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Interactions between climate change mitigation, damages, and adaptation: An intertemporal Computable General Equilibrium analysis for Ireland

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ABSTRACT

This study uses a Computable General Equilibrium (CGE) model to analyse how mitigation and adaptation strategies affect climate change impacts in Ireland. Five impacts—coastal flooding, riverine flooding, heat on labour productivity, human health, and agricultural productivity—are incorporated, along with adaptation costs and benefits for riverine and coastal flooding. Impacts are modelled through increased capital depreciation, reduced labour productivity, healthcare costs, and agricultural productivity shocks. Adaptation involves spending on coastal protection infrastructure through construction. Results indicate that adaptation can cut net climate costs by over half. Secondary general equilibrium impacts and adaptation costs overshadow initial impacts adaptation costs. GDP losses are highest without adaptation (2.6% by 2030), compared to 1.3% with mitigation and 0.6% with optimal adaptation. The study highlights the need for further research on broader impacts and adaptation strategies, emphasizing the importance of considering secondary impacts in policy assessments.

Keywords

Climate change, adaptation, macroeconomy, impact assessment, CGE modelling, Ireland

1 INTRODUCTION

Climate change is significantly impacting the environment and the economy, resulting in a range of adverse effects. These include changes in weather patterns that disrupt agriculture and productivity, as well as an increase in the frequency of storms and storm surges, leading to a higher risk of flooding harming infrastructures, the capital of exposed sectors and the living conditions of workers (Hirabayashi et al., 2013; Ortiz-Bobea et al., 2021; IPCC, 2022). Climate change mitigation aims to reduce greenhouse gas emissions and limit the extent of climate change, while adaptation measures seek to minimise the adverse impacts of unavoidable changes (IPCC, 2007; Fawzy et al., 2020; Wei & Aaheim, 2023). Both strategies are essential components of understanding and reducing the impact of climate change.

Over the past decades, climate policies have been designed, implemented and analysed to address climate change. Adaptation and mitigation policies are generally assessed in isolation of each other, although the effectiveness and costs of these policies are interconnected, and both are crucial for comprehensive decision-making (Agrawala et al., 2011; Calvin et al., 2013). A detailed economic assessment of adaptation and mitigation interactions is missing from the literature.

For Ireland, transitioning to a low-carbon economy holds immense potential benefits. Understanding the current and potential impacts of this transition is not just a necessity but also a pathway to developing effective and sustainable local climate policies. Moreover, considering the economic implications and trade-offs associated with different mitigation pathways and adaptation measures in an integrated modelling framework is a strategic move toward reducing greenhouse gas emissions in line with national and international commitments.

In recent decades, computable general equilibrium (CGE) models have emerged as valuable tools for analysing the economic implications of climate change policies (Bergman, 2005). By incorporating interactions between economic sectors, households, and governments, CGE models offer a holistic framework for assessing the macroeconomic effects of various policy interventions (Sue Wing, 2011; Babatunde et al., 2017; Dellink et al., 2019). Furthermore, CGE models can capture the dynamic feedback loops between mitigation actions, climate damages, and adaptation expenditures, providing practical insights into their combined effects on economic welfare and resource allocation.

This study aims to investigate the simultaneous and interactive effects of climate change mitigation strategies, climate damages, and adaptation costs in Ireland using a CGE approach. By integrating estimates of climate change impacts, effects of mitigation policies, and adaptation options into this unified modelling framework, we investigate the complex trade-offs and synergies inherent in climate policy decision-making. Specifically, our analysis incorporates in a CGE model the estimated impacts of climate change of riverine and coastal flooding on capital, of gradual temperature increase on labour productivity and on crop production, and shifts in private and government consumption towards healthcare expenditures. Then, we will accompany these climate change impacts with adaptation policies for riverine and coastal flooding by considering their effects on the entire economy through the increased output of the construction sector.

Our study complements the existing literature (Arndt et al., 2011; Bosello & Parrado, 2014; Steininger et al., 2016; Elshennawy et al., 2016; Kompas et al., 2018; Dellink et al., 2019; Parrado et al., 2020; Zouabi, 2021). However, unlike most of these studies, we use an intertemporal CGE model, Ireland Environment-Energy-Economy (I3E) (de Bruin & Yakut, 2021). This approach accounts for agents' forward-looking behaviour, including their ability to anticipate future economic conditions such as climate policies. It contrasts with the standard recursive-dynamic approach, where agents react adaptively to climate and economic shocks.

The paper is structured as follows: The next section will provide an overview of the existing literature on the combined impacts of climate change, damages, and adaptation costs. The third section will describe the technical details of the I3E model, and the scenarios analysed. The fourth section will present and discuss the results of the main scenarios. Finally, section five will conclude.

2 RELATED LITERATURE

The literature on climate change highlights the importance of a comprehensive approach that considers the interconnected impacts of mitigation, damages, and adaptation costs (Agrawala et al., 2011; Calvin et al., 2013). For example, Agrawala et al. (2011) suggest that any cost-effective policy response to climate change must involve significant mitigation efforts as well as investments in adaptation measures to reduce residual damages (i.e., economic losses that remain even after adaptation measures have been implemented). Therefore, this study aims to contribute to the existing body of knowledge by examining the Irish case through an intertemporal CGE model. The study will explore the interactions among various policy instruments, such as carbon pricing and adaptation strategies, and their impact on the Irish economy.

Several CGE studies highlight that climate change will impact economic activities, including economic growth, employment, and household welfare (Ciscar et al., 2011; Elshennawy et al., 2016; Steininger et al., 2016; Dellink et al., 2019; Zouabi,2021). For example, Dellink et al. (2019) showed that global annual GDP losses due to climate change could rise between 1% and 3.3% by 2060. Also, Ciscar et al. (2011) projected that future climatic conditions could cause an annual decline in household welfare within the European Union, ranging from 0.2% to 1%. Regarding impact categories, agriculture, labour productivity, and coastal and river flooding are projected to have the largest negative economic consequences.

When considering the costs and benefits of adapting to climate change, two types of adaptation are typically distinguished: planned and autonomous. Planned adaptation involves measures taken to prepare for anticipated or observed climate changes. Autonomous adaptation, on the other hand, refers to the spontaneous and self-initiated responses that occur in response to climate change impacts (Agrawala et al., 2011; Wei & Aaheim, 2023). Within the CGE framework, the substitution possibilities within agents' production and demand functions handle autonomous or market adaptation. Climate-related shocks can influence the availability and allocation of resources in the economy, leading agents to adjust their demand for and supply of goods and services based on market signals (Koopman et al., 2015; Roson & Sartori, 2016). In contrast, planned adaptation is often assumed to affect the process of capital stock accumulation, and investment is divided between productive and unproductive investments as a result (Bosello et al., 2012). However, the current CGE literature includes few studies on adaptation beyond the implicit market adaptation in the CGE framework.

The combined effects of mitigation strategies, damages, and adaptation costs have primarily been studied using Integrated Assessment Models (IAMs, e.g. Agrawala et al., 2011; Calvin et al., 2013, de Bruin et al. (2009), Bahn et al. (2022)). The general finding is that the total costs of climate change are the lowest when both mitigation and adaptation are undertaken together. IAMs include a representation of the climate cycle and how emissions result in climate change (measured by temperature change). However, their representation of the economy is simplistic, where total output is represented by a single-good Cobb-Douglas function. IAMs also do not detail the diffusion channels of climate change impacts and mitigation policies on the economy. We can observe impacts on global revenue (or output), while planning of climate change policies require to detail impacts by sectors or by household types.

Some studies have explored the impact of adaptation in a CGE setting. For instance, in a study by Bachner et al. (2019), a CGE model was used to examine the impacts of adaptation on government budgets in Austria. The study considered both the expenditure and revenue sides along with macroeconomic effects. In implementing the adaptation scenario, the study incorporated direct costs and benefits of public adaptation measures in three impact fields: Agriculture, Forestry, and Catastrophe Management (including protection from natural hazards). The costs of adaptation were divided into operating costs and investment costs. Changes in sectoral operating costs were modelled as shifts within the production cost structures, while changes in government consumption patterns and levels were implemented as additional consumption financed through cuts in transfers to private households. Changes in investment were financed through changes in savings and corresponding changes in private consumption. The authors relied on government budgets and expert knowledge to separate adaptation expenditures from total government expenditures and estimate the shares of adaptation. They found that government revenues can increase due to adaptation, offsetting additional direct public expenses for adaptation and improving the budget balance.

Similarly, Parrado et al. (2020) used a CGE model to examine the macroeconomic effects of sea-level rise adaptation on public budgets. The model included public planned expenditures for coastal protection, specifically investments in protective infrastructure such as dikes, as well as maintenance costs. These expenditures were financed through government borrowing and issuing government bonds. The model captured the effects of adaptation on the economy by considering the reduction in direct impacts of sea-level rise, such as loss of land, labour productivity, and capital, and the indirect effects on public deficits and debt accumulation. The authors found that without adaptation, all regions of the world will experience a loss in GDP due to the impact of sea-level rises. Planned adaptation, such as coastal protection measures, can significantly reduce the negative impacts of sea-level rise on GDP. The positive effects of adaptation on GDP are driven by two mechanisms: the avoided direct impacts (loss of labour productivity, land, and capital) and the public deficit effect. Adaptation reduces deficits, allowing for increased capital accumulation and growth in the long run. The financing of adaptation through government borrowing can lead to lower deficits and debt accumulation, as the benefits of adaptation outweigh the burden of adaptation debt.

Moreover, Bosello et al. (2018) examined the cost-effectiveness of agricultural adaptation, focusing on soft and hard measures. Soft measures included a shift in sowing/planting dates, manure management, and increased fertilisation. The cost per hectare of these measures varied depending on the yield loss to recover, crop type, and specific measures. Hard measures included the expansion of irrigated land through large-scale and small-scale irrigation plants. The initial investment costs and annual operation and maintenance costs for these plants were provided. The analysis showed that soft measures were sufficient to offset yield decline in the long term, but if not, irrigation expansion could be used on limited acreage. Boyd and Ibarraran (2009) also analysed the effectiveness of adaptation measures in dampening the impacts of drought on agricultural production in Mexico. They found that adaptation policies can only bring about modest changes to the economic losses caused by a drought. Adaptation measures were implemented to increase productivity in the agricultural sector, such as increasing irrigation efficiency, drought resistance of grain crops, and land available for livestock grazing. This finding is consistent with the few studies that have investigated the same issue in the intertemporal

CGE framework. For instance, Elshennawy et al. (2016) found that in Egypt, policy-led adaptation investment could reduce the GDP loss in 2050 to around 2.6%.

In summary, this literature review highlights the need for further research on the combined impacts of climate change mitigation, damages, and adaptation costs, particularly in intertemporal general equilibrium analysis. The current study assesses the magnitude and distribution of climate-induced damages and adaptation costs in Ireland using the production function approach and the I3E model. The shocks are derived from an analysis conducted by de Bruin et al. (2023), focusing on the combined impacts of coastal and river flooding, agriculture, human health, and heat effects on labour productivity. For the costs of adaptation, the focus is on flood defences, such as the costs associated with the building of dikes and dams.

3 METHODOLOGY

3.1 THE I3E MODEL

The I3E model is a multi-sectoral, multi-household, single-country small open-economy intertemporal CGE model. The following subsections explain the characteristics of each agent in a non-technical manner. Its technical description and the details of the Irish Energy Social Accounting Matrix (ESAM) used to calibrate the model are available in de Bruin & Yakut (2021b) and de Bruin & Yakut (2021a), respectively.

3.1.1 Households

The model has ten distinct Ramsey-type representative household groups (RHGs) based on the area of residence (urban and rural) and disposable income (quintiles). RHGs maximise their present discounted utility by choosing the optimal volume of total composite consumption. The disposable income consists of net-of-tax factor incomes (wage and dividend), welfare transfer and pensions from the government, and net factor income from the rest of the world.[1] The compositions of private consumption expenditures (across RHGs and commodities) and disposable income items (across RHGs) are retrieved from the Household Budget Survey (HBS) and the Survey on Income and Living Conditions (SILC), respectively.

3.1.2 Activities

The model includes 37 representative firms (or industries/activities) producing 42 commodities, including ten energy commodities. Thirty-three of these sectors maximise the present discounted value of their dividend stream, i.e., the firm's value, by choosing the investment, sector-specific capital, and labour inputs subject to the usual capital accumulation function. This is an extended profit maximisation problem with two features: *i)* the level of physical investment is a choice variable, and *ii)* is intertemporally solved. The firm's value equals the multiplication of the sector-specific capital stock and the well-known Tobin's *q*. For the remaining four (non-dividend maximising) firms, the investment expenditure is a fixed fraction of gross profit. Having intertemporal investment decisions is not a common modelling choice as the bulk of the CGE literature utilises static or recursive dynamic models. Our approach is similar to those used in Goulder (1995) and Goulder & Hafstead (2013), which, in addition to their retained earnings, also allows firms to finance their investment expenditures by issuing new shares and borrowing. Due to the absence of these two options, our approach is more similar to

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[1] Wage income tax includes social security payments of employees and employers and income tax.

Diao et al. (1999). Our approach differs from these studies since there are non-dividend maximiser firms for which Tobin's *q* is calibrated less than 1.

3.1.3 Government

The total government collects direct and indirect taxes on economic activity and production and also receives half of the total cost of the European Union Emissions Trading System (EU-ETS) due to the EU legislation. Government expenditures are public demand for commodities, transfers to households (welfare transfers and pension payments), and interest payments over the outstanding foreign debt stock. The total budget of welfare transfers is a positive function of both the aggregate unemployment rate and overall price level, measured by the consumer price index (CPI), whereas the total pension payments are indexed only to CPI. The welfare budget determination rule is important as the welfare system plays a cushioning role in the case of increased unemployment via unemployment benefits in the case of Ireland (Doorley, et al., 2021), which is also confirmed by Yakut & de Bruin (2023) in a CGE setting. Government demand for commodities, by following Cronin & McQuinn (2018), has two components: an autonomous part, fixed in nominal terms, and an induced part, a positive function of nominal GDP. Government savings, the total revenues minus the total expenditures, govern government foreign debt stock.

3.1.4 Dynamics and Equilibrium

In the I3E model, the economic and population growth rates are retrieved from the medium-term projections of Bergin et al. (2017), which are 3.3% and 0.08% per annum, respectively. The implied labour productivity growth is 2.48%. All variables are calibrated based on these growth rates under a balanced growth path assumption. As an intertemporal model, the equilibrium requires both intra-period and terminal conditions. The intra-period conditions are based on the usual supply and demand equilibrium; any market has no excess demand or supply, including factor markets. There are five terminal conditions: the value of the sectoral dividend must be equal to the return of a risk-free asset, the level of investment of each firm must be equal to the level of depreciation, government savings must cover the interest payments over the existing foreign debt stock, foreign asset holdings of households are constant, and, finally, there is no arbitrage across different assets in the economy.

The closure rule on the government accounts implies that its savings must be zero in the terminal period, and the total government consumption expenditure adjusts, which reduces the adverse welfare impacts compared to the tax rate adjustments (Holmøy & Strøm, 2013). Due to the evidence of how government expenditures evolve in Ireland, we cannot fix the government size, which has welfare implications when public goods do not appear in the utility function of households (Rausch, et al., 2010). However, the level of government savings-to-GDP ratio determines the risk premium value, making the foreign and domestic interest rates different. As the latter appears both in the Euler equation (governing household consumption) and investment function (affecting the dividend maximiser firms' investment decisions), government deficit changes affect the other agent's intertemporal decisions. Zero government savings in the terminal period also ensures no-arbitrage condition.

3.2 INCLUSION OF IMPACTS IN I3E

In this paper, we include estimated climate change impacts from agriculture, labour productivity, coastal flooding, riverine flooding, and healthcare. Estimates of impacts are taken primarily from de Bruin et al. (2024), which we will shortly discuss here. Note that this is by no means a comprehensive list of climate impacts in Ireland, where various impacts are not included, such as impacts to ecosystems, energy demand and extreme events.

3.2.1 Climate Impacts

One of the major expected impacts from climate change in Ireland is coastal and riverine flooding (Winsemius et al., 2013; IPCC, 2022). As our climate continues to warm, there is an increasing risk of more frequent and intense precipitation events, resulting in overflowing rivers and a greater likelihood of flooding. The impacts of climate change on river flooding are complex and influenced by various factors such as hydrology and the exposure of population and economic activities. To assess the direct economic impacts of river flooding on infrastructure, the GLOFRIS (i.e., GLObal Flood Risks with IMAGE Scenarios) model is commonly used. This global grid-based framework covers all major river basins worldwide and encompasses the three key factors that influence flood risk: hazard (which involves expected climate shifts or climate projections), exposure (representing socioeconomic variables like GDP and population), and vulnerability (such as flood protection standards or measures of flood adaptation) (IPCC, 2013; Winsemius et al., 2013). We employ the estimates derived from the GLOFRIS model, which were generated as part of the COACCH project, to evaluate the economic consequences of river flooding in Ireland.

The consequences of climate change, such as rising sea levels, heightened occurrences of high tides, and increased storm-surge flooding, have significant impacts on social, economic, and ecological systems (Hinkel et al., 2013). To assess the climate change-induced coastal impacts, we apply the Coastal Impact and Adaptation Model (CIAM) developed by Diaz (2016). Building upon the work of Hinkel et al. (2014), Diaz (2016) introduced CIAM, a global modelling tool aimed at estimating costs and adaptation strategies for the impacts of sea-level rises on our coasts. It subdivides the coastlines of the world into over 12,000 linear segments across the globe of varying lengths; Ireland consists of 22 unique segments. These segments are associated with physical, ecological, and socioeconomic parameters, allowing for a comprehensive analysis of impacts. A significant innovation in CIAM was its capacity to enable each segment to choose between the construction of protective dikes, as previously done by Hinkel et al. (2014), and the adoption of managed or reactive retreat strategies. CIAM addressed six categories of costs related to relative sea-level rise and extreme sea levels: (a) expenses associated with immobile capital or land inundation, (b) capital damages related to extreme sea levels, (c) costs linked to mortality, (d) outlays for protection (e.g., infrastructure), (e) costs of relocation, and (f) wetland loss. In this analysis, we exclude mortality impacts, given the general concerns and critiques of economically valuing lives.

To assess the impacts of climate change on the agricultural sector, we apply the results of the COACCH project (Boere et al., 2019), which uses crop simulation models (Environmental Policy Integrated Climate (EPIC) and Geographic Information System (GIS)-based EPIC). These dynamic system models consider various factors such as genetic characteristics, soil properties, water availability, temperature, humidity, and tillage practices to predict different stages of crop growth and outcomes like emergence, flowering, and grain yield. In addition to simulating plant growth under changing climatic conditions at a global scale including Ireland, these models also incorporate carbon and water cycles. They account for the positive impact of elevated CO2 levels on crops' productivity, thus mitigating some yield losses caused by climate change stressors. The COACCH project further used the GLOBIOM model to assess changes in production areas (Havlík et al., 2014). The GLOBIOM model is a partial equilibrium model that focuses on the agricultural and forestry sectors, as well as bioenergy. It divides the agricultural sector into various small regions where agricultural commodities are produced and traded. Consequently, data regarding crop yields from EPIC is inputted into the model to determine alterations in land allocation for different crops, adjustments in inputs used, as well as changes in overall areas dedicated to agriculture versus those dedicated to forestry and natural land.

It should be noted that this crop model, like others, has some important limitations. Firstly, they examine the impacts on crop yield of changes in climate but to not include the impacts of extreme weather and weather variability. Extreme hot days, extreme cold days, extreme winds and storms are expected to increase as global temperatures increase. These models focus on average changes in climate stimuli, which would underestimate the actual impacts of climate change. Secondly, these models focus on specific "subsistence" crops, not considering other agricultural such as fruit and vegetable tillage. These subsistence crops represent only approximately 57% of Irish Crop Gross Value Added (GVA) and only 5% of total agricultural GVA.

There are two major pathways by which climate change impacts labour productivity. The first of these pathways involves the number of hours worked by individuals, often referred to as labour supply (Graff Zivin & Neidell, 2014; Dasgupta et al., 2021; Somanathan et al., 2021). Sectors with high exposure to extreme temperatures, such as agriculture, are particularly vulnerable to this effect. When temperatures rise beyond specific thresholds, workers may reduce their working hours to safeguard their long-term health, steering clear of the risks associated with heat exhaustion or heat stroke. Secondly, climate change has a significant influence on the quality and efficiency of work during the hours employees are on the job (Kjellstrom et al., 2009; Sahu et al., 2013; Dasgupta et al., 2021). Heat stress is one of the most prominent factors contributing to this decline in productivity. de Bruin et al. (2024) estimate an impact function that relates changes in labour productivity in Ireland with the Wet Bulb Globe Temperature (WBGT) whilst considering seasonal and interaction effects. The findings indicate that, in Ireland, increased temperatures and humidity in work environments can result in decreased productivity. Their results suggest that a 1°C increase in outdoor WBGT results in a 1.6% decline in labour productivity.

Climate change has various detrimental impacts on human health, which can significantly increase rates of morbidity and mortality (Watkiss & Ebi, 2022; Woodland et al., 2023). As temperatures rise, heat waves are projected to become more frequent and severe, which will lead to a rise in cases of heat-related illnesses such as heat stroke and heat exhaustion. These conditions often place a significant strain on the cardiovascular system, particularly among individuals with pre-existing heart conditions (Liu et al., 2022). Price et al. (2024) investigate the potential impact of temperature changes on healthcare by combining data on emergency in-patient hospital admissions for Ireland from the Hospital In-patient Enquiry (HIPE) system with meteorological data from Met Eireann using panel fixed-effects methods. The empirical results indicate that higher temperatures can contribute to an increase in emergency hospital admissions. In terms of providing hospital services, the annual economic burden associated with this varies from €156,000 to €364,000 for every 100,000 population, contingent on the length of stay. Note that these estimates include a single component of health impacts and should not be interpreted as estimates for the overall impacts of climate change on human health.

3.2.2 Adaptation Measures

Estimates of adaptation costs and benefits remain scarce in the literature. Based on de Bruin et al. (2024), we include adaptation strategies for river flooding and coastal impacts. The associated adaptation measures are implemented as increased use of construction to build coastal and river protection infrastructure.

Most studies that analyse the costs and benefits of coastal and river adaptation measures use impact assessment models such as DIVA, FUND, and LISFLOOD. 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 cost-benefit 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 4.1. Benefit-cost ratio (BCR) values and % EAD reduction for river flood adaptation measures.

Adaptation measure	RCP2.6		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.

As discussed, we apply the CIAM model for coastal impacts. The CIAM model includes two forms of adaptation, building of coastal protection infrastructure and relocation costs. Table X gives the values for adaptation costs, gross damages (damages before adaptation) and residual damages (damages after adaptation) for the RCP2.6, RCP4.5 and RCP8.5 scenarios in 2030 and 2050.

Table 4.2. Coastal flooding costs in $bln 2015 and adaptation levels

	2030			2050		
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Relocation costs	0.03	0.03	0.03	0.04	0.05	0.07
Protection costs	0.02	0.02	0.02	0.02	0.02	0.03
Residual damages	0.18	0.19	0.21	0.33	0.42	0.55
Gross damages	1.18	1.23	1.41	2.00	2.31	2.85
Adaptation level	0.85	0.84	0.85	0.83	0.82	0.81

Source: CIAM model based on Diaz (2016).

3.2.3 Production Function Approach

Impacts are introduced as in de Bruin et al (2024) applying the production function method, which is described here. The I3E model's production functions are complex, therefore we will use a representative production function based on Sue Wing & Lanzi (2014) here to illustrate the implementation of impacts. We introduce a further three elements, namely production input composition, capital accumulation and consumption behaviour. Adaptation is also introduced applying the production function approach.

Output for a specific sector ($Q_{Y_{a,t}}$) is produced by labour ($Q_{L_{a,t}}$), capital ($Q_{K_{a,t}}$) and other inputs ($Q_{I_{a,c,t}}$) by good (c) according to the production technology represented by the function $FQ[\cdot]$ as shown in equation (1).. This function represents how inputs can be substituted in the production of output for a specific production sector. η represents the technological augmentation factors, which represent the productivity of the various production elements. The shift parameter $\eta_{Y_{a,t}}$ represents an equiproportional shift in productivity of all inputs while keeping substitution possibilities the same. A shift in $\eta_{K_{a,t}}$, $\eta_{L_{a,t}}$ and $\eta_{I_{a,t}}$ represent an inequiproportional shift in productivity, increasing or decreasing the relative productivity of either capital, labour or other inputs. Such a shift will change the substitutabilities across inputs as they are imperfect substitutes for each other.

$$Q_{a,t} = \eta_{Q_{a,t}} \cdot FQ\left[\eta_{L_{a,t}} L_{a,t}, \eta_{K_{a,t}} K_{a,t}, \eta_{I_{a,t}} I_{a,t}\right] \tag{1}$$

$$K_{a,t+1} = K_{a,t}\left(1 - \delta_{a,t}\right) + INV_{a,t} \tag{2}$$

$$D_{x_t} = \sum_{c=1}^{C} \alpha_{c,x_t} D_{x_t} \tag{3}$$

where $c = 1, 2, 3, \ldots, C$ and $\sum_{c=1}^{C} \alpha_c = 1$.

Productive capital ($Q_{K_{a,t}}$) is built up over time through investments ($INV_{a,t}$), however capital is depreciated over time at the rate of $\delta_{a,t}$ as show in equation (2). A shock to capital is introduced as an increase in the depreciation rate $\delta_{a,t}$. This will decrease the level of capital which feeds into equation (1).

A CGE model is build based on the concept of economic markets, where supply-demand equilibrium determines the equilibrium price. The quantity of supply of goods defined by the production function (eq.1 should equal the demand.[2] Total demand (D_{x_t}) is the sum of demand for each commodity, defined by a share (α_{c_t}) per agent (x): households (HH), government (GOV) and production sectors (A). [3] These share parameters are calibrated based on the utility maximisation problem of households, on the dividend maximisation of production sectors, and on the composition of government expenditures on commodities Climate impacts can lead to increased demand of certain commodities, which is introduced by increasing the share parameters of these commodities α_{c_t}, resulting in reduced consumption of other goods. In this analysis, the share of health care expenditures is increased for households and the government. We assume, in line with current spending patterns of the Irish public health system, that the government pays 90% of the additional costs and households pay the rest.

Table 2 gives the impacts assessed in this paper and the resulting shock in the production function, consumption function, and capital accumulation function.

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[2] This is a simplification, where in the I3E model supply is a complex nested structure of inputs and includes imports from other regions.

[3] This is a simplification, where in the I3E model demand is a complex nested structure of consumption goods and includes exports to other regions.

Table 2: Introduced impacts and adaptation in their implementation the production function

Description	Sector	function	Element	Parameter
Riverine flooding	All	Capital accumulation	Capital depreciation	δ_{ALL}
Coastal flooding	All	Capital accumulation	Capital depreciation	δ_{ALL}
Agricultural yield losses for a subset of crops	Agriculture	Production	Output productivity	$\eta_{K_{AGR}}$
Labour productivity decreases	All	Production	Labour productivity	$\eta_{L_{ALL}}$
Health care costs: Emergency admittances	Health Services	Consumption	Consumption share	α_{hs,gov_t} α_{hs,hh_t} *hs= health services* *gov=government* *hh=households*
River flooding adaptation	Construction	Production	Input share	$Q_{I_{con,a,t}}$
Coastal flooding adaptation	Construction	Production	Input share	$Q_{I_{con,a,t}}$

4 RESULTS

4.1 ADAPTATION AND DAMAGE REDUCTION

CGE models account for the redistribution of economic activity, thus autonomous adaptation to climate change is inherently modelled (Henry, 2022), as well as spill-over effects across sectors. These secondary effects were generally found to be negative in de Bruin et al. (2024), where they were discussed in detail. Given the general equilibrium aspect of the I3E model, it is problematic to disentangle autonomous adaptation from secondary impacts. Hence there is no direct discussion of autonomous adaptation here, but a focus on planned adaptation, as inputted into the model as discussed in the previous section.

Our results are generally presented as percentage changes compared to a counterfactual scenario where no climate change impacts arise, the so-called Business as Usual (BaU) case. Unless otherwise indicated, the results presented are estimated under the RCP 4.5 scenario.

To understand the impacts of adaptation, we implement four scenarios. In the first, we implement the estimated impacts (sum of wetland loss, land inundation, capital losses, and mortality impacts) when no adaptation takes place, and the resulting loss in real GDP is referred to as gross damages (GD). In the second scenario, we evaluate the estimated impacts when adaptation takes place, and the associated real GDP losses are referred to as residual damages (RD). In the third scenario, only protection costs, including relocation costs, are introduced, and the resulting GDP loss is referred to as protection (adaptation) costs (PC). In the final scenario, both residual damages and adaptation costs are implemented, reflecting the optimal mix of adaptation costs and residual impacts, and the real GDP impacts are referred to as net impacts (NET).

Figure 1 shows the percentage change in real GDP compared to the BaU of these scenarios, hence displaying gross damages, residual damages, protection costs, and net impacts. Comparing gross damages to residual damages and protection costs, it is clear that adaptation can significantly reduce the real GDP losses associated with a given level of climate change. In 2030, for example, gross damages of over 2.6% of GDP can be reduced to less than 1% residual damages at a protection cost of 0.26% by applying adaptation policies. However, the true adaptation and protection costs are even smaller as the net damages are smaller than the sum of these as shown by net impacts. This is because protective measures reduce damages.

Figure 1: Real GDP by impact scenario, % change w.r.t. BaU in 2030 for RCP4.5

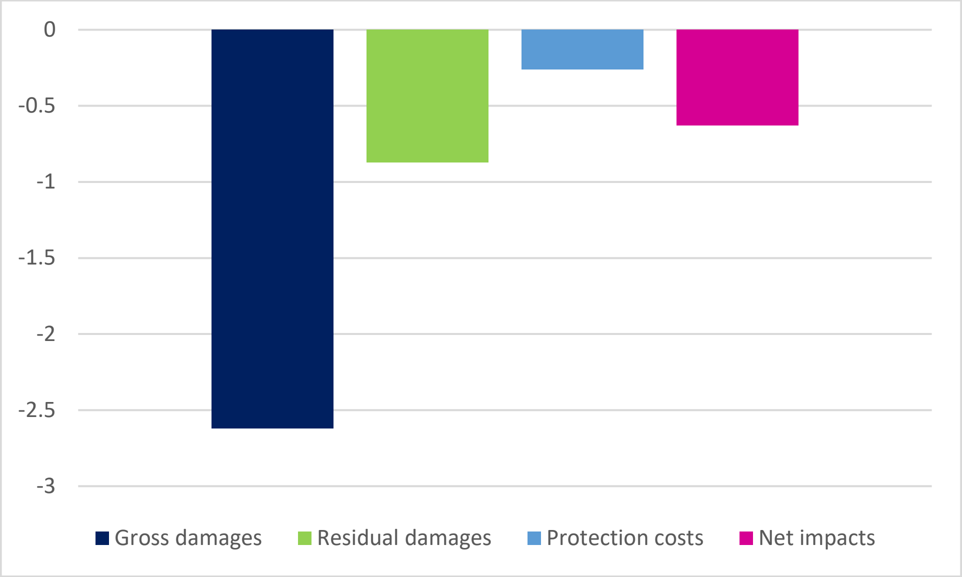
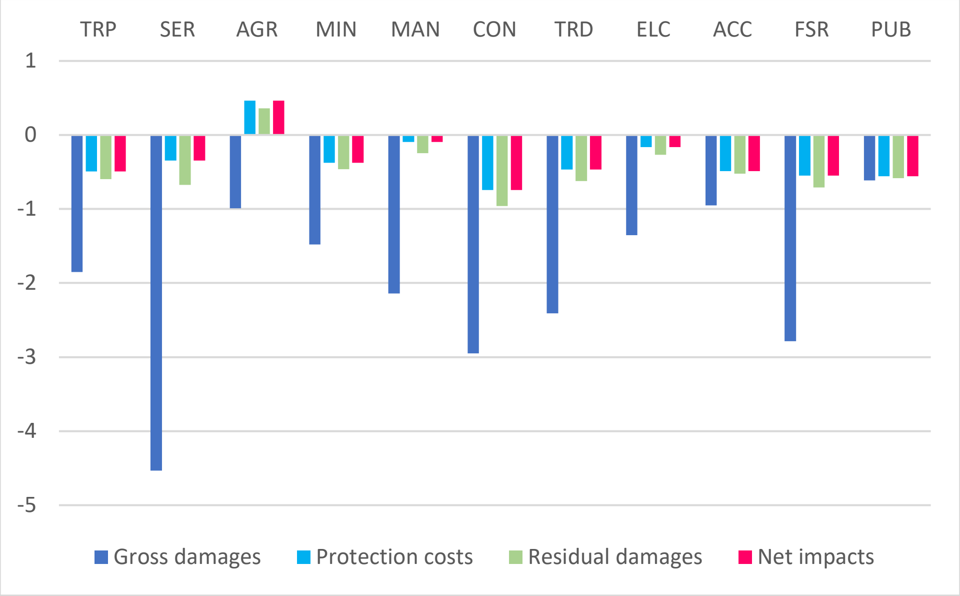


Figure 2 shows the impacts on value added (VA) across aggregate production sectors in the economy. It is clear from the figure that sectors face substantially different gross impacts from climate change, where the service sector is hit the hardest. Adaptation generally results in lower impacts on sectoral VA, with the exception of agriculture. The aggregate agriculture sector includes the primary agriculture (producing crops and livestock), forestry, and fishery sectors. The increase in construction output invokes demand for wood and wood products which, in turn, leads to an increase in demand for forestry output. Although the forestry sector’s weight in the aggregate agriculture sector is small, quite a strong improvement in construction output (from 3% in the GD scenario to less than 1% in the adaptation scenarios, compared to BaU) leads to an increase in the aggregate agriculture VA. Construction output is the commodity with the highest share in the total investment expenditures. Climate change with no adaptation, as evaluated in the gross damages scenario, hits the sector the hardest as capital stock erodes. Although the adaptation policies contributed positively to the level of economic activity in the construction sector, residual damages after adaptation are still the highest for the construction sector.

Figure 2: Value added impacts by aggregate production sector, % change w.r.t. BaU in 2030 for RCP4.5



The acronyms of sectors are as follows: TRP is Transportation, SER is Other Services, AGR is Agriculture, MIN is Mining, MAN is Manufacturing, CON is construction, TRD is Trade, ELC is Electricity Production, ACC is Accommodation, Hotels & Restaurants, FSR is Financial Services, and PUB is Public Services.

4.2 SECONDARY IMPACTS OF ADAPTATION

Adaptation costs and benefits are generally assessed based on their initial costs and their reduction in initial gross damages. The inclusion of secondary impacts is rare, but of paramount importance for understanding the true costs and benefits of adaptation. Initial impacts are the direct or first-order effects, which do not consider any market feedback. However, CGE models account for the redistribution of economic activity, thus autonomous adaptation to climate change is inherently modelled as well as secondary spillover effects (Henry, 2022). For example, increased construction output needed to build coastal protection infrastructure will reduce production across other sectors, resulting in decreased value added.

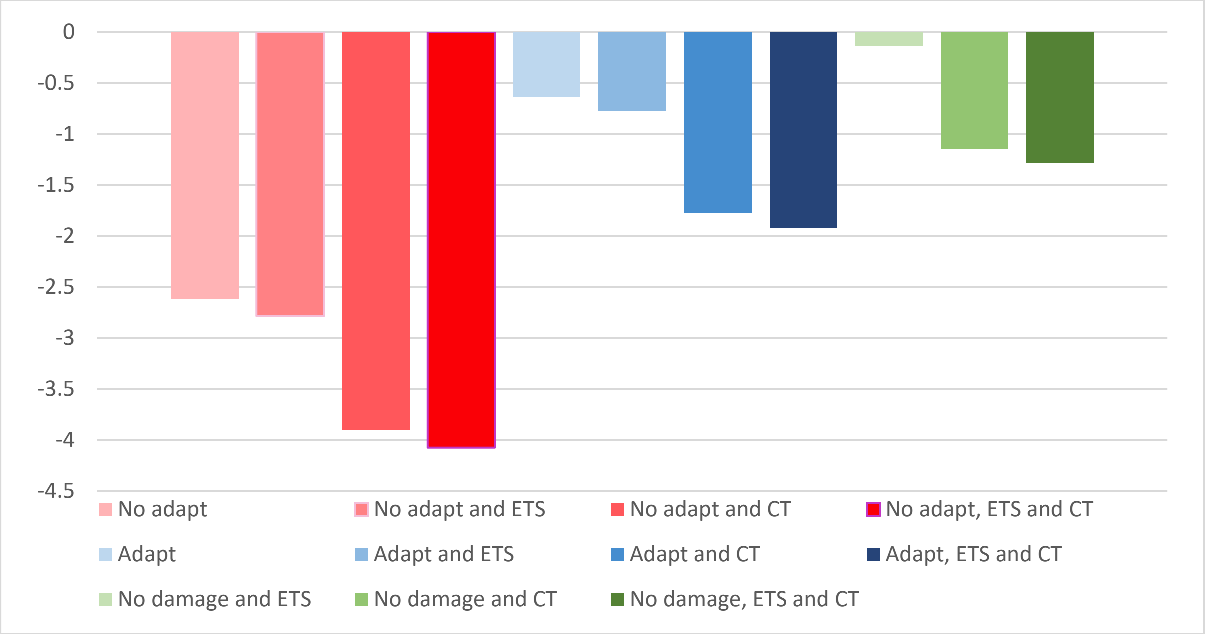
Figure 3 compares the magnitude of initial impact, i.e. the estimated loss implemented in the model (e.g. capital loss or health care cost) and secondary impact, i.e. the losses that follow on from this initial impact (e.g. through lower demand from the market or increases input costs) . Initial adaptation costs are less than 10 percent of secondary adaptation costs, whereas initial adaptation benefits are approximately 20 percent. This means that when considering the economy wide (general equilibrium) impacts of adaptation policies; both secondary costs and benefits are significantly higher *and* the factor by which they are higher is larger in the case of adaptation costs. This means that cost benefit ratios estimated without secondary impacts are likely to be overestimated.

Figure 3: Initial and secondary adaptation costs and benefits RCP4.5 by year

4.3 ADAPTATION AND MITIGATION INTERACTIONS

Carbon pricing in the forms of nationally determined carbon tax or internationally determined EU ETS price per unit of emissions allowance is the most cost-effective way of curbing GHG emissions as part of mitigation policies. In this respect, understanding the interactions between the mitigation and adaptation policies is crucial to set a better policy framework. To this end, six additional scenarios are considered in the report. The scenario denoted by *Adapt* corresponds to the net damages scenario presented above, along which both the Irish carbon tax and EU ETS price assumed to be constant at their 2022 levels. This scenario is extended in the scenario denoted by *Adapt and CT* by considering the increase in the Irish carbon tax as trajected by the Climate Act (2021), i.e., the level of the carbon tax increases by €6.5 until 2029 and by €7.5 in 2030 and reaches €100 in 2030. The scenario denoted by *Adapt and ETS* quantifies the implications of a gradually increasing EU ETS price from €82 in 2022 to €110 in 2045. The scenario of *Adapt, ETS and CT* shows the joint impacts of increasing Irish carbon tax and EU ETS price. The *No damage and CT*, *No damage and ETS*, and *No damage, ETS and CT* scenarios show the pure impacts of gradually increasing carbon pricing and ETS price in the absence of any climate change and adaptation policies effects. Whereas the *No adapt and CT*, *No adapt and ETS*, and the *No adapt, ETS and CT* scenarios show the impacts of mitigation policies when no adaptation is undertaken, but gross damages are implemented.

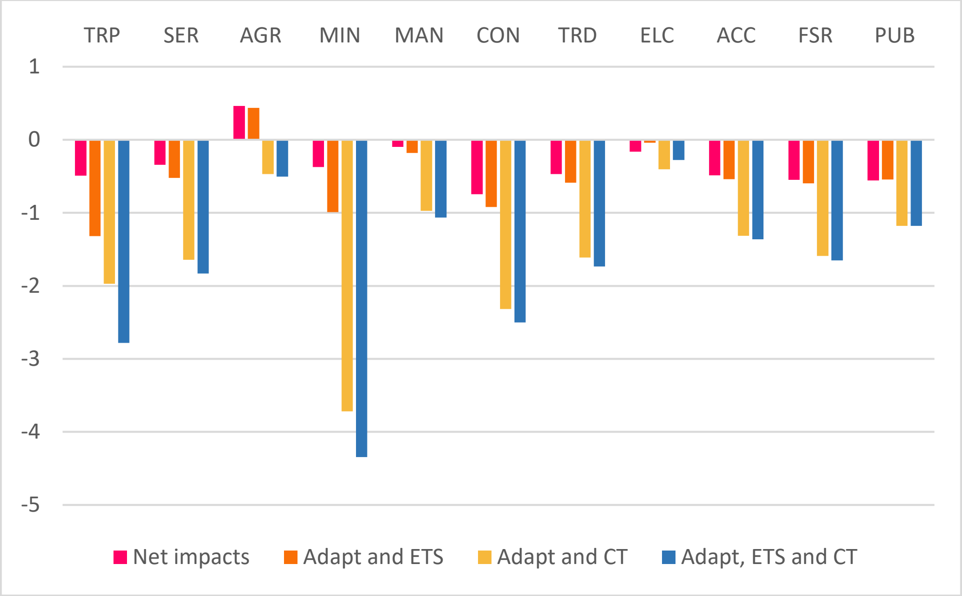
Figure 4: Real GDP by impact scenario, % change w.r.t. BaU in 2030



As Figure 4 indicates, higher carbon pricing amplifies the negative impacts of climate change and adaptation policies on the overall economic activity measured by real GDP. The negative contribution of an increased carbon tax lowers the real GDP further 1.2 percentage points (pp, *Adapt and CT* vs *Adapt*), whereas the impacts of an increased EU ETS price is limited around 0.2 pp (*Adapt and ETS* vs *Adapt*). There are two reasons for such an outcome. First, as of 2022, since around three quarters of the total Irish emissions are subject to the national carbon tax, i.e., non-ETS emissions, an increase in the carbon tax substantially lowers economic activity. In addition, the energy production and aviation sectors that have considerable importance in the Irish economy are subject to the EU ETS so an increase in the carbon tax does not affect them directly. They are affected indirectly through the reduction in economic activity in the other sectors. The second reason is that the EU ETS price is assumed to follow quite a flat pattern compared to the carbon tax. The combined effect of the higher carbon tax and EU ETS price lowers the real GDP by further 1.4 pp in 2030, compared to BaU.

The impacts without adaptation and mitigation policies are high – a reduction in real GDP of more than 2.5%. Mitigation policies themselves have adverse impacts on the economy so they further this impact to over 4%. Adaptation, however, can reduce these impacts significantly, keeping the impact in a range of 0.6% to less than 2%.

Figure 5: Value added impacts by aggregate production sector, % change w.r.t. BaU in 2030 for RCP4.5



The acronyms of sectors are as follows: TRP is Transportation, SER is Other Services, AGR is Agriculture, MIN is Mining, MAN is Manufacturing, CON is construction, TRD is Trade, ELC is Electricity Production, ACC is Accommodation, Hotels & Restaurants, FSR is Financial Services, and PUB is Public Services.

Figure 5 depicts the combined implications of adaptation policies and carbon pricing on the real value added of the aggregate sectors. In line with the real GDP impacts. All sectors are negatively affected by higher carbon prices and the aggregate mining sectors is hit the hardest, as demand for its main product, peat, declines substantially[4]. Since it is a commodity not subject to international trade, economic downturn in domestic markets makes the sector most vulnerable. The second most impacted sector is the aggregate transportation sector, which constitutes land, water, and air transportation. In the *Adapt and CT* scenario, the main source of the reduction in the sectoral VA comes from the land transportation activity, which is heavily dependent on fossil fuels of which prices increased due to the higher carbon tax. In the *Adapt and ETS* scenario, on the other hand, the main driver of the reduction in real VA is the aviation sector, of which emissions are 100% covered by the EU ETS. Therefore, the impact of the gradually increasing EU ETS price is the highest by far for the aggregate transportation sector across all sectors. The aggregate electricity sector, which comprises the conventional electricity production sector using fossil fuels, wind and other renewable sectors, is the least affected sector from higher carbon pricing. The impact of a higher carbon tax is the lowest as the sector is not subject to the tax, and the reduction in electricity demand is the lowest across all energy commodities as the process of other energy commodities increase considerably. The higher EU ETS price impact is the highest as the sector's entire emissions fall under the EU ETS. In the combined scenario of higher carbon tax and EU ETS price, the reduction in real value added of the sector becomes lower than the pure impact of a higher EU ETS price due to the dynamics observed in the CT scenario.

Given the uncertainty of what future GHG emissions will be, different scenarios have been developed by the international community of climate researchers. These scenarios of GHG emissions are an

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[4] In Ireland, peat production is regulated due to its significant environmental impact, particularly concerning carbon emissions, biodiversity, and water quality. The regulations governing peat extraction and usage aim to phase out peat by 2030 and have reduced peat production by 84% between 2018 and 2022. . Our results show that peat production would decrease as it is no longer commercially viable with climate policies.

integral part of climate change modelling and are useful for several purposes, including understanding and predicting future climate change. They help in establishing a connection between atmospheric GHG concentrations and changes in global temperature and other climate variables. By simulating various emissions scenarios in climate models, climate scientists can assess the climate system's sensitivity to various amounts of greenhouse gases.

4.4 DIFFERENT CLIMATE CHANGE FUTURES

To ensure consistency across research applying future climate change scenarios, the IPCC developed a Special Report on Emissions (SRE) with concomitant scenarios (SRES) in 2000. These scenarios were replaced by the Representative Concentration Pathway (RCP) scenarios for the IPCC Fifth Assessment Report (AR5) in 2014. RCPs represent the different future trajectories of GHG concentrations in the atmosphere based on a wide range of assumptions regarding population growth, economic development, technological innovation and attitudes to social and environmental sustainability (IPCC, 2014). For instance, all RCPs include the assumption that air pollution control becomes more stringent over time as a result of rising income levels (Van Vuuren et al., 2011). There are four main RCPs with numerical values 2.6, 4.5, 6.0, and 8.5. These numbers represent the radiative forcing (i.e., the difference between the incoming and outgoing energy from the sun) values in the year 2100.

The four RCPs comprise a mitigation scenario (RCP2.6) that results in a very low forcing level, two stabilisation scenarios (RCP4.5 and RCP6.0), and a scenario (RCP8.5) that has extremely high GHG emissions. In other words, RCP2.6 represents a pathway where GHG emissions are significantly reduced, leading to an estimated 1.6°C increase in global average temperature by 2100 relative to the pre-industrial period (1850-1900). This can be interpreted as an ambitious interpretation of the Paris Agreement reflecting the goals of the agreement and does not refer to the current pledges under the Paris Agreement which would result in significantly higher concentrations. RCP8.5 is a pathway where GHG emissions continue to grow unmitigated, resulting in a best estimate global average temperature rise of 4.3°C by 2100. We will refer to this pathway as the "no mitigation" pathway, acknowledging that this is an extreme interpretation of no climate action and refers to the worst-case scenario. RCP4.5 and RCP6.0 are two medium stabilisation pathways with varying levels of mitigation (Met Office, 2018). RCP4.5 is referred to as the "most likely" scenario and has hence been the focus of this paper so far.

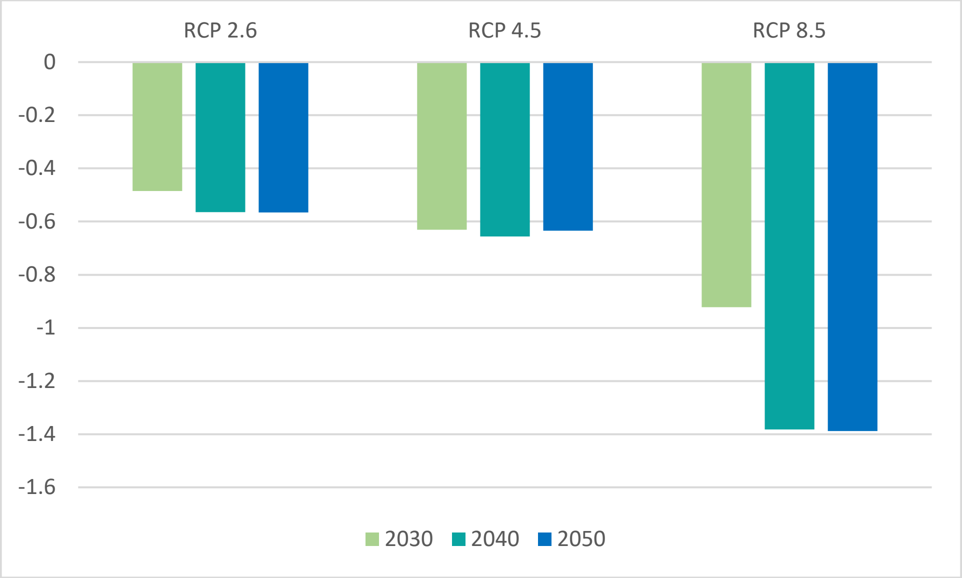
Here we examine the impacts under three RCP pathways: 2.6, 4.5 and 8.5. The increase in global mean temperature predicted by the RCP pathways for the late 21st century is shown in table 3.

Table 3: The increase in global mean temperature compared to Preindustrial level across scenarios

RCP Scenario	Change in temperature (°C) by 2081-2100
RCP2.6 "Paris Agreement"	1.6 (0.9 to 2.3)
RCP4.5 "most likely"	2.4 (1.7 to 3.2)
RCP8.5 "no mitigation"	4.3 (3.2 to 5.4)

The different RCP scenarios are driven by global mitigation efforts, the concomitant net impacts for the Irish economy are presented in Figure 6. As can be seen from the figure the impacts across RCPs differ considerably. RCP 2.6 and 4.5 results in a reduction in real GDP of around 0.5% and 0.6%, respectively, which subtly but generally gets worse over time. In contract, RCP 8.5 results in a reduction of almost 1% in 2030 and further to a reduction of almost 1.4% by 2040 and 2050. This highlights the importance of international cooperation on climate change mitigation for Ireland. Mitigation options are often discussed in terms of their additional cost to the Irish economy. It was clear from the previous section that the effects of the climate change impacts considered outweighed the impacts of the mitigation option considered. When we include the impacts of international cooperation (RCP 2.6 versus RCP 8.5), the benefits of Ireland contributing and collaborating with other nations on mitigation are clear.

Figure 6: Net impacts of climate change, real GDP as % change w.r.t. BaU across RCP scenarios



5 CONCLUSION

This paper investigated the interaction of mitigation and adaptation in a CGE setting for Ireland. Based on estimates from the literature, five climate change impacts are implemented into an intertemporal CGE model for Ireland (I3E). These impacts are coastal flooding, riverine flooding, heat effects on labour productivity, human health, and agricultural productivity. Additionally, adaptation costs and benefits for riverine flooding and coastal impacts from the literature are implemented into the model.

Based on a production function approach, riverine and coastal impacts are introduced as capital losses through an increased capital depreciation rate for production sectors. Labour productivity impacts are implemented by a reduction in overall labour productivity across skill types. Human health impacts are introduced based on estimates of increase emergency hospitalisations, whose costs are borne by households and the government. Agricultural impacts on a subset of crops are introduced through a Total Factor Productivity shock on the agricultural production sector. Adaptation in the form of the building of coastal protection infrastructure is modelled as increased spending on construction by production sectors.

Our estimates find that adaptation can significantly decrease the impacts of climate change for Ireland, where net climate change costs more than halved when adaptation is applied. Gross impacts before adaptation vary across sectors, where services are impacted most. Costs associated with adaptation affect most sectors negatively and vary less across sectors than gross damages.

Secondary impacts are estimated through the mechanisms implicit in CGE modelling, where markets and behaviour adjust based on price changes. Initial adaptation costs are less than 10 percent that of secondary adaptation costs, whereas initial adaptation benefits are approximately 20 percent. This means that when considering the economy wide (general equilibrium) impacts of adaptation policies; both adaptation costs and benefits are significantly higher and the factor by which they are higher is larger in the case of adaptation costs. These means that cost benefit ratios estimated without secondary impacts are likely to be overestimated.

Overall, we find that the resulting real GDP and sectoral value added losses are highest for climate change impacts without adaptation with a loss of 2.6% of real GDP in 2030. Second highest are the impacts of mitigation policies (increased carbon tax and EU ETS price) with a loss of 1.3% in the same year. Climate change impacts with optimal adaptation result in the lowest losses of 0.6% of real GDP in 2030.

We also investigate the interactions between adaptation and mitigation policies and find that the sectoral spread of value added losses differ considerably between climate change impacts, adaptation and mitigation policies. We do not find that any specific sector is hit hard by both impacts and mitigation policies. We also do not find any secondary interaction between adaptation and mitigation, i.e. introducing a mitigation policy with or without adaptation will not change its relative impacts significantly.

From a global perspective, international efforts to reduce emissions through the Paris Agreement will significantly decrease net climate change impacts for Ireland, where net impacts in 2040 under the Paris Agreement (RCP 2.6) are almost three times lower than in a no mitigation scenario (RCP 8.5), i.e. 0.56% decrease in real GDP as opposed to a 1.38% decrease in real GDP. This highlights the importance of international cooperation on climate change mitigation.

From a policy perspective, further research is needed to understand the full range of climate change impacts Ireland is facing and the adaptation strategies that can be applied to reduce these impacts. Our results show that secondary impacts will play a pivotal role in both climate change impacts and adaptation. Policy assessments need to include secondary impacts to ensure adaptation policies are evaluated at their true economy wide costs. Finally, our results confirm the importance of Ireland continued commitment to emission reduction helping to ensure a global effort to reduce emissions and hence climate change impacts.

This paper has several caveats that should be mentioned. This paper considered only five types of climate change impacts, a complete analysis should include more impacts such as storms, extreme events, biodiversity and non-yield agricultural impacts. Furthermore, the shocks implemented could be further refined, such as capital losses to specific sectors based on their location. Future work should focus on including adaptation, implementing more types of impacts and specific shocks such as changes in particular types of capital. Finally only two distinct adaptation options were implemented due to lack of further estimates of adaptation costs and benefits, a comprehensive analysis would include more adaptation options.

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