costs and benefits of the impacts of climate change in Ireland. Section 3 reviews the available adaptation options and discusses how they are being implemented. Section 4 presents the methods for estimating the costs and benefits of the adaptation measures, along with some estimates of costs and benefits. Section 5 discusses the barriers to implementing adaptation measures, policy, and institutional challenges. Finally, section 6 concludes with a summary of key findings and their implications for future policy and decision-making regarding climate change adaptation in Ireland.

2 Climate change adaptation options

Ireland has been taking proactive steps to address the potential impacts of climate change by formulating and implementing various adaptation measures to build resilience against changing climatic conditions. These measures are outlined in national policies, such as the National Adaptation Framework (NAF) and sectoral adaptation plans. The NAF is a roadmap to create a climate-resilient economy and society by prioritising and integrating climate adaptation actions into all national policies and plans. On the other hand, sectoral adaptation plans are sector-specific strategies that manage climate risks and climate-related hazards (Department of the Environment, Climate and Communications, 2018, 2020; Flood et al., 2020). This section examines these policies and provides an overview of various adaptation measures concerning flood risk management, agriculture, health, and biodiversity. The goal is to assess the level of adaptation planned and/or being implemented.

2.1 Flood risk management

Flood risk management in Ireland is a comprehensive approach that combines engineering solutions, natural resource management, policy development, and community involvement. The goal is to minimise the impacts of flooding and improve society's resilience to this significant hazard. Critical components of flood risk management in Ireland include:

Flood risk assessment

Flood risk assessment involves identifying flood-prone areas, analysing potential flood scenarios, and evaluating the consequences of inundation. This includes mapping floodplains, assessing river flows, and evaluating coastal vulnerability.

Flood forecasting and early warning systems

Here, advanced hydrological models and real-time monitoring are used to predict flood events and promptly notify at-risk communities. Such systems are critical in reducing the impact of floods by giving residents and authorities sufficient time to implement evacuation plans and take protective measures.

Flood defence infrastructure

This includes the physical structures built and maintained to reduce the likelihood and severity of flooding. These structures include dams, flood walls, and flood barriers. They are designed to contain floodwaters, divert flow away from populated areas, and protect critical infrastructure such as roads, bridges, and utilities.

Natural flood management

Natural flood management involves using nature-based solutions to mitigate flood risk. These methods include restoring wetlands, creating floodplains, and reforesting upland areas. Doing so slows water runoff, absorbs excess water, and minimises the possibility of downstream flooding. In addition, natural flood management techniques contribute to the creation of habitats for wildlife and enhance ecosystem resilience.

Land use planning and floodplain management

This involves implementing zoning regulations, floodplain development controls, and flood risk assessments for planning applications. The primary objective is to incorporate flood risk considerations into land use planning decisions. This is done to prevent development in flood-prone areas and ensure that new developments are robust enough to withstand flooding.

Community engagement and resilience-building

This involves educating and training on flood safety, facilitating community flood action groups, and promoting measures to enhance community resilience.

2.2 Agriculture, forestry and seafood

Various adaptation options are being employed in the agriculture, forestry, and seafood sectors to address the challenges posed by climate change. Some of the current adaptation measures include:

Diversification of crops and livestock

Farmers are reducing their vulnerability to climate variability and extreme weather events by diversifying their crop and livestock portfolios. This involves experimenting with new crop varieties, adopting drought-resistant crops, and introducing alternative livestock breeds better suited to the changing climatic conditions.

Improved water management

Farmers are adopting water management techniques to address changing precipitation patterns and water availability challenges. These techniques include the implementation of rainwater harvesting, improving irrigation efficiency, and managing drainage. By optimising water use, mitigating drought risks, and reducing soil erosion and nutrient runoff, these measures help to ensure sustainable agricultural practices.

Adoption of sustainable agricultural practices

Farmers are increasingly adopting sustainable agricultural practices to enhance soil health, biodiversity, and resilience to climate change impacts. These practices include conservation tillage, crop rotation, agroforestry, and integrated pest management, which can help improve soil fertility, increase crop resilience, and reduce greenhouse gas emissions.

Climate-smart forestry

Foresters are implementing climate-smart forestry practices to adapt to changing environmental conditions and ensure the resilience and productivity of forest ecosystems. This involves promoting mixed-species forests, selecting tree species resilient to climate change, and enhancing forest management techniques to improve forest health and resilience.

Marine spatial planning and ecosystem-based management

To ensure the sustainable use of marine resources and protect aquatic ecosystems from the impacts of climate change, authorities are implementing marine spatial planning and ecosystem-based management approaches. This includes designating marine protected areas, regulating fishing activities, and promoting habitat restoration and conservation measures.

Research and innovation

There is ongoing research and innovation in agriculture, forestry, and marine sectors to develop new technologies, tools, and practices that enhance resilience to climate change. Researchers focus on climate-resilient crop varieties, forest management strategies, marine ecosystem monitoring technologies, and sustainable fisheries management approaches.

2.3 Health

The healthcare sector is taking various measures to combat the challenges posed by climate change. Some of the adaptation options include:

Heatwave response plans

Authorities have developed and are executing heatwave response plans to safeguard vulnerable individuals such as the elderly, children, and those with pre-existing health conditions from the adverse impacts of extreme heat events. These plans involve issuing public health advisories and heatwave warnings and providing cooling centres and access to drinking water.

Air quality management

This involves implementing measures to improve air quality and reduce the health impacts of air pollution, which can exacerbate respiratory and cardiovascular conditions. Additional measures include promoting cleaner energy sources, reducing emissions from transportation and industry, and implementing air quality monitoring and public health advisories during periods of poor air quality.

Climate-resilient healthcare infrastructure

The goal is to guarantee that healthcare facilities and services are resilient to climate-related hazards like severe weather conditions and power failures. This involves evaluating and upgrading healthcare infrastructure, creating emergency response strategies, and ensuring the continuity of care during extreme weather events.

Public health education and outreach

Conducting public health education and outreach campaigns to raise awareness about the health risks of climate change and promote adaptive behaviours. This includes providing information on heatwave preparedness, vector-borne disease prevention, and air quality management strategies to help individuals and communities protect their health.

Research and surveillance

Research and surveillance are conducted to monitor the health impacts of climate change, identify vulnerable populations, and assess the effectiveness of adaptation measures. This includes epidemiological studies, health impact assessments, and data collection on climate-sensitive health indicators to inform decision-making and policy development.

2.4 Biodiversity

Various measures are being taken to address the challenges posed by climate change in the context of biodiversity management. The options available for adaptation include:

Habitat restoration and conservation

This involves restoring degraded habitats, creating wildlife corridors, and protecting critical habitats such as wetlands, woodlands, and coastal areas to support biodiversity and ecosystem services. These projects are implemented to enhance ecosystem resilience to climate change impacts.

Species conservation and management

This includes monitoring populations, establishing protected areas, and implementing recovery plans for threatened species to protect vulnerable and endangered species from the impacts of climate change. The objective is to ensure their long-term survival and resilience.

Climate-smart land management practices

This involves promoting climate-smart land management practices such as agroforestry, reforestation, and sustainable land use planning to enhance ecosystem resilience and carbon sequestration. These practices help improve soil health, water retention, and biodiversity while mitigating greenhouse gas emissions and improving ecosystem services.

Integrated water resource management

This approach involves restoring rivers and lakes, managing water quality, and regulating water abstraction to protect freshwater ecosystems and aquatic biodiversity from the impacts of climate change. The objective is to ensure the sustainability of marine ecosystems and freshwater resources.

Research and monitoring

This includes ecological surveys, biodiversity monitoring programs, and modelling studies to assess the impacts of climate change on ecosystems and biodiversity. The aim is to identify vulnerable species and habitats and evaluate the effectiveness of adaptation measures. This information is used to inform decision-making and adaptive management strategies.

2.5 Ecosystem-based adaptation

Ecosystems are crucial in adapting to climate change as they provide services that promote human well-being and increase resilience to the impacts of climate change. Ecosystem-based adaptation (EbA) is a nature-based technique that involves using ecosystem services to reduce vulnerability and increase the resilience of communities and ecosystems to climate change (Doswald et al., 2014). Ecosystems support climate change adaptation, including water regulation and quality control, coastal erosion and flood protection, carbon sequestration, and biodiversity and ecosystem services (Pramova et al., 2012). For instance, forests can regulate water flow and quality, reducing the chances of flooding and droughts. Wetlands can absorb excess water during heavy rainfall, reducing the risk of flooding and erosion. Coastal ecosystems like mangroves and salt marshes can protect against coastal erosion and flooding by absorbing wave energy and reducing the impact of storm surges.

Besides these significant services, ecosystems provide numerous co-benefits supporting human well-being and contributing to sustainable development (IPCC, 2014; Zusman et al., 2021). EbA can promote sustainable land use practices and ecotourism development, improving food security and increasing local incomes. It can also help conserve biodiversity and cultural heritage, which can have social and economic benefits.

Although ecosystems are crucial in adapting to climate change, they are often undervalued and lack sufficient funding in adaptation planning and decision-making processes (Clark et al., 2018). This oversight can result in the degradation and depletion of ecosystems, diminishing their capacity to provide vital services and exacerbating the impacts of climate change. To maximise the benefits of EbA, it is critical to integrate ecosystem considerations into climate change adaptation planning and decision-making processes. This involves identifying priority ecosystems and services, developing policies and regulations to support EbA, and including local communities and stakeholders in implementing EbA initiatives. In this respect, the recently published 4th National Biodiversity Action Plan (NBAP) underscores Ireland's commitment to protecting and restoring its ecosystems, species, and genetic diversity. It provides a framework for coordinated action, resource allocation, monitoring, and reporting on biodiversity conservation efforts, with the overarching goal of preserving Ireland's rich natural heritage and promoting sustainable development for present and future generations.

2.6 Adaptation measures in response to climate change impacts

This section highlights the adaptation measures being implemented or considered in Ireland in response to the impacts of climate change.

Flood Risk Management Plans

The Office of Public Works (OPW) has developed flood risk management plans for over 300 communities across the country. These plans include flood defences, emergency response plans, and flood forecasting, which serve as a framework for managing the risk of flooding. Additionally, the OPW has implemented various measures to adapt to impacts of coastal erosion and flooding. These measures include beach nourishment, dune restoration, and the construction of sea walls and other protective structures.

Sustainable Farming Practices

The Department of Agriculture, Food, and the Marine has introduced several initiatives to promote sustainable farming practices in Ireland, including the Sustainable Agricultural Production Scheme and the Green Low-Carbon Agri-Environment Scheme. These initiatives encourage farmers to adopt sustainable practices such as crop rotation, reduced tillage, and agroforestry, which help mitigate the impacts of climate change.

Renewable Energy

Ireland aims to produce 70% of its electricity from renewable sources by 2030. The country has made significant progress towards this target, with renewable energy sources accounting for over 40% of electricity generation in 2020. Developing wind and solar energy infrastructure has been key to achieving this target.

Urban Heat Island Mitigation

Dublin City Council has implemented measures to mitigate the impacts of urban heat islands, where the temperature is significantly higher than in surrounding rural areas due to the urban heat island effect. These measures include the installation of green roofs, the planting of trees and other vegetation, and the development of cool pavements and other reflective surfaces.

Biodiversity Action Plan

This plan recognises the intrinsic value of biodiversity and its interconnectedness with various aspects of society, including agriculture, forestry, fisheries, tourism, and human health. It provides a framework for coordinated action, resource allocation, monitoring, and reporting on biodiversity conservation efforts, with the overarching goal of preserving Ireland's rich natural heritage and promoting sustainable development for present and future generations.

3 Estimating the costs and benefits of adaptation options

When investing in adaptation, it is important to consider the costs, benefits, and trade-offs associated with different options. This requires using various evaluation methods and criteria, such as efficiency and effectiveness, to assess different adaptation measures based on the agreed objectives. By quantifying the economic implications of adaptation, policymakers, stakeholders, and communities can make informed decisions on allocating resources and prioritising actions to achieve the most effective and efficient outcomes. This section discusses different methodologies, highlighting key steps and considerations used to estimate the costs and benefits of various agriculture, flood protection, and health adaptation measures. In addition, it draws on several data sources to estimate the costs and benefits of these measures in Ireland.

3.1 Assessment methods

Different approaches are used to evaluate the potential costs and benefits of adaptation options. These include cost-benefit analysis, cost-effectiveness analysis, multi-criteria analysis, economic modelling, and expert elicitation (Watkiss, 2009). Each approach has strengths and limitations, and it is important to understand their differences to conduct thorough and informative evaluations. With this knowledge, decision-makers can choose the most efficient and effective adaptation options that align with their objectives.

3.1.1. Cost-Benefit Analysis

Cost-benefit analysis is a commonly used approach for evaluating the economic effectiveness of measures aimed at adapting to climate change. This method involves assessing the monetary costs and benefits of different adaptation options to provide decision-makers with valuable insights into potential returns on investment, trade-offs, and the impacts of different strategies in enhancing resilience against climate-related risks (Hanley & Barbier, 2009; Chiabai et al., 2015; Kuik et al., 2016; Atkinson et al., 2018; Cahill & O'Connell, 2018; O'Mahony, 2021). The process includes several key steps:

1. Identification of Adaptation Options: The first step in conducting a CBA is to identify a range of potential adaptation measures that address the impacts of climate change in a specific context. This may include investments in infrastructure, policy interventions, behavioural changes, and technological innovations to reduce vulnerability and enhance resilience.

2. Definition of Objectives and Criteria: Clear objectives and evaluation criteria are established to guide the analysis. Objectives may include reducing damage from climate-related hazards, protecting public health, preserving ecosystems, or enhancing social resilience. Criteria such as economic efficiency, effectiveness, equity, feasibility, and sustainability are used to evaluate the performance of adaptation options.

3. Estimation of Costs: The costs associated with each adaptation option are quantified, including initial investment, operation and maintenance costs, and any additional costs incurred over the project's lifecycle. Costs are categorised into capital, recurrent, and other relevant expenditures, with detailed cost estimates obtained from relevant sources such as project proposals, financial reports, and expert consultations.

4. Valuation of Benefits: The benefits of adaptation measures are assessed in terms of the avoided or reduced damages, losses, or negative impacts of climate change. These benefits are monetised using market prices, replacement costs, or other valuation techniques and include avoided infrastructure damages, increased agricultural yields, reduced healthcare costs, preserved biodiversity, enhanced ecosystem services, and improved societal well-being.

5. Discounting: Future costs and benefits are discounted to their present value using an appropriate discount rate, typically based on the opportunity cost of capital or social discount rate. Discounting ensures that future costs and benefits are appropriately weighted relative to present values and facilitates comparison across time periods.

6. Decision-making: The decision-maker can determine the most economically efficient adaptation options with the most significant net benefits after discounting. An adaptation option is considered efficient if its net present value (NPV), which is the difference between the present value of the benefits and the present value of the costs, is greater than zero (United Nations Framework Convention on Climate Change (UNFCCC), 2011). Alternatively, an adaptation option is also efficient if it has a benefit-cost ratio (BCR) greater than one or a higher internal rate of return (IRR), which is the discount rate that makes the NPV equal to zero. BCR is the ratio of the present value of benefits to the present value of costs.

Cost-benefit analysis (CBA) is attractive as it assesses tangible and intangible benefits, such as avoided damages, improved health outcomes, and enhanced ecosystem services. It provides a comprehensive understanding of the potential returns on investment. However, CBA has limitations in that it may not consider non-market values associated with environmental goods and services, social or cultural values, and distributional impacts. This often leads to inequitable outcomes, overlooking the needs of vulnerable populations. Furthermore, potential important secondary impacts are generally ignored.

3.1.2. Cost-Effectiveness Analysis

Cost-Effectiveness Analysis (CEA) is a decision-making tool that helps assess the viability of climate change adaptation measures by comparing their costs to selected physical targets. Unlike traditional cost-benefit analysis (CBA), which measures benefits in monetary terms, CEA focuses on the cost per unit of target achieved, allowing decision-makers to identify the most efficient use of resources in achieving adaptation objectives. CEA evaluates adaptation options where benefits, including biodiversity and ecosystem services, are challenging to express in monetary terms (Balana et al., 2011; UNFCCC, 2011; Atkinson et al., 2018). The process involves several key steps:

1. Definition of Outcome Measures: The initial step in CEA involves defining outcome measures or targets that reflect the effectiveness of adaptation measures in achieving their intended objectives. Outcome measures may include reductions in vulnerability, increases in resilience, improvements in ecosystem services, avoided damages or losses, or other relevant indicators of climate resilience. Outcome measures are selected based on the goals and priorities of the adaptation process and may vary across different contexts and sectors.

2. Estimation of Costs: The costs associated with each adaptation measure are quantified, including initial investment, operation and maintenance costs, and any additional costs incurred over the life cycle of each option. Costs are categorised into capital expenditures, recurrent costs, and other relevant expenditures, with detailed cost estimates obtained from project proposals, financial reports, and expert consultations. Costs are typically expressed in monetary terms to facilitate comparison across different options. Like CBA, all costs are discounted to their present value using an agreed discount rate.

3. Measurement of Effectiveness: Adaptation measures are evaluated based on their effectiveness in achieving the defined outcome measures. Effectiveness may be assessed using quantitative or qualitative indicators, such as changes in vulnerability indices, ecosystem health improvements, disaster risk reductions, or other relevant metrics. Data on effectiveness are collected through monitoring, evaluation, and performance assessments conducted during or after the implementation of adaptation measures.

4. Calculation of Cost-Effectiveness Ratios: Cost-effectiveness ratios are calculated for each adaptation measure by dividing the total costs by the achieved outcomes. Cost-effectiveness ratios represent the cost per unit of outcome achieved and provide decision-makers with a standardised measure of efficiency. Measures with lower cost-effectiveness ratios are considered more efficient, as they achieve greater outcomes relative to their costs.

CEA is a useful method to compare different adaptation options when it is not possible to quantify benefits in monetary terms. It helps identify the most cost-effective option to achieve a specific objective. However, CEA alone may not provide a complete decision-making tool as it only considers benefits in one dimension, such as cost-effectiveness. Other important factors such as equity, feasibility, and co-benefits should also be considered when selecting the best option (UNFCCC, 2011).

3.1.3. Multi-Criteria Analysis

Multi-criteria analysis (MCA) is a technique used for decision-making that simultaneously considers several criteria or goals to evaluate climate change adaptation strategies. Each criterion is given a weight, and an overall score is calculated for each adaptation option using these weights. The adaptation option with the highest score is selected. MCA provides an alternative way to evaluate adaptation options when only partial data is available, cultural, and ecological factors are difficult to quantify, and monetary benefit or effectiveness is not the only consideration (de Bruin et al., 2009; Balana et al., 2011; UNFCCC, 2011; Atkinson et al., 2018; Flood et al., 2020).

MCA involves several key steps, beginning with the identification of criteria and objectives. This involves identifying a set of criteria and objectives that stakeholders consider important for evaluating adaptation measures. These criteria may include economic efficiency, effectiveness, equity, social justice, environmental sustainability, feasibility, and stakeholder preferences. Objectives are defined based on the goals of the adaptation process and may vary depending on the context and priorities of decision-makers.

The second step involves the weighting of criteria. Stakeholders assign weights to each criterion to reflect their relative importance in decision-making. Weighting is typically done through consultation and deliberation among stakeholders, considering their values, preferences, and expertise. Techniques such as surveys, workshops, and interviews may be employed to ensure that diverse perspectives are adequately represented in the weighting process.

The third step is evaluating adaptation options. Adaptation measures are evaluated against the defined criteria using qualitative or quantitative assessments. Adaptation options are scored or ranked for each criterion based on their performance, with higher scores indicating better alignment with the objectives. Decision support tools, such as scoring matrices, decision trees, or analytical hierarchy processes, may be used to facilitate the evaluation process and ensure transparency and consistency.

The fourth step is the trade-off analysis. MCA allows for exploring trade-offs between different criteria and objectives, recognising that achieving one objective may entail compromising another. Decision-makers examine how adaptation options perform across multiple criteria and identify potential trade-offs or synergies between them. Sensitivity analysis and scenario testing can help assess the robustness of the results and explore alternative decision pathways under different conditions.

The final step is integrating stakeholder preferences. MCA facilitates this by ensuring that adaptation measures reflect the needs and priorities of diverse stakeholders. Stakeholder engagement activities, such as focus groups, stakeholder workshops, and participatory decision-making processes, are essential for eliciting preferences, building consensus, and fostering ownership of the outcomes.

The MCA approach is a structured framework that promotes stakeholder engagement and consensus-building in decision-making. This participatory method enhances the legitimacy and acceptability of the selected adaptation strategies, resulting in greater support and buy-in from stakeholders. However, the method has challenges, such as assigning weights, especially when the number of criteria is large and diverse. In addition, the subjectivity in weighting criteria and scoring alternatives may introduce biases and uncertainties into the decision-making process, leading to inconsistent or subjective outcomes.

3.1.4. Expert elicitation

Expert elicitation is a method that is used to gather and combine expert judgment and knowledge to estimate the costs and benefits of climate change adaptation measures. This method involves seeking input from people or groups with relevant expertise in climate science, economics, engineering, and other fields. Expert elicitation provides valuable insights and informed estimates when empirical data is limited or uncertain (Morgan & Henrion, 1990; Morgan & Keith, 1995; Zickfeld et al., 2007; Hagerman et al., 2010). The approach involves the following key steps:

1. Selection of Experts: Experts are selected based on expertise, experience, and knowledge relevant to the specific adaptation measures under consideration. Experts may include scientists, policymakers, practitioners, and other stakeholders with domain-specific knowledge of climate change impacts, adaptation strategies, economic valuation, and risk assessment. Interdisciplinary panels of experts are often convened to ensure diverse perspectives and comprehensive coverage of relevant topics.

2. Elicitation of Expert Judgment: Experts are engaged through structured elicitation processes, such as workshops, surveys, interviews, or Delphi techniques, to elicit their judgment, opinions, and estimates regarding the costs and benefits of adaptation measures. Elicitation methods may vary depending on the complexity of the adaptation measures and the availability of data. Experts are asked to provide quantitative estimates, qualitative assessments, or probability distributions based on their knowledge and expertise.

3. Integration of Expert Responses: Expert responses are aggregated and synthesised to derive consensus estimates or distributions of costs and benefits for each adaptation measure. Statistical techniques, such as Bayesian updating, weighted averaging, or meta-analysis, may be used to combine individual expert judgments and account for uncertainties and variability in the estimates. Consensus-building techniques are employed to resolve disagreements and reconcile divergent viewpoints among experts.

4. Validation and Sensitivity Analysis: The validity and robustness of expert estimates are assessed through validation against empirical data, comparison with alternative sources of information, and a sensitivity analysis to test the impact of different assumptions, expert opinions, and uncertainties on the results. Sensitivity analysis helps identify influential factors and sources of uncertainty that may affect the reliability and credibility of the estimates.

Expert elicitation is useful for gathering insights from various sources, such as scientists, practitioners, and policymakers. This allows for a comprehensive understanding of complex issues and can help overcome data limitations and uncertainties (Usher & Strachan, 2013). Decision-making processes can be more robust by combining expert judgments with qualitative insights to create quantitative analyses. However, expert elicitation is not without its limitations. It is prone to bias and subjectivity due to personal experiences, cognitive biases, or group dynamics that may influence expert judgments. Furthermore, eliciting and synthesising expert judgments is often not well-documented or standardised, leading to a lack of transparency and reproducibility.

3.2. Estimates of costs and benefits

This section draws on several data sources to estimate the costs and benefits of various adaptation measures in Ireland. These sources comprise economic and (bio)physical models, peer-reviewed, grey, and technical literature. The cost and benefit estimates provided in this section are mainly indicative since the precise numbers may vary significantly, depending on various factors like the size and scale of the adaptation project. However, these estimates offer helpful information for adaptation planning and policy discussions.

3.2.1. Coastal and river flooding

Strategies for adapting to coastal and river flooding can be classified into three categories: protection, retreat, and accommodation (IPCC, 2007; Agrawala et al., 2008; Dottori et al., 2020; Vousdoukas et al., 2020). Protection aims to shield these areas from flooding by constructing physical structures like floodwalls and nature-based measures like mangrove planting and floodplain restoration. Retreat strategies involve moving or abandoning development in high-risk or flood-prone areas that are no longer safe to inhabit. This may involve voluntary buyouts of at-risk properties, managed relocation of infrastructure and communities to safer locations, or restoring natural habitats to create buffer zones between the sea and development. Accommodation involves accepting and adapting to rising flood risks by adjusting land use and development practices to reduce vulnerability to erosion and flooding. This may include designing buildings and infrastructure to be more resilient to flooding, implementing setback policies to limit development in high-risk areas, and creating green spaces that absorb floodwater.

Most studies that analyse the costs and benefits of coastal and river adaptation measures use impact assessment models such as DIVA, FUND, and LISFLOOD (Tol & Anthoff, n.d.; Hinkel and Klein, 2009; Alfieri et al., 2016a, 2016b). These models aim to minimise the total costs of climate change by considering the costs of adaptation and the residual damages caused by floods or wetland loss. In simpler terms, the benefits of proposed adaptation measures are expressed as a reduction in the risk of floods or "expected annual damage" (EAD). Table 1 presents benefit-cost ratios (BCR) and percentage EAD reduction for four river flooding adaptation measures under two climate scenarios in Ireland. The results indicate that investing in flood adaptation measures may be economically desirable, with BCR exceeding one for all adaptation measures. Among the measures, damage reduction measures for buildings and the building of retention areas to store flood waters have the highest BCR, indicating that implementing these measures can effectively lower impacts in Ireland. For coastal flood adaptation measures, a study conducted by Vousdoukas et al. (2020) estimates that protecting Irish coastlines will bring benefits that far outweigh the costs, with benefit-to-cost ratios of 6.1 and 7.9 under moderate and high emission scenarios, respectively.

Table 1. Benefit-cost ratio (BCR) values and % Expected Annual Damage (EAD) reduction for river flood adaptation measures.

Adaptation measure	SSP1-RCP2.6		SSP2-RCP4.5	
	BCR	EAD reduction	BCR	EAD reduction
Protection	1.7	36%	2.6	38%
Building of retention areas to store flood waters	2.2	64%	2.7	67%
Retreat	1.3	29%	1.3	30%
Damage reduction measures for buildings	5.6	50%	5.7	50%

Source: Based on Ward et al. (2017), Lincke et al. (2019), and Dottori et al. (2020), the BCR values represent the total discounted costs and benefits from 2020 to 2100.

The Coastal Impact and Adaptation Model (CIAM) is a global modelling tool aimed at estimating costs and adaptation strategies for coastal segments. It subdivides the coastlines of the world (excluding Antarctica) into over 12,000 linear segments of varying lengths. These segments are associated with physical, ecological, and socioeconomic parameters, allowing for a comprehensive analysis of their impacts. The model includes 29 unique coastal segments within Ireland.

Table 2 displays the CIAM model estimates for Ireland of gross damages (i.e. total damage costs in the no adaptation scenario), residual damages (total damage costs in the optimal fixed adaptation scenario) and adaptation costs (relocation and protection costs) in the optimal fixed adaptation scenario (Diaz, 2016). These estimates reflect the high damage reduction potential of coastal protection where the adaptation levels reflect the fraction of gross damages that can be reduced through adaptation which varies between 0.81 and 0.90. The benefits of adaptation far outweigh the cost with an approximate BCR of between 23 and 75.

Table 2. Adaptation estimates from the CIAM model in billions (US$ 2010)

	2050			2100		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Relocation costs	0.04	0.05	0.07	0.06	0.05	0.08
Protection costs	0.02	0.02	0.03	0.03	0.03	0.04
Residual damages	0.33	0.42	0.55	0.58	0.71	0.97
Gross damages	2.00	2.31	2.85	4.58	7.03	7.11
Adaptation level	0.83	0.82	0.81	0.87	0.90	0.86
BCR	28	25	23	47	75	47

Source: CIAM model based on Diaz (2016).

3.2.2. Agriculture

Agricultural adaptation measures can be broadly categorised into farm and public (Agrawala et al., 2008; Fankhauser, 2010). Farm-level adaptation includes actions by individual farmers or farm operators, such as diversification of production, adjusting the timing of operations, irrigation, and regulating input use like fertilisers. These measures are relatively low or no-cost. On the other hand, public-level adaptation refers to broader policy interventions, support programs, and infrastructure investments implemented by national and regional governments. These measures are aimed at supporting farmers in adapting to changing climatic conditions. Public-level adaptations complement farm-level adaptations and include public goods like research on drought-resistant crop varieties and climate forecasts. However, these measures often require substantial financial resources.

Estimating the cost of agricultural adaptation measures is challenging because most studies focus on farm-level adjustments, which are assumed to entail low or no cost. Studies that provide cost estimates of public-level adaptation measures focus on investments in physical capital like irrigation infrastructure, research in drought-resistant seed varieties, and agricultural extension (McCarl, 2007). However, these estimates vary widely as they depend on factors such as location and scale.

Using simplified assumptions and several data sources, including available data from government reports and expert opinions, unit cost estimates are provided for some adaptation options in Ireland's agriculture. To indicate the level of uncertainty in our estimates, both lower and upper bounds are provided.

1. The cost of crop diversification may range from €100 to €500 per hectare for purchasing seeds of resilient crop varieties or implementing crop rotation practices.

2. The cost of soil conservation measures, such as cover cropping or reduced tillage, may range from €50 to €500 per hectare.

3. The investment cost in irrigation infrastructure can range from €2,000 to €10,000 per hectare for drip irrigation systems, depending on the complexity of the system and the size of the area to be irrigated.

4. The cost of insurance premiums may range from €50 to €500 per hectare per year depending on factors such as the level of coverage, the perceived risk, and the insurance provider.

5. The cost of investing in climate-resilient infrastructure (such as greenhouses or windbreaks) may range from €5,000 to €100,000 per hectare, depending on the scale and complexity of the project.

6. The cost of investment in research and development may range from tens of thousands to millions of euros, depending on the scope and duration of the project.

Studies have shown that implementing agriculture adaptation measures can result in increased productivity, reduced risk of crop failure, and improved resilience to climate change.

The available literature suggests that implementing adaptation measures at the farm level can result in significant benefits. However, the magnitude of these benefits varies based on factors such as the region, crop, and the level of climate change. Most studies employ crop impact models to demonstrate that changes in farm management practices can significantly offset projected declines in yield. Estimates of these benefits range from 23% to as high as 200% (Tan & Shibasaki, 2003; Agrawala et al., 2008).

3.2.3. Health

Estimating the costs and benefits of health adaptation measures is a complex task. One of the reasons for this complexity is the challenge of distinguishing between the components of investing in public health infrastructure needed to address climate change and those required due to social and demographic trends (Chiabai et al., 2015). However, unit cost estimates are provided for some health adaptation measures in Ireland based on simplified assumptions, available data from government reports, and expert opinions. To indicate the uncertainty margins of the estimates, lower and upper bounds are provided.

1. The cost of implementing heatwave response plans, including public health advisories, cooling centres, and outreach campaigns, can range from €1 million to €5 million per year, depending on the scale and scope of the program.

2. The initial investment required to retrofit healthcare facilities to withstand extreme weather events and power outages and develop emergency response plans can range from €20 million to €100 million, with ongoing maintenance costs of €1 million to €5 million per year.

3. Strengthening surveillance systems for vector-borne diseases and implementing control measures, such as mosquito control programs and public education campaigns, could require an investment of €500,000 to €2 million annually.

4 Barriers to implementation

Ireland has taken significant steps in developing adaptation strategies to tackle the challenges posed by climate change. However, putting them into action is not a simple task. This section investigates the obstacles that prevent the effective implementation of adaptation measures across different sectors in Ireland. The aim is to identify the significant challenges, gaps, and obstacles that must be overcome to promote greater resilience and sustainability in a changing climate.

4.1 Identification of barriers

Adaptation measures are essential for addressing the impacts of climate change. However, several barriers can hinder their implementation. Identifying these barriers is crucial for developing effective policies and practices for adaptation. This section will discuss the main obstacles that can hinder the implementation of adaptation measures in Ireland.

1. Lack of awareness is one of the primary barriers to implementing adaptation measures. Many stakeholders, including policymakers, businesses, and the public, may not fully

understand the risks of climate change and the benefits of adaptation. This leads to a lack of political will and insufficient funding for adaptation initiatives.

2. Limited resources can be a significant challenge to implementing adaptation measures. It can require significant financial and technical resources, which are often unavailable or insufficient. This can be particularly challenging for small and medium-sized enterprises, local communities, and vulnerable groups, which may lack the financial and technical capacity to implement effective adaptation measures.

3. Institutional and legal barriers can also hinder the implementation of adaptation measures. Complex regulatory frameworks, conflicting mandates, and institutional fragmentation can impede stakeholder coordination and collaboration, making it challenging to develop and implement effective adaptation policies and practices.

4. Lack of data and information is another significant challenge to effective adaptation planning and decision-making. In many cases, the data and information necessary to develop and implement adaptation measures may be incomplete, outdated, or unavailable, making it difficult to assess the risks and identify the most effective measures.

5. Resistance to change can also be a significant barrier to implementing adaptation measures. Stakeholders may resist changes in business practices or land use patterns or may be reluctant to adopt new technologies or approaches, particularly if they perceive these changes as costly or disruptive.

4.2 Policy and institutional challenges

To implement effective climate change adaptation measures in Ireland, several policy and institutional challenges need to be addressed. One of the most significant challenges is the need for constant coordination and integration of climate change adaptation policies across different sectors and levels of government. This requires a whole-of-government approach that engages multiple stakeholders, including national and local governments, private sector actors, civil society organisations, and communities.

Another challenge is ensuring adequate funding and resources for developing and implementing climate change adaptation measures. This includes funding for research, monitoring, and evaluation of adaptation strategies and funding for implementing adaptation measures.

Furthermore, addressing climate change adaptation also requires addressing social and economic inequalities and promoting social justice. Vulnerable populations, such as low-income communities, and marginalised groups, are likely to be disproportionately affected by climate change impacts. Therefore, it is crucial to ensure that adaptation policies and measures are inclusive and equitable and that the voices and perspectives of these groups are heard and considered in decision-making processes.

Institutional capacity building is also important to support effective climate change adaptation in Ireland. This includes building the capacity of government agencies, civil society organisations, and communities to understand and respond to the complex challenges of climate change adaptation. Capacity building can also involve developing new skills and knowledge, strengthening networks and partnerships, and promoting collaboration and knowledge-sharing across different sectors and levels of government.

Finally, effective climate change adaptation requires continuous learning and adaptation. This means regularly monitoring and evaluating the effectiveness of adaptation measures and adjusting them as needed to ensure they remain relevant and effective over time. It also involves learning from best practices and experiences from other countries and sectors and incorporating this knowledge into Ireland's climate change adaptation policies and practices.

5 Conclusion

This paper analyses climate change adaptation options and their economic costs and benefits, aiming to provide cost estimates that can support economic analysis of adaptation research and decision-making in Ireland. It also highlights the challenges and opportunities of adapting to a changing climate.

The paper suggests that investing in flood adaptation measures is crucial. Damage reduction measures for buildings and construction of retention areas are highly cost-efficient and have significant potential to mitigate future damages and losses. The paper also offers cost estimates for different agricultural and health adaptation measures, emphasising the importance of proactive investment in safeguarding key sectors from the impacts of climate change.

It is essential to understand that the cost estimates provided in the paper are relatively conservative, as not all cost categories are included in the estimation. Therefore, they should be used with caution and with some room for error. Moreover, the paper identifies barriers to implementing adaptation measures, including financial constraints, policy gaps, and institutional limitations. This underscores the need for sustained collaboration, innovation, and knowledge sharing to overcome these obstacles and facilitate effective adaptation planning and implementation.

Overall, the paper contributes to building a more resilient and sustainable future for the country in the face of climate change uncertainties. By highlighting the economic implications of adaptation options and identifying pathways for overcoming implementation barriers, it provides a good foundation for continued research, monitoring, and action. This will be essential to enhancing Ireland's adaptive capacity and ensuring the well-being and prosperity of its citizens in a changing climate.

6 References

Agrawala, S., Bosello, F., Carraro, C., de Bruin, K., de Cian, E., Dellink, R., & Lanzi, E. (2011). Plan or React? Analysis of Adaptation Costs and Benefits using Integrated Assessment Models. *Climate Change Economics*, *2*(3), 175–208. http://www.jstor.org/stable/climchanecon.2.3.175

Agrawala, S., Crick, F., Fankhauser, S., Hanrahan, D., Jette-Nantel, S., Pope, G., Skees, J., Stephens, C., Tepes, A., & Yasmine, S. (2008). *Economic aspects of adaptation to climate change costs, benefits and policy instruments: costs, benefits and policy instruments* (S. Agrawala & S. Fankhauser, Eds.). OECD. https://doi.org/10.1787/9789264046214-en

Alfieri, L., Feyen, L., & Di Baldassarre, G. (2016a). Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies. *Climatic Change, 136*(3-4), 507-521. https://doi.org/10.1007/s10584-016-1641-1

Alfieri, L. Feyen, L., Salamon, P., Thielen, J., Bianchi, A., Dottori, F., & Burek, P. (2016b). Modelling the socio-economic impact of river floods in Europe. *Natural Hazards and Earth System Sciences, 16*(6), 1401-1411. https://doi.org/10.5194/nhess-16-1401-2016

Atkinson, G., Mourato, S., & Pearce, D. (2018). *Cost-Benefit Analysis and the Environment*. OECD. https://doi.org/10.1787/9789264085169-en

Bachner, G., Bednar-Friedl, B., & Knittel, N. (2019). How does climate change adaptation affect public budgets? Development of an assessment framework and a demonstration for Austria. *Mitigation and Adaptation Strategies for Global Change*, *24*(7), 1325–1341. https://doi.org/10.1007/s11027-019-9842-3

Balana, B. B., Vinten, A., & Slee, B. (2011). A review on cost-effectiveness analysis of agri-environmental measures related to the EU WFD: Key issues, methods, and applications. *Ecological Economics*, *70*(6), 1021–1031. https://doi.org/10.1016/j.ecolecon.2010.12.020

Boere, E., Batka, J., Folberth, M., Karstens, C., Kindermann, K., Krasovskii, G., Leclere, A., Wang, D., & Weindl, X. (2019). *D2.2 Impacts on agriculture, forestry & fishery*. https://www.coacch.eu/wp-content/uploads/2020/05/D2.2_after-revision-to-upload.pdf

Cahill, N., & O'connell, L. (2018). *Cost-Benefit Analysis, Environment and Climate Change*. http://files.nesc.ie/nesc_secretariat_papers/No_15_CBA_Env_and_ClimateChange.pdf

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Ha, M. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* https://doi.org/10.59327/IPCC/AR6-9789291691647

Chiabai, A., Hunt, A., Galarraga, I., Lago, M., Rouillard, J., Sainz De Murieta, E., Tepes, A., Troeltzsch, J., & Watkiss, P. (2015). *Using cost and benefits to assess adaptation options*. www.econadapt.eu

Clark, R., Reed, J., & Sunderland, T. (2018). Bridging funding gaps for climate and sustainable development: Pitfalls, progress and potential of private finance. *Land Use Policy*, *71*, 335–346. https://doi.org/10.1016/j.landusepol.2017.12.013

Climate Change Advisory Council. (2022). *ANNUAL REVIEW*. https://www.climatecouncil.ie/media/climatechangeadvisorycouncil/contentassets/publications/CCAC-ANNUAL-REVIEW-2022.pdf

Dasgupta, S., van Maanen, N., Gosling, S. N., Piontek, F., Otto, C., & Schleussner, C.-F. (2021). Effects of climate change on combined labour productivity and supply: an empirical, multi-model study. *The Lancet Planetary Health*, *5*(7), e455–e465. https://doi.org/10.1016/S2542-5196(21)00170-4

de Bruin, K., Dellink, R. B., Ruijs, A., Bolwidt, L., van Buuren, A., Graveland, J., de Groot, R. S., Kuikman, P. J., Reinhard, S., Roetter, R. P., Tassone, V. C., Verhagen, A., & van Ierland, E. C. (2009). Adapting to climate change in The Netherlands: an inventory of climate adaptation options and ranking of alternatives. *Climatic Change*, *95*(1–2), 23–45. https://doi.org/10.1007/s10584-009-9576-4

de Bruin, K., Kyei, C. K., & Henry, L. (2024). *Climate Change Impacts and Associated Economic Costs in Ireland.*

Department of the Environment Climate and Communications. (2020). *Sectoral Adaptation Planning*. https://www.gov.ie/en/collection/51df3-sectoral-adaptation-planning/

Desmond, M., O'brien, P., & Mcgovern, F. (2017). *A Summary of the State of Knowledge on Climate Change Impacts for Ireland*. www.epa.ie

Devoy, R. J. N. (2008). Coastal Vulnerability and the Implications of Sea-Level Rise for Ireland. *Journal of Coastal Research*, *242*, 325–341. https://doi.org/10.2112/07A-0007.1

Doswald, N., Munroe, R., Roe, D., Giuliani, A., Castelli, I., Stephens, J., Möller, I., Spencer, T., Vira, B., & Reid, H. (2014). Effectiveness of ecosystem-based approaches for adaptation: review of the evidence-base. *Climate and Development*, *6*(2), 185–201. https://doi.org/10.1080/17565529.2013.867247

Dottori, Francesco., Mentaschi, Lorenzo., Bianchi, Alessandra., Alfieri, Lorenzo., & Feyen, Luc. (2020). *Adapting to rising river flood risk in the EU under climate change*. https://joint-research-centre.ec.europa.eu/peseta-projects/jrc-peseta-iv/river-floods_en

Emmet-Booth, J. P., Dekker, S., & O'brien, P. (2019). *Climate Change Mitigation and the Irish Agriculture and Land Use Sector*.

European Environment Agency. (2013). *Adaptation in Europe – Addressing Risks and Opportunities from Climate Change in the Context of Socioeconomic Developments*. https://library.wmo.int/records/item/46890-adaptation-in-europe-addressing-risks-and-opportunities-from-climate-change-in-the-context-of-socio-economic-developments?offset=6

Fankhauser, S. (2010). The costs of adaptation. *WIREs Climate Change*, *1*(1), 23–30. https://doi.org/10.1002/wcc.14

Flood, S., Paterson, S., O'connor, E., O'dwyer, B., Whyte, H., Le Tissier, M., & Gault, J. (2020). *National Risk Assessment of Impacts of Climate Change: Bridging the Gap to Adaptation Action*. https://www.epa.ie/publications/research

Flood, S., & Sweeney, J. (2012). *Quantifying Impacts of Potential Sea-Level Rise Scenarios on Irish Coastal Cities* (pp. 37–52). https://doi.org/10.1007/978-94-007-4223-9_5

Hagerman, S., Dowlatabadi, H., Satterfield, T., & McDaniels, T. (2010). Expert views on biodiversity conservation in an era of climate change. *Global Environmental Change*, *20*(1), 192–207. https://doi.org/10.1016/j.gloenvcha.2009.10.005

Hanley, N., & Barbier, E. B. (2009). *Pricing Nature: Cost–Benefit Analysis and Environmental Policy*. Edward Elgar Publishing.

Hinkel, J. (2005). DIVA: an iterative method for building modular integrated models. *Advances in Geosciences*, *4*, 45-50.

Hinkel, J. & Klein, R. J. (2009). Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool. *Global Environmental Change*, *19* (3), 384-395.

Intergovernmental Panel on Climate Change (IPCC). (2022). *Climate Change 2022 – Impacts, Adaptation and Vulnerability* (H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama, Eds.). Cambridge University Press. https://doi.org/10.1017/9781009325844

IPCC. (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Edited by*.

Kjellstrom, T., Lemke, B., Otto, M., Hyatt, O., & Dear, K. (2014). *Occupational Heat Stress*. http://www.climatechip.org/

Kuik, O., Scussolini, P., Mechler, R., Mochizuki, J., Hunt, A., & Wellman, J. (2016). *Assessing the economic case for adaptation to extreme events at different scales Dissemination level Public*. www.econadapt.eu

Lincke, D., Hinkel, J., Ginkel, K. van, Jeuken, A., Botzen, W., Tesselaar, M., Scoccimarro, E., & Ignjacevic, P. (2019). *D2.3 Impacts on infrastructure, built environment, and transport*. https://www.coacch.eu/wp-content/uploads/2019/11/D2.3_final_ottimizzato.pdf

Matthews, H. D., & Caldeira, K. (2008). Stabilizing climate requires near-zero emissions. *Geophysical Research Letters*, *35*(4). https://doi.org/10.1029/2007GL032388

McCarl, B. A. (2007). *Adaptation Options for Agriculture, Forestry and Fisheries. A Report to the UNFCCC Secretariat Financial and Technical Support Division*. https://unfccc.int/files/cooperation_and_support/financial_mechanism/application/pdf/mccarl.pdf

Mirsaeidi, M., Motahari, H., Taghizadeh Khamesi, M., Sharifi, A., Campos, M., & Schraufnagel, D. E. (2016). Climate Change and Respiratory Infections. *Annals of the American Thoracic Society*, *13*(8), 1223–1230. https://doi.org/10.1513/AnnalsATS.201511-729PS

Morgan, M. G., & Henrion, M. (1990). *Uncertainty: A Guide to Dealing With Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge University Press.

Morgan, M. G., & Keith, D. W. (1995). Subjective judgements by climate experts. *Environmental Science & Technology*, *29*(10), 468A-476A. https://doi.org/10.1021/es00010a003

O’Mahony, T. (2021). Cost-Benefit Analysis and the environment: The time horizon is of the essence. *Environmental Impact Assessment Review*, *89*, 106587. https://doi.org/10.1016/j.eiar.2021.106587

Pascal, M., Sweeney, J., Cullen, E., Schwartz, J., & Goodman, P. (2013). Heatwaves and mortality in Ireland, planning for the future. *Irish Geography*, *46*(3), 203–211. https://doi.org/10.1080/00750778.2014.898125

Pramova, E., Locatelli, B., Djoudi, H., & Somorin, O. A. (2012). Forests and trees for social adaptation to climate variability and change. *WIREs Climate Change*, *3*(6), 581–596. https://doi.org/10.1002/wcc.195

Rocklöv, J., & Dubrow, R. (2020). Climate change: an enduring challenge for vector-borne disease prevention and control. *Nature Immunology*, *21*(5), 479–483. https://doi.org/10.1038/s41590-020-0648-y

Tan, G., & Shibasaki, R. (2003). Global estimation of crop productivity and the impacts of global warming by GIS and EPIC integration. *Ecological Modelling*, *168*(3), 357–370. https://doi.org/10.1016/S0304-3800(03)00146-7

Tol, R., & Anthoff, D. (n.d.). *FUND Model*. https://www.fund-model.org/

United Nations Environment Programme. (2023). *Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions (again)*. United Nations Environment Programme. https://doi.org/10.59117/20.500.11822/43922

United Nations Framework Convention on Climate Change. (2011). *Assessing the costs and benefits of adaptation options: An overview of approaches*. https://unfccc.int/resource/docs/publications/pub_nwp_costs_benefits_adaptation.pdf

Usher, W., & Strachan, N. (2013). An expert elicitation of climate, energy and economic uncertainties. *Energy Policy*, *61*, 811–821. https://doi.org/10.1016/j.enpol.2013.06.110

Vousdoukas, M. I., Mentaschi, Lorenzo., Mongelli, Ignazio., Ciscar, J. Carlos., Hinkel, Jochen., Ward, Philip., Gosling, Simon., & Feyen, Luc. (2020). *Adapting to rising coastal flood risk in the EU under climate change*. https://joint-research-centre.ec.europa.eu/peseta-projects/jrc-peseta-iv/coastal-floods_en

Ward, P. J., Jongman, B., Aerts, J. C. J. H., Bates, P. D., Botzen, W. J. W., Diaz Loaiza, A., Hallegatte, S., Kind, J. M., Kwadijk, J., Scussolini, P., & Winsemius, H. C. (2017). A global framework for future costs and benefits of river-flood protection in urban areas. *Nature Climate Change*, *7*(9), 642–646. https://doi.org/10.1038/nclimate3350

Watkiss, P. (2007). *Climate change: the cost of inaction and the cost of adaptation*.

Watkiss, P. (2009). *Potential costs and benefits of adaptation options: A review of existing literature*. https://unfccc.int/resource/docs/2009/tp/02.pdf

Zickfeld, K., Levermann, A., Morgan, M. G., Kuhlbrodt, T., Rahmstorf, S., & Keith, D. W. (2007). Expert judgements on the response of the Atlantic meridional overturning circulation to climate change. *Climatic Change*, *82*(3–4), 235–265. https://doi.org/10.1007/s10584-007-9246-3

Zusman, E., Chae, Y., Kim, H., & Farzaneh, H. (2021). An Introduction to Co-benefits: Core Concepts and Applications. In H. Farzaneh, E. Zusman, & Y. Chae (Eds.), *Aligning Climate Change and Sustainable Development Policies in Asia* (pp. 1–15). Springer Singapore. https://doi.org/10.1007/978-981-16-0135-4_1