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An overview of climate change impacts, adaptation strategies, and future climate in Ireland

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Abstract

To achieve the agreed goals of the Paris Climate Agreement, Ireland has taken significant steps through its ambitious climate legislation. While setting climate policies is paramount to ensure a transition to a low carbon economy, creating a better understanding of the future climate, the impacts of climate change and potential adaptation strategies is vital to prepare Ireland. This paper aims to provide a brief summary of impacts and adaptation strategies, including modelling approaches, numerical estimates, and Ireland's future climatic conditions. Climate forecasts suggest that in the future, Ireland will face significant challenges. This paper discusses Ireland's exposure to observed and future climate change in several sectors including agriculture, labour productivity, coastal flooding, and health. Adaptation measures that are promoted and implemented include the strengthening of flood defences and coastal protection, support for sustainable agriculture as well as incorporating climate resilience into urban planning and infrastructure development. This paper also indicates the need for more research on climate impacts facing Ireland. Although considerable research has been carried out and there is an active research community working on climate and adaptation issues, empirical estimates for some impact categories in Ireland are lacking or outdated.

1 Introduction

The urgency of reducing greenhouse gas (GHG) emissions from anthropogenic sources to reduce their rising concentrations in the Earth's atmosphere is raised by the latest World Meteorological Organisation (WMO) report, "Global Annual to Decadal Climate Update." It shows that the annual average near-surface global temperature will be 66% more likely than not to exceed the 1.5ºC threshold, often used in global climate change negotiations and set out in the Paris Agreement, in the next five years, i.e., 2023 to 2028 (WMO, 2023). Similarly, the synthesis report (SYR) of the IPCC Sixth Assessment Report (AR6) emphasizes the need to limit global warming to 1.5ºC by reducing GHG emissions by 84% of 2019 levels by 2050 (IPCC, 2023). The reports make it clear that there is a growing acceleration in climate change, raising the need to step up action on mitigation and adaptation.

Ireland has taken proactive steps by implementing ambitious climate legislation to contribute to global efforts to reduce anthropogenic GHG emissions. The Climate Action and Low Carbon Development (Amendment) Act 2021 lays out a pathway to transition the country to a low-carbon society and economy by 2050. In this regard, the government announced the carbon budgets and sectoral emissions ceilings in 2022 with the aim to achieve a 51% reduction in GHG emissions by 2030, relative to 2018 levels. Also, the National Adaptation Framework (NAF) sets out a roadmap to build a climate-resilient economy and society through prioritizing and mainstreaming climate adaptation actions into all national plans and policies. Moreover, Ireland's climate legislation identifies and assigns responsibilities to key sectors and stakeholders including communities, government, civil society, and businesses. In so doing, the legislation underscores the point that preparing for climate change impacts and prioritizing climate adaptation requires a multi-stakeholder and cross-sectoral approach.

Human-induced climate change unequivocally causes widespread adverse impacts and related losses and damages to nature and societies. Climate change involves, in addition to increases in temperature, more variability in temperature and precipitation, increased occurrences of extreme weather events, and a rise in sea levels (IPCC, 2023). The impact of these climatic changes on societies and economies is uncertain but is expected to be significant and intensify in the future.

Ireland will not be spared from these impacts. Between 1890 and 2013, the average temperature in Ireland increased by 0.9°C and is predicted to rise to between 1°C and 1.6°C by mid-century (García & Dwyer, 2020). Ireland has also seen periodic flooding and extreme rainfall in recent decades along the north and west coasts. Moreover, as an island country where around 60% of the population lives within 10km of the coast, rising sea levels present a growing concern for a large share of the population (Sweeney, 2020). Although the current state of knowledge gives some insights into the potential climate change impacts for Ireland and the adaptation options that can be applied to combat these impacts, a detailed rigorous economic assessment is lacking. A better understanding of these impacts is necessary to prepare society as well as allow for effective adaptation strategies. Though a lot of work has been done within the NAF, adaptation options across sectors are hard to compare making adaptation prioritisation an impossible task. An economic assessment of climate impacts and adaptation options is necessary to allow for the most efficient adaptation policies.

This paper provides an overview and update of the impacts of climate change in Ireland alongside relevant adaptation options. Also, it examines Ireland's past and future climate based on climate data and simulations provided by Met Eireann and the Irish Centre for High-End Computing (ICHEC).

2 Ireland's Climate: Observed and Projected

2.1 Observed

Historical data shows that Ireland's climate is changing. Between 1890 and 2013, the annual average surface air temperature increased by around 0.9^{o}C, with 15 of the top 20 warmest years on record occurring since 1990. This observed rise in temperature is evident across all seasons (García & Dwyer, 2020). Figure 1, below, shows the annual air temperature anomalies for Ireland for the period 1900-2021 compared with the 1961-1990 average, confirming this warming trend.

Also, between 1989 and 2018, annual precipitation increased by 6% relative to the 30-year period 1961 to 1990, with 2006 to 2015 being the wettest on record. Moreover, the country has experienced five large-scale storms in the last seven years that disrupted the economy, and communities in addition to creating considerable damage to properties (i.e., Storm Ophelia in 2017, Storm Eleanor in 2018, and in 2021 Storms Darcy, Arwen, and Barra). These observations and events are in line with global trends regarding changes in precipitation patterns, increases in average temperature, sea level rise, and the increased intensity of extreme weather events (IPCC, 2023). Together, these observations provide evidence of changes in the Earth's climate system beyond natural variability.

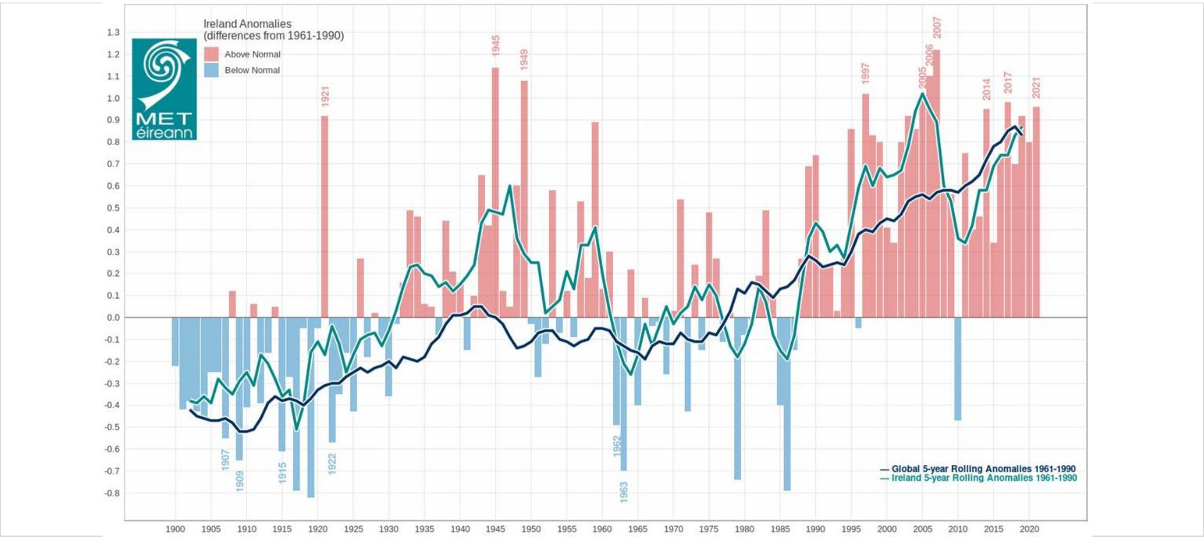

Figure 1: Ireland Annual Air Temperature Anomalies 1900 And 2021.

Source: Met Eireann Annual Climate Statement for 2021. Notes: This figure shows the annual air temperature anomalies in Ireland for the period 1900-2021 compared with the 1961-1990 average. Bars represent the yearly anomaly; the turquoise blue line is the Irish 5-year rolling average anomaly and the navy-blue line the worldwide 5-year average anomaly.

2.2 Projected

Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) have been developed and applied to describe future climate projections. We provide a summary of these as follows.

The Intergovernmental Panel on Climate Change (IPCC), the authorized international body for assessing the science related to climate change, developed the RCPs and SSPs as part of its Fifth Assessment Report (AR5) to replace the SRES (i.e., Special Report on Emissions Scenarios) set of scenarios used in previous Assessment Reports (IPCC, 2014). RCPs are a set of scenarios that aim to provide a consistent framework for the assessment of climate change mitigation and adaptation strategies. They are pathways of future trends in greenhouse gas (GHG) emissions and concentrations based on how humans will behave, in terms of population growth, socioeconomic development, energy use, and technological development. There are four main RCPs with numerical values 2.6, 4.5, 6.0, and 8.5. The numbers are based on radiative forcing (i.e., the difference between the incoming and outgoing energy from the sun) values in the year 2100. Specifically:

- The **RCP2.6** scenario is one in which substantial reductions of GHG emissions can be expected immediately and without delay due to significant mitigation efforts. That is, it represents a world with substantial climate policy measures and a focus on sustainable development.
- The **RCP4.5** scenario assumes moderate GHG emissions reductions. This implies some climate change policy measures but also substantial reliance on fossil fuels.
- The **RCP6.0** scenario is based on a trajectory of medium to large GHG emissions without significant mitigation actions. That is, it represents a world with fragmented climate policies and a mix of fossil fuels and renewable energy sources.
- The **RCP8.5** scenario assumes a rise in GHG emissions with no climate mitigation efforts. That is, it represents a world with limited climate policy measures and a heavy reliance on fossil fuels.

The SSPs are a set of scenarios aimed at providing a consistent framework for examining the interaction between socioeconomic development and climate change, which is similar in concept to RCPs. The five SSPs reflect several possible futures based on different assumptions of future societal trends. The following summary of SSP narratives is based on Riahi et al. (2017):

- **SSP1** (Sustainability – taking the green road): this scenario represents a future characterized by gradual, but pervasive shifts towards a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. This implies a world with a balanced use of resources and a transition to renewable energy sources.
- **SSP2** (Middle of the road): this scenario represents a future that does not differ significantly from historical trends in the areas of social, economic, and technological

development. This means a world where societal and environmental policies evolve slowly, with some improvements but also persistent challenges.

- **SSP3** (Regional rivalry – a rocky road): this scenario represents a future marked by resurgent nationalism, concerns about competitiveness and security, and regional conflicts that push countries to increasingly focus on domestic or, at most, regional issues. This means a world with growing inequalities, regional conflicts, and uneven access to resources.
- **SSP4** (Inequality – a divided road): this scenario represents a future characterized by highly unequal investments in human capital, combined with increasing disparities in economic opportunity and power with the attendant consequences being increasing inequalities and stratification both across and within countries. This means a world with significant social disparities, resource depletion, and environmental degradation.
- **SSP5** (Fossil-fuelled development – taking the highway): this scenario represents a future where the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy-intensive lifestyles. This means a world heavily reliant on fossil fuels, with high GHG emissions and limited climate change mitigation efforts.

To predict and project changes in the Earth's climate, climate scientists use Global Circulation Models (GCMs) which are a physical representation of the Earth's climate system that accounts for factors such as GHG concentrations and solar radiations (IPCC, 2013; Auffhammer, 2018). Specifically, they are numerical models that are designed to represent the complex processes and interactions that drive the Earth's climate in terms of the atmosphere, land surface, ocean, and ice cover. GCMs such as EC-EARTH and HadGEM2-ES, are used for several purposes such as the projection of key climate variables including precipitation, humidity, and surface temperatures (Hazeleger et al., 2010; Collins et al., 2011) . However, their outputs are at a lower or coarser spatial resolution, mostly at 50km grid spacing.

To overcome this limitation and accurately model the Irish climate, climate researchers at the ICHEC and Met Éireann use Regional Climate Models (RCM) to downscale the output of GCMs to obtain more localized climate projections or high spatial resolution (~4km) data (Nolan & Flanagan, 2020). A range of models and scenarios are then used to ensure that the climate projections are robust and reliable.

The biophysical impacts of climate change put the Irish economy at risk. The four key climate change risks identified for Europe by the IPCC in its WGII Sixth Assessment Report are (i) heat-related death and illness of humans and ecosystems, (ii) crop loss due to the combined effects of heat and droughts, (iii) water scarcity across sectors, and (iv) the effects of flooding on people, infrastructure and economies (IPCC, 2023). The key Irish climatic hazards and impacts are likely to result from: slow-onset effects of a gradual increase in temperatures and the rise in sea levels on the economy; sudden and extreme changes in precipitation patterns, and in the character of weather extremes such as storms, flooding, sea surges and droughts; and the combination of slow- and sudden-onset (Desmond, O'Brien, & McGovern, 2017). It is therefore crucial to plan for a range of possible climate change scenarios and their respective impacts.

In the future, Ireland will be exposed to higher mean temperatures according to their simulation analysis. The mean annual temperature is projected to increase by 1-1.6°C by the middle of the century (i.e., 2040-2061) compared to the reference period 1981-2000, under the RCP4.5 climate scenario (which roughly corresponds the continuation of current climate policies). However, this projection shows variations in temperature across the country that are expected to be marked by increased temperatures in eastern regions. By the middle of the century, heatwaves are also expected to increase, with the largest increases in the southeast (Nolan & Flanagan, 2020). For precipitation, a substantial decrease is projected for the summer months although, non-summer months are projected to record marginal changes. Overall, it is projected that precipitation will be more diverse by the middle of this century because of an increasing frequency of droughts and heavy rainfall events.

3 Climate Change Impacts

Impacts of climate change consist of direct economic damages induced both by, for example, extreme weather events, and on the long-term productive capacity of the economy due to gradual changes in climatic conditions. Climate change affects the long-term determinants of growth, i.e., the productivity of labour and capital, and the dynamics of capital accumulation. Evidence shows that projected changes in the distribution of temperature and precipitation will shift the productivity in the agricultural, fishery, and forestry sectors, reduce outdoor labour productivity, shift the energy demand, affect the energy supply, disrupt infrastructure such as transport and telecommunications, and can induce capital asset loss through fluvial floods and sea-level rise. Economists assess these impacts by evaluating climate-induced change on Gross Domestic Product (GDP) in the medium to long term (2050 to 2100) relative to a counterfactual scenario in the absence of climate change.

In the economic literature, these impacts have been estimated on a global scale, using a variety of methods. Results vary depending on the scope of impacts included and the methodology employed (Piontek et al., 2021). For example, top-down econometric assessments linking temperature and GDP variations, warming of 4 °C may cause a 10-23% decline in annual global GDP by 2100 relative to global GDP without warming, due to temperature impacts alone (Burke et al., 2015; Kalkuhl & Wenz, 2020).

A recent EU-funded project, CO-designing the Assessment of Climate CHange costs (COACCH) provides a comprehensive economic assessment of various climate change impacts for regions in the EU (Boere et al., 2019). The COACCH project uses a bottom-up approach, which evaluates the compounded impacts of climate change on EU GDP at the regional level. In their approach, climate change impacts are assessed individually and aggregated into a macroeconomic model. This project provides the most detailed state of the art estimates currently available. It includes impacts for Ireland and shows that the overall impacts of climate change are negative and will likely decrease Irish GDP from -0.1% to -1.2% by 2050 relative to GDP without climate change. According to this analysis, most impacts come from losses in capital assets from fluvial flooding and climate-induced decreases in labour productivity. Note, however that many important impacts, such as health impacts, are not included in these estimates.

This type of study provides global or regional evidence of the economic impacts of climate change and is limited in capturing the specifics of the climate and economy of a small country like Ireland. There is currently no study which has assessed the impacts of climate change in detail for Ireland at the country-level, and across different scenarios. This paper will provide outputs that will begin to fill this gap.

3.1 Agriculture

The agricultural impacts of climate change are arguably the most well-documented in the literature. The projected changes in climatic conditions such as rising temperatures, increased concentration of CO_2, and changes in the patterns of precipitations all affect crop yield and agricultural productivity in important ways. However, the jury is still out on the overall impacts of climate change on agricultural productivity, particularly at the global level, as the role of adaptation by farmers and the benefits of CO_2 fertilization are difficult to project and model (Roson & Sartori, 2016).

Agriculture in Ireland has both economic and societal values. In terms of economics, the sector contributes significantly to employment, exports, and Gross National Income (GNI). For example, in the year 2019, its contribution to employment and gross national income is 7.1% and 6.7% respectively (Department of Agriculture, Food, and Marine, 2020). On the societal side, it forms part of the identity of many rural communities in the country, giving it a social significance beyond the production of food (Emmet-Booth et al., 2019). Therefore, understanding how climate change impacts the entire industry and its subsectors is important for economic, societal, and policy reasons.

A variety of model approaches, which include crop simulation models, integrated assessment models, and econometric models, are used to study the impact of climate change on agriculture. Crop simulation models provide direct access to the impact on plant growth of changes in precipitation, temperature, shifts in pests and disease, soil characteristics, and crop management practices. As a result, they are used to estimate yields and assess the vulnerability of different crops to climate change (Kephe et al., 2021). In addition, they allow researchers to assess the role of farm-level adaptation (such as crop diversification, irrigation, and changes in land use practices) in mitigating the negative impacts of climate change. Estimates for crop yield changes can then be fed into a partial or general equilibrium model to better understand the economic costs of climate change in agriculture. Moreover, Integrated Assessment Models (IAM) combine climate models with economic and social factors to assess the agricultural impacts of climate change including changes in the supply and demand of food as well as trade patterns. By using different models and data sources, researchers can understand and forecast the complex interactions between climate change and agriculture (Roson & Sartori, 2016).

Climate change impacts on the agricultural sector in Ireland have been assessed following a biophysical approach within the COACCH project (Boere et al., 2019). This method assessed climate change impacts on the sector in two-steps: first by assessing the direct impact of climate change on crop yields using a biophysical model, and second by accounting for farmers' responses in input management to climate-induced crop yields using an agro-economic model.

The direct climate change impacts on crop yields are obtained from the EPIC (i.e., Environmental Policy Integrated Climate) and GEPIC (i.e., Geographic Information System (GIS)-based EPIC) crop simulation models (Folberth et al., 2012; Izaurralde et al., 2006; Liu et al., 2007; Williams, 1995). These two models are dynamic system models that relate inputs (e.g., genetic characteristics of the crop, soil characteristics, water, nutrients, temperature, humidity, tillage) to the stages of crop growth (emergence, flowering, grain development, etc.) and predict plant biomass, grain yield, and often other biological or physical outcomes such as changes in soil carbon or residual soil moisture. These models are a gridded representation of climate and agronomic condition at global scale, including Ireland. They also incorporate carbon and water cycles. They are thus tailored to investigate the plant growth under environmental pressures such as climate change. These models also account for the CO_2 fertilization effect which smooths yield losses. Indeed, increased levels of atmospheric carbon dioxide increase the rate of photosynthesis, and plant growth, thus partly offsetting the impact of changes in weather conditions. However, the effectiveness of this effect is uncertain and challenging to model, due to its high heterogeneity among plant species and local conditions (IPCC, 2023).

In the second step, the biophysical impacts of climate change on crop yields are used as inputs into an agro-economic model which determines land reallocation and effective productivity changes as well as price changes as farmers' final input and output changes (Boere et al., 2019). This agro-economic model determines the underlying change in land allocation from a Ricardian perspective. Climate change alters the relative productivity of crops in certain regions, making the conditions favourable. Thus, farmers will autonomously adapt by switching to more favourable crops, but also accounting for the conditions on the markets for commodities, i.e., commodity prices. The COACCH project obtains changes in areas of production using the GLOBIOM model (Havlík et al., 2014). The GLOBIOM model is a partial equilibrium model covering the agricultural and forestry sectors and including bioenergy. It decomposes the agricultural sector into small regions producing and trading agricultural commodities. Thus, the model is fed with crop yield data from EPIC and gives the changes in land allocation for each crop, changes in the input used, and changes in total agricultural area versus forestry, and natural land (Boere et al., 2019).

It is important to underline that this method does not directly assess the impact of climate change on livestock and on ecosystem services. The hybrid approach developed in the COACCH project only accounts for climate change effects on crops, which are ultimately used to feed livestock and thus have an impact on livestock meat and dairy production (Boere et al., 2019). One can still argue that climate change impacts on livestock are partially included in this approach since the COACCH project evaluates the change in meat production due to changes in animal feeding. This is significant in the case of Ireland, given that more than 80% of the value added from the sector comes from animal products.

Finally, results are disaggregated for the two 2013 Irish NUTS-2 regions: the "Border, Midland and Western'' and the "Southern and Eastern'' regions. The "Southern and Eastern" region is the core agricultural region, with two million hectares of cropland and grassland as opposed to the 0.9 million hectares for the "Border, Midland and Western". The former region produces 66% of the agricultural output value of Ireland. Changes in temperature are also expected to follow a North/South gradient. For winter months, increases in median temperature are expected to reach 1.2°C for the most northern point in Ireland, as opposed to a 0.8°C increase in the most southern points. For summer months, the increase in median temperature for northern parts of Ireland is expected to reach 0.8°C, against a 1.3°C increase in southern areas of Ireland. Also, scenarios for heatwaves exhibit a north-west to south-east gradient, suggesting that the "Southern and Eastern" region will experience a hotter climate overall, relative to the mild changes for the "Border, Midland and Western" region.

The direct impacts of climate change on crop yields obtained from the EPIC model are moderately positive. EPIC shows that crop yields in Ireland will tend to increase for most crops, and under most RCPs. Crop increases tend to be larger under the RCP4.5 than under RCP2.6 scenario for most crops because of the CO_2 fertilization process. However, for RCP8.5, the deteriorating impacts of climate change are not offset by the CO_2 fertilization process. The increase in crop yields ranges between 15% to 25% among crops by 2070 for RCP4.5. Again, these positive impacts are likely to be a lower-bound estimate of the climate change impacts on the agricultural sector. In particular, the approach employed in the COACHH project does not incorporate impacts from losses in ecosystem services, pests, and diseases, water availability, as well as extreme weather events (Boere et al., 2019). Indeed, future projections (2071 to 2100) of the Irish climate show limited changes in average temperature and precipitation. However, the distribution of extreme weather events is also affected, with an increase in the number of hot days and an increase in the occurrence of droughts. Thus, a biophysical approach accounting for the full distribution of the weather and its effect on plant growth is required in the future to properly estimate the impacts of climate change on the Irish agricultural sector.

The GLOBIOM model allows us to represent the change in land use (Havlík et al., 2014). Land use evolution tends to evolve in opposite directions between the two regions considered. The "Southern and Eastern'' region is likely to observe an increase in the cropland area and a decrease in grassland. The estimated increase in cropland is 20% by 2070 under RCP4.5, and the decrease in grassland is about 30%. The "Border, Midland and Western" region is likely to decrease its cropland (of about 20% under RCP4.5 by 2070) while stabilizing its grassland area and increasing the natural land area. The differences between the two regions might be explained by the relative productivity differences. The core agricultural region is likely to gain productivity in major crops, hence increasing its area devoted to crops and reducing the area devoted to pasture. On the other hand, the profitable increase in crop production is already absorbed by the "Southern and Eastern'' region, which is relatively more productive, so the "Border, Midland, and Western" region reduces the area devoted to crops.

The crop mixture is also affected by these changes in crop yields. Farmers tend to reallocate areas towards crops that are more profitable, i.e., accounting for productivity gains but also for costs and price changes. The area devoted to barley is likely to decrease in both regions. Barley is the crop with the largest area in Ireland and is projected to decrease in its area by 20% across Ireland by 2070 under RCP4.5 – as opposed to a doubling in the area devoted to oats, and a decrease/stabilization in wheat. Importantly, the GLOBIOM model shows a massive increase in the area devoted to other green fodders – such as grass, alfalfa (lucerne), brassica, or brassica used to feed livestock. The area nearly doubles in the "Southern and Eastern region'' by 2070 under RCP4.5, which is consistent with the decrease in grassland: more livestock would be fed by crops grown in Ireland.

Ultimately, the COACCH project calculates the impact of climate change on effective crop yields, by measuring the total production of different crops, after accounting for changes in land allocation and inputs used, over the total area devoted to each crop (Boere et al., 2019). However, it is important to stress once again that this assessment of climate change's impact on the Irish agricultural sector does not account for several meaningful factors, such as water availability, increases in the prevalence of pests and diseases, and extreme weather events. Furthermore, important agricultural produce is not considered, such as fruit and vegetables, and mushrooms. Unfortunately, no study implements an exhaustive study of the agricultural impacts of climate change in the Irish context. Thus, future work needs to expand the scope of the impact on agriculture and avoid restricting analysis to the impact of average temperature and precipitation on crop yields. Thus, these results need to be taken with caution.

A study by Xie et al. (2018) reveals a potential reduction in barley yields in Ireland due to projected drought and heat conditions under future climate scenarios. In their estimation, under the RCP8.5 scenario, this may lead to a 193% increase in beer prices (including trade impacts) from the middle of the century with the attendant consequences on beer consumption. They combined the Decision Support System for Agrotechnology Transfer (DSSAT) crop simulation model with a global economic model (i.e., the Global Trade Analysis Project model) to evaluate the effects of extreme drought and heat on global barley production and beer supply. Holden et al. (2003) also used the DSSAT model, but they project an increase in barley yields across all areas in Ireland by the middle of the century, with yields between 8 to ten tonnes per hectare. However, for non-irrigated potatoes, they project a reduction in yields of between one and four tonnes per hectare across major growing areas as temperature increases and droughts become more frequent in the future. Furthermore, climate change is projected to shave around €1-2 billion per annum off Irish agricultural output by the middle of the century through its impacts on crop yield losses, flooding, and the emergence and spread of pests and diseases (Flood, 2013).

3.2 Labour Productivity

Labour productivity will be directly and indirectly affected by climate change. Changes in weather patterns, as well as rising temperatures and extreme weather events, will directly affect the performance of workers, particularly outdoor workers such as farmers and construction workers (Kjellstrom et al., 2009; Roson & Sartori, 2016). These indirect effects will result from reduced economic activity because of the increased frequency of extreme weather events and changes in precipitation patterns that can have a negative impact on agricultural production, disrupt supply chains and affect manufacturing processes (Zappalà, 2023). These disturbances may result in reduced working hours and lower output, leading to decreased overall labour productivity.

Panel data analysis is often used to assess the direct impact of climate change on labour productivity. The method leverages historical data to estimate the relationship between a climate variable or a measure of heat stress and labour productivity while accounting for both time and cross-sectional variation in the data. It also allows researchers to control for other factors such as work practices and worker characteristics to identify the specific impact of climate change on labour productivity. Simulation modelling can also be used to assess the impact of climate change on labour productivity. This approach uses computer models that combine different climate scenarios and economic variables to study the evolution and interactions between labour productivity, climate change, and other key factors (Kjellstrom et al., 2009; Roson & Sartori, 2016).

Wet Bulb Globe Temperature (WBGT) is the often-used heat exposure indicator when examining labour productivity. It measures human heat stress by combining temperature, humidity, wind speed, and solar exposure with high values indicating a higher level of thermal stress (Kjellstrom et al., 2016; Szewczyk et al., 2021). By using historical and future WBGT estimates in addition to climate change projections, researchers can study the past and potential impacts of climate change on labour productivity across sectors and regions.

Empirical studies confirm that higher temperatures projected due to climate change will have a negative impact on labour productivity albeit at varying degrees across sectors and regions (Kjellstrom et al., 2009; Roson & Sartori, 2016; Gosling et al., 2018; Szewczyk et al., 2021). At the sector level, the most significant impact will be seen in agriculture and construction. Southern Europe (including Spain, southern Italy, and southern Greece) is projected to see the largest decline in labour productivity of about 17% by the end of the century, under a high-warming scenario and in the absence of adaptation. Projected labour productivity losses for Ireland are in the range of zero to 5% depending on the climate scenario (Gosling et al., 2018).

3.3 River Flooding

Climate change is expected to increase the risks of river flooding through increased frequency, intensity, and duration of precipitation events. To estimate the direct economic costs of river flooding on the built environment and infrastructure, the GLOFRIS model is widely applied. It is a grid-based global framework that includes all main river basins worldwide (Winsemius et al., 2013). In addition, it captures the three components that determine flood risk, that is, hazard (i.e., the expected shifts in climate or climate projections), exposure (i.e., the magnitude of socioeconomic variables such as GDP and population), and vulnerability (i.e., flood protection standard or a measure of flood adaptation) (IPCC, 2013). Flood risk assessment using GLOFRIS involves the following steps. First, the framework generates a baseline hazard which is carried out using information from PCR-GLOBWB, a global hydrological model that calculates where and when flooding may occur, including the inundation extent and depth (Winsemius et al., 2013). Next, GLOFRIS is used to generate future hazard flood projections by running the model with bias-corrected meteorological data from one of the global circulation models (such as EC-EARTH, HadGEM2-ES, and MIROC5) endorsed by the Coupled Model Intercomparison Project (CIMP). In the final step, the derived flood hazard data from GLOFRIS is combined with exposure (with data coming from the HYDE database which gives information on the fraction of each grid cell that falls in an urban area) and vulnerability data (based on the FLOPROS database which provides information on local flood protection standards). This is done to obtain an indicator for flood risk in terms of expected annual damage (EAD), affected GDP, and affected population (Winsemius et al., 2013). Intuitively, EAD weights the damage caused by flooding in each grid cell by the probability of the flooding event occurring in that grid cell (Ignjacevic et al., 2020).

The COACCH project employed the GLOFRIS model to estimate the direct economic costs of river flooding in Ireland under different climate (based on the Representative Concentration Pathways, RCP), socioeconomic (based on the Shared Socioeconomic Pathways, SSP), and adaptation scenarios (Lincke et al., 2018). The projections are displayed in Tables 1 and 2.

Table 1: Expected Annual Damage for River Flooding in Ireland under a no-adaptation scenario.

SSP	RCP	2020	2030	2040	2050	2060	2070
SSP1	RCP2.6	2.31	7.8	14.45	21.83	29.4	37.63
SSP1	RCP2.6	4.83	16.39	30.2	46.15	62.96	81.51
SSP2	RCP4.5	2.85	7.75	13.12	18.78	24.36	29.76
SSP2	RCP4.5	5.7	16.49	28.15	40.63	53.17	65.46
SSP2	RCP6.0	2.95	7.85	13.11	18.52	24.01	30.03
SSP2	RCP6.0	5.89	16.6	27.86	39.73	52.1	66.22
SSP5	RCP8.5	2.63	9.48	19.63	33.53	51.3	74.25
SSP5	RCP8.5	5.61	20.6	42.89	74.54	115.73	169.25

Data Source: COACCH Project (Lincke et al., 2018). Notes: EAD values represent changes with respect to the year 2010. Units are in millions of euros (2015) PPP.

Table 2: Expected Annual Damage for River Flooding in Ireland under an optimal adaptation scenario.

SSP	RCP	2020	2030	2040	2050	2060	2070
SSP1	RCP2.6	0.96	3.24	6.04	8.96	11.81	14.82
SSP1	RCP2.6	1.72	5.89	11.04	16.59	22.19	28.17
SSP2	RCP4.5	1.24	3.17	5.38	7.7	9.95	12.07
SSP2	RCP4.5	2.21	5.74	9.64	13.69	17.63	21.4
SSP2	RCP6.0	1.29	3.22	5.38	7.58	9.79	12.19
SSP2	RCP6.0	2.31	5.87	9.77	13.68	17.52	21.51
SSP5	RCP8.5	1.06	3.79	7.92	13.38	20.26	29.07
SSP5	RCP8.5	1.92	6.92	14.29	24.02	36.21	51.86

Data Source: COACCH Project (Lincke et al., 2018). Notes: EAD values represent changes with respect to the year 2010. Units are in millions of euros (2015) PPP.

Table 1 shows that expected annual damage due to river flooding will increase in the coming years if no adaptation strategies are implemented (judging by the magnitude of the values across the rows). Moreover, the damages are projected to be higher if current socioeconomic practices or worse ones are followed (judging by the magnitude of the values along the columns). Although Table 2 depicts a similar pattern to Table 1, it reveals the importance of adaptation measures given that the EADs reported in Table 2 are about 50% lower than those in Table 1.

3.4 Coastal Flooding

The risk of flooding in coastal regions will increase under climate change as rising temperatures warm the oceans and melt ice caps and glaciers, causing sea levels to rise. This is already evident in island countries like Ireland. According to satellite data, seas around the country have increased by about 4 to 6 cm since the early 1990s (Dwyer and Devoy, 2012).

One of the tools used to assess the economic costs of sea-level rise (SLR) to the coastal infrastructure is the Dynamic Interactive Vulnerability Assessment (DIVA) model (Hinkel, 2005; Hinkel & Klein, 2009; Hinkel et al., 2010; Hinkel et al., 2014). DIVA is an integrated assessment model that integrates information on the physical environment, ecosystem services, and socioeconomic factors to evaluate the exposure, vulnerability, and adaptive capacity of coastal zones to extreme water levels caused by a sea-level rise, at global and regional scales. The model is based on a global database of the world's coasts (excluding Antarctica) and includes metrics such as the amount of land and wetland losses due to extreme water levels, the total cost of damages due to floods, the number of people potentially flooded due to extreme water levels, and the potential costs of adaptation to reduce the risk of coastal flooding (Hinkel & Klein, 2009; Lincke et al., 2018). In other words, DIVA consists of several modules representing biophysical processes and economic costings in addition to different adaptation strategies (such as raising dikes and nourishing beaches).

In DIVA, the world's coast is divided into over twelve thousand segments of different lengths but with homogenous characteristics, with each segment containing about eighty thousand biophysical and socioeconomic parameters (Vafeidis et al., 2008). Also, for each segment of the coastline, a stylized model of the floodplain is generated. Flood risk is then considered in terms of expected annual damage to assets and/or the expected number of people flooded.

The DIVA model was used in the COACCH project to estimate the economic costs of SLR to Irish coastal infrastructure (Lincke et al., 2018). The estimation was done for two cost variables, sea flood cost and protection cost (consisting of sea dike construction and maintenance costs) under different scenarios of sea-level rise (i.e., high, medium, and low), adaptation (no adaptation and BAU adaptation), climate (i.e., using the RCPs), and socioeconomic (i.e., using the SSPs). Figure 2 displays Ireland's projected evolution of coastal flooding and protection costs under the RCP 2.6 climate scenario. Unsurprisingly, the cost of coastal flooding is projected to rise with rising sea levels and with no adaptation measures. The same pattern (i.e., the cost rises with rising sea level) is true for the BAU (i.e., Business as Usual) adaptation scenario except that from the middle of the century, the cost estimates reduce by a factor of about 40 compared with the values under no adaptation, which is why the bottom-left graph appears flat. Again, as will be expected, protection cost rises with rising SLR and under the BAU adaptation scenario. It should be noted that no adaptation assumes that dikes remain at their 2015 levels whereas BAU adaptation assumes that dikes are raised in accordance with SLR and growing wealth in each region or country.

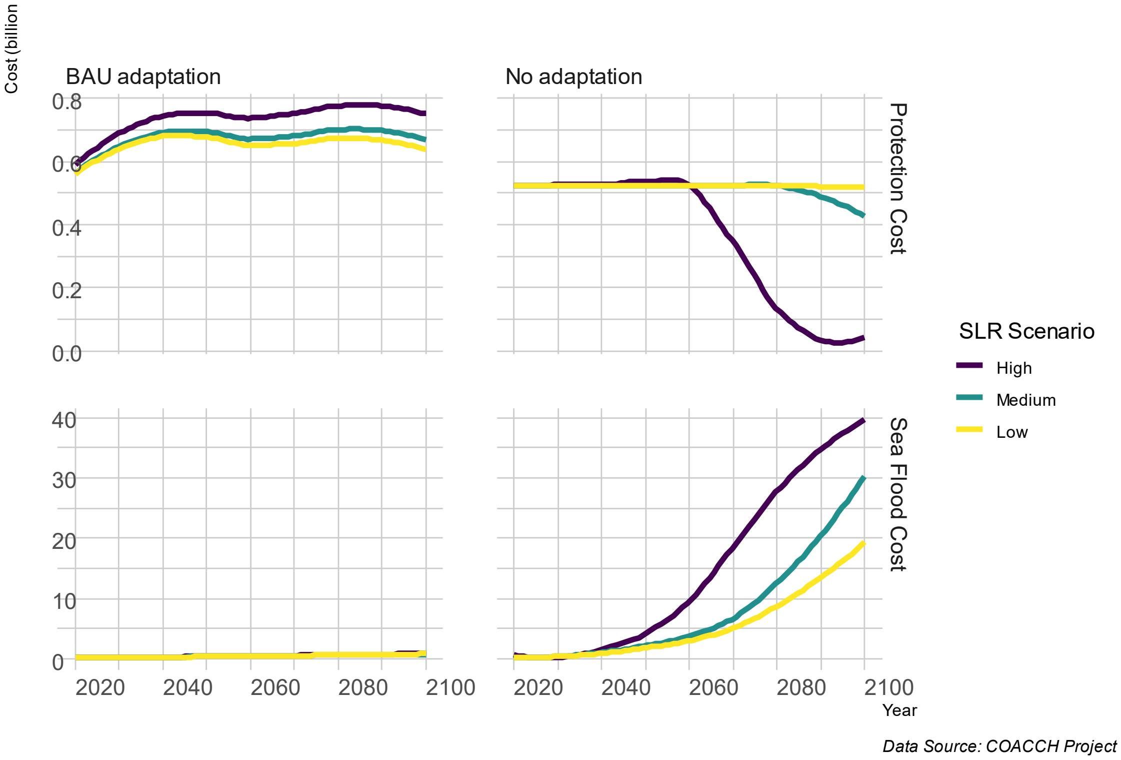

Figure 2: Coastal Flooding and Protection Costs for Ireland under RCP 2.6.

A study by Paranunzio et al. (2022) also examined the risk of coastal flooding because of climate change but only across the county of Dublin. They projected that by the middle of the century, the number of communities at risk of coastal flooding in the county will increase by around 26% and 67% respectively under RCP4.5 and RCP8.5, with communities like Howth, Portmarnock, and Malahide being the most at risk.

3.5 Health

Climate change will increase people's exposure to extreme weather events, heat stress, declining air and water quality, and vector-borne diseases like tick-borne diseases and malaria, with adverse impacts on human health. For instance, changes in temperature and rainfall patterns due to climate change will affect the geographic spread and transmission dynamics of vector-borne diseases. In countries with limited access to healthcare and infrastructure, this will lead to higher mortality rates (Rocklöv & Dubrow, 2020). As the climate warms, heatwaves are also expected to be more common and intense, which will lead to a rise in cases of heat-related illnesses like heat stroke and heat exhaustion. This will be particularly severe in urban areas which are expected to experience higher levels of warming due to the combination of direct temperature rise caused by climate change and the urban heat island (UHI) effect. This effect alters the local climate and leads to higher temperatures as well as increases in heat-related illness and mortality. The UHI effect is driven by the additional heat in urban areas due to replacing the natural land covers with materials, such as asphalt and concrete that absorb and retain heat (Ščasný et al., 2019).

Observational studies and scenario modelling are among the methods used to investigate the effects of climate change on health indicators, such as mortality, morbidity, and heat-related stress. Observational studies are used to understand the relationship between meteorological variables and health indicators based on mathematical or statistical models. These models can be empirical (i.e., based on observed statistical associations, patterns, and trends) or process-based, that is, those which consider the basic biological processes and mechanisms associated with the transmission of illness and disease dynamics (Rocklöv & Dubrow, 2020). By controlling for other relevant or confounding factors, such as age, socioeconomic status, and underlying health conditions, researchers can estimate the specific impact of climate change on health indicators for a specific time period and geographic region.

The COACCH project estimated the projected burden of heat stress on mortality in Europe over the period 2030-2099 under various RCPs scenarios. Mortality was calculated using regionally pooled epidemiological associations that link heat exposure (temperature) to health effects (death) using historical time series data drawn from 115 empirical locations across Europe (Ščasný et al., 2019). The projections for Ireland are displayed in Table 3. The estimates show that, if trends in greenhouse gas emissions do not change, the risk for heat-related deaths in Ireland is likely to rise over the next decades. Another study projects that the health impacts (including heat and cold-related diseases, malaria, and dengue) of a 3°C increase in the average temperature on Ireland's GDP could be about -0.0404% (Roson & Sartori, 2016).

Table 3: Heat-attributable mortality in Ireland

	Deaths			
	2030-2039	**2050-2059**	**2070-2079**	**2090-2099**
RCP2.6	206	316	356	216
RCP4.5	206	407	491	483
RCP8.5	173	482	982	1399

Data Source: COACCH Project (see www.coacch.eu).

3.6 Tourism

Ireland is a very popular destination for tourists around the world, due to its rich natural landscapes, mild maritime climate influenced by the Atlantic Ocean, long coastline, and extensive estuaries (Sweeney, 2020). For example, in 2018, it is estimated that approximately 11 million visitors passed through Ireland generating 15 billion dollars, which represents about 4% of the country's Gross National Product (GNP) (World Tourism Organization, 2023). However, projected climate change (including sea level rise and extreme weather events) will threaten Ireland's landscapes, seascapes, and economic gains from the tourism sector. For instance, climate change-induced sea level rise and coastal erosion can pose risks to Ireland's picturesque seaside towns, beaches, and coastal infrastructure by reducing their aesthetic appeal and accessibility. The effect of this could be to deter tourists and reduce the demand for coastal tourism (Jones & Phillips, 2011). Changing climate and precipitation patterns can also have an impact on nature-based tourism as they affect ecosystems and biodiversity, affecting habitats for wildlife and natural attractions that draw tourists.

Quantitative and qualitative methods are used in empirical studies to assess the impact of climate change on tourism demand. Quantitative methods use climate indices (like the tourism climate index) and tourism demand models to investigate the impact of climate change on tourism. On the contrary, qualitative methods rely on surveys and experts' opinions to predict the interaction and relationship between climate change and tourism (Schleypen et al., 2019). The Hamburg Tourism Model (HTM) is an often-used econometric simulation model for analysing and forecasting tourism demand (Hamilton et al., 2005; Hamilton & Tol, 2007). The model takes both demand and supply side factors into account to give a comprehensive view of the tourism sector. To estimate the number of visitors and their characteristics, demand-side factors such as visitor demographics, travel behaviour, income levels, and macroeconomic indicators are used, while supply-side factors such as hotel capacity, transport infrastructure, cultural attraction, and events are used to analyse the availability and quality of tourism resources (Hamilton et al., 2005; Hamilton & Tol, 2007).

Overall, it is evident from empirical studies that there is a strong relationship between tourism and climatic conditions, but additional factors such as family ties, ease of access, and language also play an important role (Hamilton et al., 2005; Hamilton & Tol, 2007; Jones & Phillips, 2011; Prettenthaler et al., 2022). The general conclusion is that climate change will shift tourism patterns to a higher altitude and latitude while increasing domestic tourism in colder countries and vice versa for warmer ones. Based on the Hamburg tourism model, Hamilton & Tol (2007) project that climate change will increase the number of domestic holidays taken by Irish people by between 7% and 15% by the end of the century depending on the climate scenario.

4 Climate Change Adaptation

The National Adaptation Framework (NAF) is part of the climate policy initiatives adopted by the Irish Government to enhance Ireland's resilience as well as its ability to deal with the projected impacts of climate change, while achieving a just transition and sustainable development outcomes. The framework covers measures to protect the environment, ecosystems, and critical infrastructure, such as water supply, transport networks, and energy systems. Actions include strengthening seawalls and flood management systems and promoting climate-resilient agriculture and forestry practices. The NAF provides adaptation plans for 12 sectors including agriculture, forestry and seafood, biodiversity, built and archaeological heritage, transport infrastructure, electricity and gas networks, communications networks, flood risk management, water quality and water services infrastructure, and health. Overall, by developing the NAF, Ireland recognises that the key to effective adaptation will be robust governance, sound policy, and active participation from all sectors of society. [1] Several sectors are considered below.

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[1] This and the next sections are informed by the National Adaptation Framework (NAF, 2018) and the Climate Action Plan (CAP, 2023).

4.1 Agriculture

In the area of climate-resilient agriculture and forestry practices, Ireland is making an active effort to implement environmentally sound farming techniques like the diversification of crops, management of water resources, and precision farming. There is also an active promotion of agroforestry, which involves integrating forests into agricultural areas to create benefits such as carbon sequestration and improved water management. The aim is to improve the sector's adaptive capacity and reduce greenhouse gas emissions.

4.2 Coastal Protection

Coastal defence infrastructure, managed retreat solutions, nature-based solutions, and early warning systems are some of the adaptation options being considered to safeguard Ireland's extensive coastal area against sea level rise, increased storm events, and coastal erosion. Coastal defence infrastructure involves constructing and maintaining seawalls, breakwaters, and revetments to reduce erosion and protect coastal communities and infrastructure. Also, managed retreat solutions, which involve relocating communities, infrastructure, and assets away from high-risk coastal areas to safer locations, are ideal where coastal areas are highly vulnerable and long-term protection is not economically or environmentally feasible. Early warning systems include monitoring coastlines, and collecting data on sea-level rise, storm events, and erosion rates to inform emergency planning and decision-making. While nature-based solutions utilize natural systems and processes (i.e., restoring and creating coastal habitats such as salt marshes, dunes, and mangroves) to provide coastal protection and enhance resilience.

4.3 Flood Management

Ireland is also at risk of flooding; therefore, effective flood management strategies are paramount. This includes the construction and maintenance of flood protection measures, such as embankments or barriers to floods, along with improvements in river and drainage systems. In addition, natural flood management techniques, such as restoring wetlands and creating floodplains, are also being employed to store and slow down floodwaters.

4.4 Public Health

Strengthening the public health systems to respond to changes in disease patterns and severe weather events are adapted measures within this area. This involves the development of early warning systems for heat waves and implementing heatwave management plans, healthcare facilities' resilience to climate events, and the promotion of awareness about health risks related to climatic phenomena by raising Public Awareness and Climate Education.

5 Suggestive Barriers to Adaptation

While the NAF lays out a roadmap for addressing climate change adaptation in Ireland, several barriers can hinder effective implementation. Among them are uncertainty and lack of data, technological barriers, financial constraints, political will, and lack of awareness and understanding of the risks and impacts of climate change.

Uncertainty and lack of data

Uncertainty related to the effects of climate change is often present, which makes it difficult to anticipate what risks and vulnerabilities this poses for individual sectors and regions. As a result, the development of strong adaptation plans and decision-making procedures could be hampered by a lack of relevant quality data, including climate projections.

Financial constraints

Several significant resources are required for the implementation of adaptation measures. Therefore, a significant volume of adaptation projects can be difficult to implement due to low funding and competing priorities, particularly for emerging countries or poor regions. Efforts to adapt can also be hampered by the absence of access to finance, which may include investments and insurance.

Lack of awareness and understanding

Adaptation efforts may be hampered by a lack of awareness and understanding of the risks and impacts of climate change. Decision-makers, individuals, and communities may not prioritize adaptation or allocate enough resources for its implementation when they do not understand the urgency and significance of climate change.

6 Conclusion

Scientific and observational evidence, in terms of extreme weather events, rising temperatures, and altered precipitation patterns, continue to document changes in the Earth's climate system that is beyond natural variability. As a result, efforts to reduce humanity's contribution to those changes and tackle the threat of climate change have increased both at global and national levels. This paper provided a summary of impacts and adaptation strategies, including modelling approaches, numerical estimates, and Ireland's climatic conditions in the coming years.

This paper confirmed that Ireland is exposed to, and at risk from, the effects of observed and future climate change in several sectors such as agriculture, labour productivity, coastal flooding, and health. In addition, climate forecasts suggest that in the future, the country will face significant challenges from increasing climate impacts.

This paper also highlighted that there are scant and, in some cases, outdated empirical estimates for some impact categories in Ireland, although considerable research has been carried out. It also documents that there is an active research community working on climate and adaptation issues. Most studies present estimates for Europe and its larger regions, which makes it challenging for the characteristics of Ireland to be adequately represented. categories.

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