ECONADAPT

The Economics of Adaptation

Funded by the European Union

Deliverable 8.2: Modelling autonomous adaptation with the GEM-E3 model and planned adaptation with the ICES model

Methodology and results

Francesco Bosello (CMCC), Ramiro Parrado (CMCC), Juan Carlos Ciscar (JRC), Wojtek Szewczyk (JRC)

Deliverable number	D8.2
Work Package Number	WP8
Submission date	July 2016
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	Modelling autonomous adaptation with the GEM-E3 model and planned adaptation with the ICES model Methodology and results
Authors:	Francesco Bosello (CMCC), Ramiro Parrado(CMCC), Juan Carlos Ciscar(JRC), Wojtek Szewczyk(JRC)
Other Contributors	Anna Dellarole (University of Milan), Elisa Delpiazzo(CMCC), Sally Brown (University of Southampton), Jochen Hinkel (Global Climate Forum), Daniel Lincke(Global Climate Forum)
Date:	July 2016
Contact details	Name, email of lead author
Work Package Number	WP 8
Deliverable number	D8.2
Filename:	D8.2-Master-Executive-Summary.docx D8.2.1-Autonomous-Adaptation.docx, D8.2.2-Planned-Adaptation-Agriculture.docx D8.2.3-Planned-Adaptation-Sea-Level-Rise.docx
Document history:	version 1.0
Type of Activity	RTD
Nature	R = Report, O = Other
Dissemination / distribution level	PU = Public:
Citation:	Deliverable 8.2 of the ECONADAPT Project.
Copyright:	

The ECONADAPT project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 603906.

To find out more about the ECONADAPT project, please visit the web-site: www.econadapt.eu

For further information on the ECONADAPT project contact Alistair Hunt at: ecsasph@bath.ac.uk

Executive Summary

This deliverable describes the methodology and main results of modelling adaptation to climate change with two different Computable General Equilibrium (CGE) models: CAGE-GEME3 and ICES. Each CGE model addresses different aspects of the adaptation process and, together, they provide insights on the specific nature of adaptation. Given the scope of the analysis and the extent of the report, we present Deliverable 8.2 in three chapters as separate reports, as follows:

Deliverable 8.2: *"Modelling autonomous adaptation with CAGE-GEME3 and ICES: Methodology and results".* Two-page executive summary

Chapter 1: Deliverable 8.2.1 *"Modelling autonomous adaptation with the CAGE-GEME3 model"*

Chapter 2: Deliverable 8.2.2 *"The implications of irrigation as a planned adaptation measure on an economy wide context"*

Chapter 3: Deliverable 8.2.3 "*Modelling planned adaptation for coastal zone protection in a general equilibrium framework"*

Autonomous Adaptation

The first Chapter reports on application of CAGE-GEME3 model for quantitative analysis of autonomous adaptation for a set of four climate impact areas: agriculture, sea level rise (SLR), energy and labour productivity. The general equilibrium model is used to explore dynamics of markets' reaction to climate change impacts under different assumptions regarding these markets' ability to react which, consequently, allows for valuation of the adjustments in terms of income and welfare. The main mechanisms explored to control the degree of autonomous adaptation in the general equilibrium model relate to changes in sectoral mobility of labour, technical substitution between labour and capital, and flexibility of international trade. With the aid of several examples the results identify how different market mechanisms can play different roles and be of different importance for the autonomous adaptation depending on local characteristics of regional economy, on the specificity of climate impacts anticipated for the region, and on international trade linkages between the region and the rest of the economy.

In global terms, the results suggest that autonomous adaptation can reduce the effects of climate impacts by a third, approximately, both regarding the GDP and welfare losses; thus the global GDP loss could be 1% rather than 1.4%. Although the adaptive labour market is the main driver of the autonomous adaptation at the world level, this globally aggregated result is underpinned by a great deal of differences at regional and sectoral levels. In the EU, the region that absorbs most of the avoided damages thanks to market adaptation is the UK and Ireland region, followed by Southern Europe and the Central Europe North regions. In general, it seems that the welfare-enhancement effect of adaptation diminishes relatively when moving to lower latitudes. Related to the population, the UK and Ireland region would have an additional 120 US$ gain in per capita terms thanks to adaptation. The Northern Europe region would be 60 US$ and that of the Southern Europe region being 50 US$.

Planned Adaptation

The remaining Chapters (two to three) use the ICES model to assess the economic implications of planned adaptation measures to specific climate change impacts. This will provide additional insights about the economy-wide and indirect effects of putting into practice measures that proactively seek to reduce the expected damages of climate change. Given that these impacts and the related adaptation measures are different in nature, the ICES model has been developed into two different versions to better capture adaptation specificities.

Chapter two addresses climate change impacts on agriculture and the choice faced by farmers to use irrigation services in order to contrast the negative effects on crop yields. Consequently the ICES-IRR model has been extended to explicit irrigation services in the cost structure of agricultural production representing irrigation as an endogenous choice of farmers to contrast losses due to diminishing crop yields. The new specification enriches the land supply structure of ICES introducing different land rents and imperfect flexible land conversion between pasture and cropland, irrigable and rainfed land and among different crop industries. Moreover, it takes into account the additional capital, operation and maintenance costs that farmers face when they decide to expand irrigation.

Results show that when irrigation cannot be expanded, lower latitude countries are those most negatively affected either in terms of decreased crop production or lower GDP that can reduce by -1.4% in Asian countries by mid-century. Some higher latitude countries, e.g. Northern EU and the Former Soviet Union could experience slight GDP gains as a consequence of higher crop yields. Against this background, irrigation expansion can be an effective adaptation option in particular for lower latitude countries enabling higher production and lower GDP losses. However, gains compared to the no adaptation case are tiny in percent terms. Converting rainfed into irrigable land and expanding irrigation services is costly and in the end increase further agricultural prices which compresses demand expansion. The final effect of flexible irrigation is a reallocation of crop production from developed to developing countries which are advantaged in relative terms by a combination of lower irrigation costs with the initial climatic impacts.

The second example of planned adaptation examined is coastal protection against sea level rise (SLR). This is a typical case requiring public interventions to coordinate huge investments addressed to build protective infrastructure that will become a quasi-public good. To address properly this issue the ICES model has been enhanced with a more detailed description of the public sector, the main actor in charge of raising and channelling the investments necessary to build and maintain sea barriers (ICES-XPS). In addition, a specific adaption module has been built in to accommodate the required adaptation investment flows and expenditures. To provide a range of results taking into account uncertainty in climate projections we use the output of the DIVA model for two RCPs (2.6 and 8.5) with projections coming from two GCMs (NorESM and MIROC-ESM).

In a scenario where coastal protection is not enhanced, almost all world regions suffer a GDP loss with the exception of South Korea. The most damaged countries are in Asia, while EU regions would experiment moderate GDP losses lower than 1% in 2050.

When coastal protection takes place, the highest GDP gains compared to the case of no protection are observed mostly in developing countries where SLR impacts are markedly high and adaptation expenditures particularly effective. In the remaining regions GDP gains are also experienced, but are lower. The beneficial effect of adaptation on GDP is the result of two mechanisms. The first one regards the avoided direct impacts (loss of labour productivity, land and capital). The second one is the public deficit effect. When adaptation to SLR reduces GDP losses, it also triggers a tax interaction effect which produces higher tax revenues. Therefore the government borrows less from households savings and have to pay a lower debt service both of which allows for an increased capital accumulation in the long run.

As a general conclusion, support to adaptation in deficit spending might be not necessarily bad for GDP growth, and might also trigger positive effects on public finance sustainability. This highlights a potentially interesting policy outcome. Adaptation expenditure could enable virtuous processes even though initially financed with debt.

ECONADAPT

The Economics of Adaptation

Funded by
the European Union

Deliverable 8.2.1: Modelling autonomous adaptation with the CAGE-GEME3 model

Wojtek Szewczyk and Juan Carlos Ciscar
(JRC-IPTS)

Deliverable number	8.2
Work Package Number	8
Submission date	22 March 2016
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	Modelling autonomous adaptation with the CAGE-GEME3 model
Authors:	Wojtek Szewczyk and Juan Carlos Ciscar
Other Contributors	
Date:	22 March 2016
Contact details	Wojtek Szewczyk (Wojciech.szewczyk@ec.europe.eu)
Work Package Number	WP8
Deliverable number	D8.2
Filename:	D8.2.1-Autonomous-Adaptation.doc
Document history:	Version 1.0
Type of Activity	RTD
Nature	R = Report, O = Other
Dissemination / distribution level	PU = Public: PP = Restricted to other programme participants (including the Commission Services); RE = Restricted to a group specified by the consortium (including the Commission Services); CO = Confidential, only for members of the consortium (including the Commission Services)
Citation:	
Copyright:	

The ECONADAPT project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 603906.

To find out more about the ECONADAPT project, please visit the web-site: www.econadapt.eu

For further information on the ECONADAPT project contact Alistair Hunt at: ecsasph@bath.ac.uk

Table of Contents

List of Figures

List of Tables

1. Introduction

The IPCC (2007) defines climate adaptation as the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities". Climate change is already happening and there is therefore a need to adapt to it. Indeed, adaptation to climate change has drawn more and more attention in recent years, as for instance with the launch in 2013 of the EU adaptation strategy.

The human systems' adaptation to climate change is a complex phenomenon with several dimensions. The following categories can be distinguished: planned (also named public), autonomous (also named spontaneous, private or market-based), reactive, proactive, direct, indirect, short- and long-run types of adaptation (see Annex D).

The adaptation process considers changes to the way that some sections of the economy function. Thus for the structured analysis of the autonomous adaptation it is important to consider different direct and potential indirect implications of the adaptation-induced decisions.

Aaheim and Aason (2008) discuss the *direct* and *indirect* effects related to autonomous adaptation: the direct autonomous adaptation refers to the changes made by autonomous economic agents when confronted with climate change. Examples include using more water or fertilisers in agriculture in order to compensate for lower rainfall. The indirect effect of the autonomous adaptation refers to the wider market response of demand and supply resulting from the initial direct effect. The propagation of the indirect response in the economy will depend on the specificity of the economic trade network and can have both domestic and international effects. Those effects are captured with the computable general equilibrium (CGE) models. Indeed, the CGE class of models capture both the first order effects of a shock (direct effect) and the second and higher order effects (indirect effects).

This report focuses on the quantitative analysis of autonomous adaptation for a set of climate impacts. This complements the ECONADAPT work in WP8 with public adaptation. Four climate impact areas are considered: agriculture, sea level rise (SLR), energy and labour productivity. A general equilibrium model is used in order to explore the influence of various autonomous adaptation mechanisms in the model, namely changes in the labour mobility across sectors and the degree of substitution of international trade.

The proposed modelling framework allows the exploration of the transmission mechanisms through which the climate impacts propagate throughout the economy, affecting in the end the overall economic activity (GDP) and consumer's welfare. In this respect, the preliminary results should be interpreted as a way to identify trends and mechanisms rather than be a precise quantitative assessment. Moreover, as the coverage of climate impact is quite limited (notably the report does not consider some key climate impacts such as effects on ecosystem services or those associated with passing tipping points), this analysis does not intend to make a comprehensive assessment of how much private adaptation could reduce climate impacts.

This rest of this report is structured as follows: Section 2 introduces the CAGE-GEME3 model used for the analysis of autonomous adaptation, followed by presentation on how autonomous adaptation is accounted for in the structure and theory of the model. The Section also discusses the climate data used and the implemented experimental design. Section 3 presents and discusses the climate impacts at the global level with and without adaptation, while Section 4 concentrates on summary analysis of the market adaptation for the EU regions. Section 5 provides detailed, in-depth analysis of several examples illustrating the mechanisms of market adaptation at work for different climate impacts and various EU regions. Section 6 concludes and indicates areas of further research.

2. Methodological framework

This section reviews the main elements of the methodology underlying this study. It starts with the main features of the CGE model, focusing on how autonomous adaptation has been considered in that setting. The source of the climate shocks estimates is also presented.

2.1. CAGE-GEME3 CGE model

The CGE class of models is well suited for the simulation and analysis of autonomous adaptation. The general equilibrium mechanisms, which propel CGE models and which determine how the economic agents react when constraints that they face are changing, represent, in fact, the mechanism underpinning the autonomous adaptation. The CGE models capture both the direct and indirect effects of private adaptation for the variety of economic agents considered (usually, government, households and firms). The bilateral trade linkages, a standard feature in most CGE models, allow for tracking how the adaptation response in one of the sectors or by one of the agents propagates within the country or region, but also beyond the national border via international trade.

The model employed for this analysis, CAGE-GEME3[1], is a static multi-country, multi-sector computable general equilibrium model of the world economy linking the economies through endogenous bilateral trade. The CAGE database is mainly based on the Global Trade Analysis Project (GTAP) database, version 8 (Narayanan et al., 2012)[2].

The GTAP database provides input-output tables for a large set of countries/regions and commodity categories. The CAGE-GEME3 model has 19 sectors and 25 regions[3]. The major individual countries in the climate negotiations have been included separately (Brazil, Canada, China, India, Indonesia, Japan, Korea, Mexico, Russia, South Africa and the USA). The European Union is split into five regions: UK and Ireland, Northern Europe, Central Europe North, Central Europe South and Southern Europe. The remaining regions are Australasia, Rest of South Asia, Rest of sub-Saharan Africa, Rest of Europe[4], Rest of South-East Asia, Rest of Former Soviet Union, Middle East & North Africa, Central America & Caribbean and South America.

The CGE analysis of climate impacts follows a static comparative approach (as in e.g. Aaheim et al., 2012; Hertel et al. 2010; and Ciscar et al. 2012), estimating the counterfactual of future climate change (simulated in the 2080s) occurring under the current socioeconomic conditions. Therefore, the climate shock-induced changes would occur in the economy as of today.

---

[1] See Annex A - Description of the CAGE-GEME3 model. The full model description and mathematical model statement is provided in the Annex of Pycroft et al. (2015).

[2] https://www.gtap.agecon.purdue.edu/

[3] The CAGE sectors and regions are detailed in: Annex A - Description of the CAGE-GEME3 model

[4] The Rest of Europe region includes the following countries: Albania, Bosnia and Herzegovina, Macedonia, Montenegro, Norway, Serbia, and Switzerland

The implications of that choice are widely discussed in Ciscar et al. (2012). In contrast, a 'dynamic' approach would account for changes that the economy and society will undergo until the end of the century, and apply the climate shocks to the version of economy as in 2100. Climate impacts might become larger as they would affect a bigger economy. Considerations of how adaptation might be in the future would need to be made. Development of such representation of future economy, however, would require numerous assumptions about factors shaping the societal and economic development. The assumptions would be required to envisage impact of demography, technology (existing and new), degree of adaptation to climate change (both planned and autonomous), societal preferences and more. All these assumptions would bear a (high) degree of uncertainty and would further complicate the interpretation and validity of the final results.

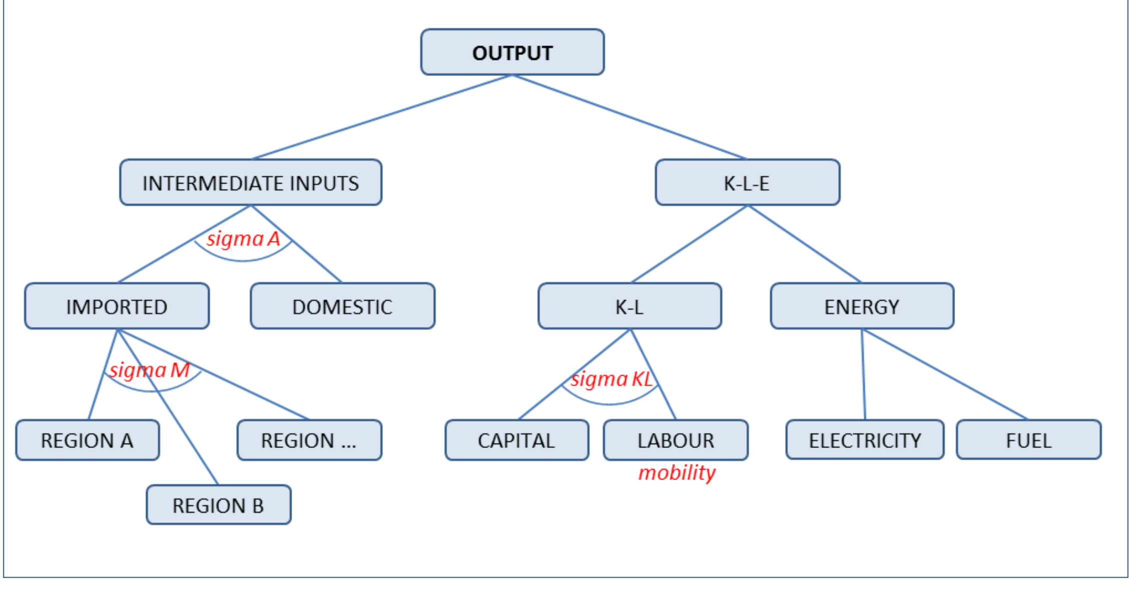
2.2. Accounting for autonomous adaptation in CAGE-GEME3

For the ECONADAPT project, the CAGE-GEME3 model was tailored to explore the implications of the various possible autonomous adaptation mechanisms that relate to labour mobility, both across sectors and regions, the degree of substitutability between capital and labour in the production function and the degree of substitutability for trade flows and domestic production.

In particular, the adaptation-related mechanisms include three specific mechanisms. **Figure 1** identifies where the key parameters to control the autonomous adaptation mechanisms are positioned within the model's production structure:

(1) control of labour mobility (*mobility*);
(2) control of substitution possibilities between capital and labour to account for changes in the available technologies (*sigma KL*);
(3) control of the degree of trade rigidity. This is implemented by modifying the substitution elasticity both between domestically produced and imported goods and services, and between imports from different regions (*sigma A and sigma M,* respectively).

Figure 1: Production structure in the CAGE-GEME3 model.



The parameters' range applied in the simulations were based on the literature and determined experimentally[5]; the relevant details are discussed below.

Mobility of primary factors of production

There are two main types of labour mobility: geographical and occupational. Geographical mobility[6] refers to a worker's ability to work in a particular physical location, while occupational mobility refers to a worker's ability to move between different economic sectors. The labour mobility can help to smooth out sectorial consequences of negative climate impacts, but its effectiveness depends on how easily workers can gain employment in new sectors. For example, if due to the reduction in fuels demand the employment in the fuel-related sectors declines, the laid-off workers would be looking for new employment opportunities.

The CAGE-GEME3 model distinguishes two factors of production: capital and labour. The labour mobility is specified via a constant elasticity of transformation (CET) function (like in Bosello and Parrado, 2014), with the elasticity of transformation parameter, *mobility*, determining the responsiveness of the factors' supply to the wage differentials across different employing sectors. For the parameter's value close to zero labour is very sluggish (sector-specific) and is not capable of moving across sectors. Then the lower the value of the parameter is (towards $-\infty$), the more mobile labour becomes. The base value of the *mobility* parameter, -1, reflects current mobility possibilities within the EU[7]. To increase rigidity of the markets, ie to eliminate adaptive capacity of the markets, the mobility parameter is reduced to -0.01, the value which allows for a very limited movement of labour between sectors. The immobile labour cannot change occupations; hence it has to remain in the original sector of employment, in spite of the climate shocks.

Capital is assumed to be mobile across sectors (but not across regions) and it is not modified in this study.

Substitutability between primary factors of production

The elasticity of substitution between capital and labour, *sigma_KL*, is reduced in the counterfactual experiment to 0.1 to reflect less favourable technological options available to substitute the inputs (see Appendix **Table 32** and **Table 33** for the elasticities' values).

Trade rigidities

As presented in **Figure 1** imports are modelled in a two-level nested system with separate elasticity determining (a) the substitution possibilities between imports from different regions (*sigma_M*, lower nest) and (b) the substitution possibilities between the imported and domestically produced goods and services (*sigma_A*). In order to reduce the adaptive capacity of trade substitution the parameters are reduced to 30% of their original values (see Appendix **Table 32** and **Table 33** for the specific elasticities' values).

---

[5] The parameters creating market rigidities where gradually changed to the point where the model could be solved for all the climate impact categories.

[6] The geographical mobility is not addressed in this study due to the aggregation of the model, which does not contain any intra-national geographical detail.

[7] The occupational in the EU mobility remain rather low in its member states albeit the right for free movement of labour (Barslund, 2015).

Three series of simulations are performed (**Table 1**) in order to analyse the degree and value of the autonomous adaptation:

1. The benchmark case reflects the current adaptive capacity of the markets,
2. the semi-rigid case assumes a reduction in the flexibility of adaptation into the trade structure,
3. the rigid scenario introduces an all-rigid markets by restricting both trade and also the production factors ability to adapt (the degree of substitutability between capital and labour).

Table 1: Controls of autonomous adaptation in CAGE-GEME3 model

Adaptation capacity	***Factors of production***	***Capital-labour substitution technology***	***Trade flexibility***
Adaptive markets	Mobile as the reference economy (*mobility*=-1)	As in the current economy (*sigma_KL*=0.5)	Flexible as empirically estimated by sector (see Table 32 and Table 33 for specific values)
Semi-rigid markets	Mobile as the reference economy (*mobility*=-1)	As in the current economy (*sigma_KL*=0.5)	Restricted trade by lowering the elasticities by 70%
Rigid markets	Reduced labour mobility (*mobility*=-0.01)	Reduced substitution between capital and labour (*sigma_KL*=0.1)	Restricted trade by lowering the elasticities by 70%

2.3. Climate shocks input

Four climate impacts are considered in the subsequent analysis: impacts in Agricultural Crops production (AGRI), impact of Sea Level Rise (SLR), Labour Productivity (LPROD), and Energy Demand (ENER). **Table 2** details the climate shocks

Agriculture

Agriculture yield changes from the FP7 ClimateCost project are used to simulate the global climate impacts in the agriculture sector. The A1B IPCC SRES scenario has been applied. The scenario implies approximately a global temperature increase of 4ºC, compared to the pre-industrial level. **Table 2** presents the global and regional yield changes. The global yield loss (excluding the effects of any climate-induced land-use change) is estimated at 5%. Regarding the developing countries, the South Asia and Rest of South-East Asia regions, India and Indonesia are the most negatively affected by climate change, with yield change losses between 14% and 21% for the high emission scenario. Other regions are also projected to undergo large yield losses, such as Mexico, South Africa and the Southern

Europe region. The Northern Europe region, China, Canada, Russia and the UK and Ireland could experience positive yield changes, according to the agriculture model simulations.

Sea Level Rise

For the Sea Level Rise, the scenario assumes a rise of sea level by 2100 of 0.47m, which is consistent with the A1B IMAGE scenario, assuming 2.4°C by the 2050s, and 3.8°C by the 2090s. Most of the regions are subject to capital losses below 1%. The largest capital losses in Europe would occur in Central Europe north (1.3%) and Northern Europe (0.3%). In terms of changes in obliged consumption the largest absolute increase would occur in China (over 24bn$), followed by the Rest of South-East Asia and Central Europe north regions and the USA. At the other end of the scale, the lowest increase in obliged consumption would happen in South Africa, Central America and Caribbean and Mexico. The simulated changes in obliged consumption are directly related to the number of people migrating, a direct output of the DIVA model (the migration cost per person is estimated to be three times the per capita income).

Energy Demand

The Energy Demand reflects the economic implications of changes in energy demand for heating and cooling resulting from future climatic change, where the warmer climate is expected to lead to reduced demand for heating in winter, and increased demand for cooling in summer. The analysis considers the A1B climate change scenario of the IPCC SRES scenarios, which represent a medium-high emission trajectory with warming of about 4ºC by 2100 as compared to the preindustrial levels[8]. The analysis of economic implications of future changes in energy and electricity demand for heating and cooling is based on output of the POLES (Prospective Outlook on Long-term Energy Systems) model. The model uses socio-economic projections and detailed climate simulation data (A1B) to produce coherent simulations for future demand of oil, coal, gas and electricity for residential and service sectors. Table 2 shows percent changes by 2085 for the energy demand for gas, coal, oil and electricity by the domestic and service sectors for the A1B scenario. The overall observed pattern across the regions is a reduction in the use of gas, coal and oil (except South East Asia) and an increase in the use of electricity. The increase in demand for electricity for air conditioning depends on both the average use of electricity for air conditioning per household (climate effect) and on the fraction of household actually using the air conditioning (saturation effect) – hence the large increases in some countries (10-15 times-fold).

[8] Please note that in this section due to country mapping used in the POLES model the region Rest of South East Asia (RoSEAsia) is merged with region South Asia (SAsia).

Table 2: Implementation of climate impacts shocks

	Agriculture (A1B)	Sea Level Rise (A1B)		Labour productivity (RCP 8.5)					Energy demand change, % (A1B)							
	Crops productivity reduction %	Capital loss, %	Obliged consumption increase, bn US$	Temperature (WBGT)		Reduction in labour productivity %			Domestic demand				Service sector demand			
				Reference (outdoor)	Future increase	Heavy	Moderate	Light	Gas	Coal	Oil	Ele	Gas	Coal	Oil	Ele
China	11	-0.08	24.0	18.1	3.8	-10.7	-3.4	-1.6	-26.1	-25.6	-15.5	260.2	-28.6	-28.4	-22.4	25.6
Japan	-13	-0.49	3.4	17.6	3.4	-8.5	-1.8	-0.5	-16.9	-16.4	-8.5	265.5	-15.5	-15.4	-11.2	16.8
Korea	-10	-0.42	4.2	16.5	3.6	-8.9	-1.6	-0.4	-23.7	-23.8	-12.9	1473.4	-25.3	-25.3	-19.2	55.6
Indonesia	-14	-0.12	0.9	27.2	3.2	-32.7	-5	-0.6	0.0	0.0	0.0	780.4	-0.1	0.0	-0.1	5.3
India	-18	-0.05	4.5	25.0	3.8	-24.4	-7.9	-3.8	-82.0	-81.9	-52.4	765.9	-94.4	-94.4	-83.6	14.9
Australasia	-5	-0.07	0.3	24.1	2.9	-19.4	-2.4	-0.2	-55.9	-55.9	-2.6	63.0	-70.8	-70.8	-32.1	9.6
South Asia	-21	-0.13	2.6	23.9	3.9	-23.2	-9.7	-5.1	0.2	0.2	0.1	897.4	45.7	45.8	35.0	17.8
Rest of South-East Asia	-21	-0.56	15.3	23.2	3.5	-23.1	-5.8	-1.8	0.2	0.2	0.1	897.4	45.7	45.8	35.0	17.8
Canada	13	-0.17	0.8	12.2	4.2	-1.4	0	0	-21.1	-21.1	-3.5	28.8	-22.7	-22.6	-16.0	8.2
USA	-9	-0.28	4.7	17.1	3.7	-6.1	-0.7	-0.1	-24.8	-24.8	-2.9	62.7	-32.3	-32.0	-18.2	12.2
Mexico	-17	-0.01	0.2	21.3	3.4	-8.6	-1.6	-0.4	-0.3	-0.3	-0.1	1581.6	-0.5	-0.5	-0.3	49.7
Brazil	1	-0.03	0.3	24.2	3.4	-18.7	-2.5	-0.4	0.0	0.0	0.0	1405.2	0.0	0.0	0.0	27.5
Central America and Caribbear	-8	-0.01	0.1	23.8	3.2	-13.2	-0.7	0	0.0	0.0	0.0	529.1	0.0	0.0	0.0	12.3
Rest of South America	0	-0.18	1.6	21.3	3.1	-12.1	-2.6	-0.8	-16.8	-16.8	-5.1	185.9	-24.3	-24.3	-8.8	20.7
Middle East and North Africa	-11	-0.06	2.5	19.3	3.4	-7	-0.7	-0.2	-13.1	-24.5	-6.6	12.6	-38.9	-26.1	-19.8	16.9
Sub-Saharian Africa	-6	-0.01	0.5	23.6	3.7	-18.8	-3.2	-0.5	0.0	0.0	0.0	1028.7	0.0	0.0	0.0	23.4
South Africa	-14	-0.01	0.0	19.8	3.2	-3.8	-0.1	0	-0.1	-0.1	0.0	841.3	-7.7	-7.7	-6.2	91.6
Northern Europe	24	0.34	0.9	12.6	3.2	-0.1	0	0	-22.1	-20.9	-6.2	-3.5	-24.8	-23.3	-16.9	40.4
UK & Ireland	6	0.31	2.2	14.6	2.5	0	0	0	-19.7	-21.1	-6.8	4.4	-26.2	-25.6	-15.0	139.2
Central Europe North	-2	1.26	6.8	14.5	3.1	-2.3	-0.2	0	-22.3	-19.2	-11.9	-0.6	-21.1	-20.0	-14.6	64.5
Central Europe South	-4	0.23	1.8	15.5	3.3	-1.5	-0.1	0	-22.5	-21.5	-10.2	3.4	-23.1	-21.8	-16.0	47.1
Southern Europe	-20	0.18	1.1	17.4	3.1	-2.3	-0.2	0	-27.5	-22.7	-11.9	202.3	-27.9	-10.9	-14.2	61.5
Rest of Europe	-12	-0.20	0.8	14.5	3.3	-1.1	0	0	-6.1	-13.8	-7.2	57.3	-31.7	-22.6	-19.5	138.1
Russia	7	-0.04	1.0	11.9	3.6	-0.7	0	0	-21.1	-20.8	-7.7	1.9	-21.1	-20.4	-14.9	2.5
Rest of former USSR	5	-0.02	0.2	14.5	3.3	-1.5	-0.2	-0.1	-15.3	-15.6	-5.8	2.0	-17.4	-18.2	-13.2	17.5

Labour productivity

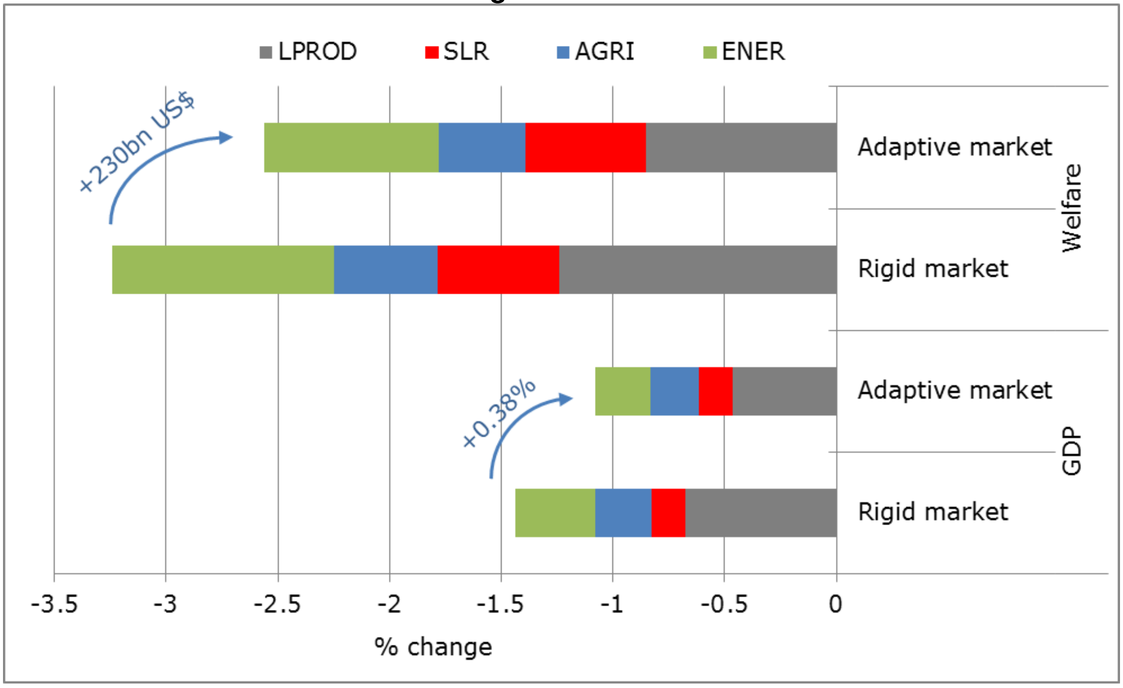
Climate fluctuations can directly influence human labour and increased heat exposure can negatively affect labour productivity[9]. **Table 2** lists the values of the labour productivity shock in each region by type of labour. The productivity reductions are higher for more labour intense occupations by construct, although the magnitude of the specific occupations being affected depends on the region-specific circumstances. For example, the most affected performance of heavy labour is in Indonesia; however the moderate work is most affected in South Asia. The heavy labour sectors are most affected in Indonesia (over 30%), India, South and South-East Asia, Australia, New Zealand, Sub-Saharan Africa, South America (about 20%).The largest reduction in labour productivity is simulated to occur in the tropical belt where the initial (historical) temperatures are above 26 degrees Wet Bulb Globe Temperature (WBGT) in the reference, so every increase in temperature contributes negatively to the productivity.

[9] The following preliminary analysis has been made at JRC-IPTS. For more details on the methodology and results please see the "heat stress and labour productivity" Annex report.

3. Global Impacts

Figure 2 and **Table 3** show the change in the world's GDP and consumer welfare (Equivalent Variation, EV, measured as change in real consumption above the subsistence level), which are further divided into the contributions from the specific climate impacts.

Figure 2: Global GDP and Welfare change (%) from climate impacts with adaptive and rigid markets



Under the rigid market conditions, the effects of the considered climate change impacts are estimated at -1.46% of the global GDP or -3.3% of the global welfare. The same climate impacts simulated under adaptive markets conditions return lower GDP and welfare effects of, respectively, -1.08% and -2.56%. Therefore, the ability of the markets to adapt to the climate impacts alleviate the negative climate shocks by 0.38% of world's GDP and 0.75% of global welfare, which is equivalent to 230 bn US$ in the money metric form.

Table 3: Change in global GDP and EV for different climate impacts for rigid and adaptive markets[10]

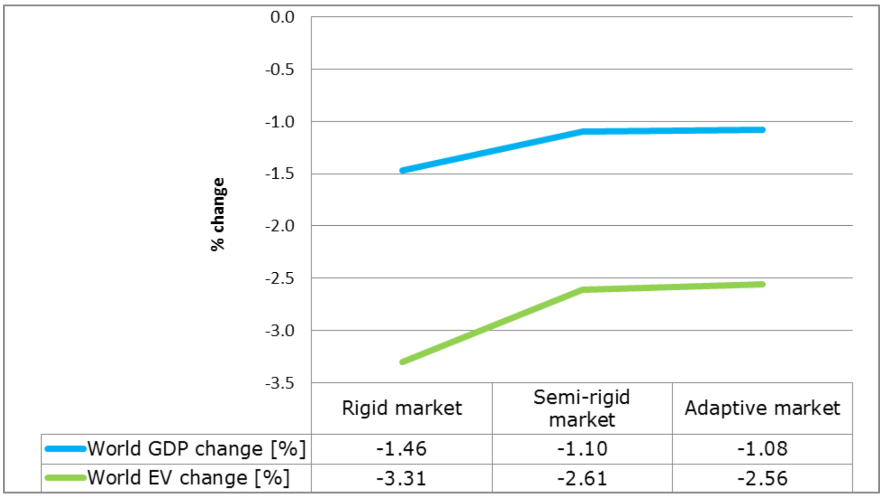
	GDP, %		EV, %	
	Rigid market	Adaptive market	Rigid market	Adaptive market
AGRI	-0.253	-0.218	-0.465	-0.385
SLR	-0.152	-0.151	-0.541	-0.540
ENER	-0.359	-0.246	-0.992	-0.780
LPROD	-0.675	-0.464	-1.243	-0.854
Total	*-1.464*	*-1.079*	*-3.305*	*-2.558*

For further analysis it is useful to consider the two sides of each specific impact category (AGRI, SLR, ENER and LPROD). The negative side is the share that specific impact contributes to the total global GDP loss. For example, in the rigid market conditions, out of the total loss of -1.46% GDP the Labour productivity is responsible for -0.68%, which is a 47% share. On the other, the positive side, out of the 0.38% of the alleviation effect due to market adaptation 0.21% is due to reduction of the negative effects of the Labour Productivity impacts, which is a 59% share. Second largest impact is the Energy Demand, which is responsible for about 25% of the overall GDP reduction and of about 30% of the alleviation benefit. Almost 20% of the total impact attributes to Agriculture with about 10% of the alleviation effect. Finally, the Sea Level Rise brings about 13% of the total global GDP impacts but, interestingly, does not contribute almost at all to the alleviation effect (0.3%). These effects are further explored and explained in the rest of the report.

Information presented on **Figure 3** provides insight into how the two main types of the autonomous adaptation considered – via trade and via labour market – separately affect the GDP and welfare at the global level. Both the GDP and the EV results suggest that, at the global scale, an adaptive labour market brings relatively more benefits, when compared to adaptation via trade. The flexibility in the mobility of labour allows to avoid 0.36% of GDP loss and, more importantly, 0.7% of welfare loss. The adaptation via adjustment of trade patterns alleviates additional 0.02% of GDP and 0.05% of welfare impacts.

[10] The totals presented in the table do not exactly reflect the arithmetic sum of the constituent impacts due to some interactions of impacts that the modelling accounts for.

Figure 3: Change in global GDP and welfare (EV) for three degrees of market rigidity.



It must be stressed that the greater benefit from adaptation via labour market compared to the trade flexibility observed at the global scale is not repeated for all the constituent countries and regions. As will be further explored in this report, particularly in chapters 4 and 5, the two types of adaptation can indeed take different proportions depending on region-specific factors and connections with the rest of the world economy via international trade.

4. Overview of market adaptation in the EU

This chapter reviews the mechanisms and effects of market adaptation for the five EU regions considered in this report. The first section summarises the GDP effects, while the rest of the chapter takes an in-depth view into the welfare effects that accompany the autonomous adaptation process.

At the EU aggregate level the welfare value of the autonomous adaptation to impacts of the four climate shocks is estimated at about 23bn US$. This value is calculated as the difference of welfare loss between the rigid market conditions and the full adaptation scenario (**Table 4**), and it is interpreted as a welfare gain realised by means of the economic mechanisms of market adaptation.

Table 4: Welfare reduction across the EU regions with rigid market, adaptive market, and the value of the adaptation (in bn US$)

	Rigid market	Adaptive market	Welfare adapatation value
UK & Ireland	-43	-36	8
Northern Europe	-5	-3	2
Central Europe North	-73	-67	5
Central Europe South	-28	-26	2
Southern Europe	-67	-60	7
EU	-215	-192	23

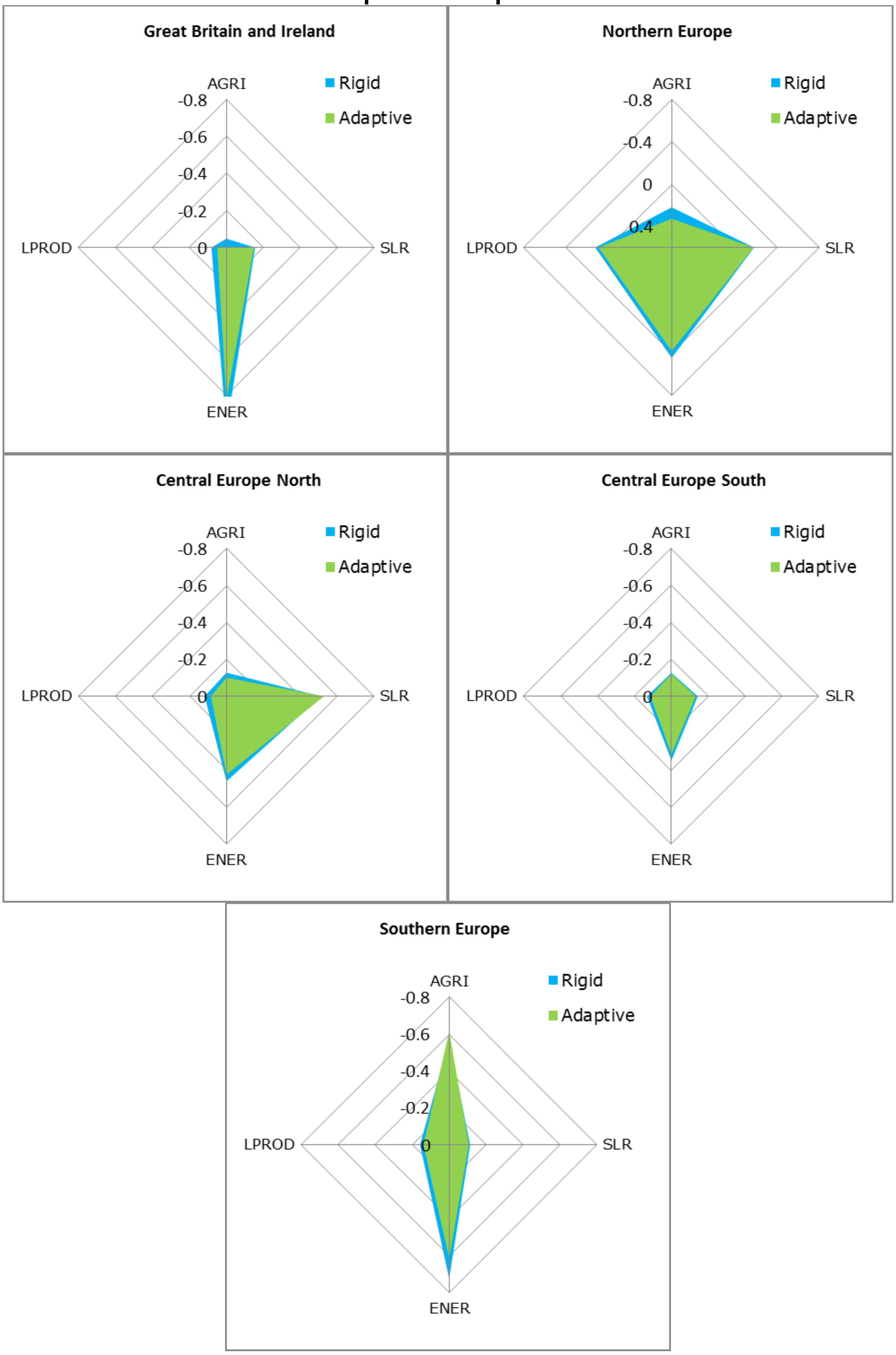
This aggregate value of adaptation masks a great deal of impacts and responses varying at the regional and sectoral levels. The next sections of this chapter will look into the more detail picture of the autonomous adaptation in the EU regions.

4.1. GDP effects of the market adaptation

The effects of the different climate impacts on the GDP for the EU regions are presented on graphs in **Figure 4** (for the detailed numerical results see **Table 34** in the Appendix). Each graph of **Figure 4** represents the GDP changes in one of the EU regions, with the four climate impacts represented in the four axes (spokes) of the radar graph: impact of agriculture is represented at the upper part of the vertical axis, sea level rise effect is depicted at the right hand side of the vertical axis, the energy effect is measured at the lower side of the vertical spoke, and the GDP change from labour productivity is shown at the left hand side of the horizontal axis. The blue area on the graphs represents the GDP change estimated under the rigid market conditions, while the green area, superimposed on the blue shape, shows the change in GDP when the markets are allowed to adapt. In effect, the blue outline visible on the figures can be interpreted as the effect of adaptation in the GDP terms.

In general, it seems that the market adaptation mechanisms alleviate the negative GDP effects (most of the impacts) and amplifies the positive GDP effects (e.g. agriculture in Northern Europe). Exceptions include two cases: further increase of SLR impact in Central and Northern Europe from -0.65% to -0.66% of GDP following the adaptation, and increase of impact of agriculture in Southern Europe from -0.56% to -0.62% of GDP. Other interesting results include the reduction in United Kingdom and Ireland's GDP from the agricultural impacts, despite the productivity shock being positive (6% in **Table 2**). All these cases are further explored in the detailed analysis of impacts in section 5.

Figure 4: Change in the EU regions' GDP from the climate impacts with and without the private adaptation



The impact of adaptation on GDP following the climate shocks appears to be particularly small in the case of SLR. Across the regions, it brings only an improvement of 0.01% of GDP.

In the United Kingdom and Ireland region the total GDP loss is reduced from 1.27% to 1.02% with the market adaptation process. The magnitudes by the constituent impacts, in the decreasing order and for the rigid market case, are: impacts from changes in the energy demand (-0.98%), followed by SLR (-0.16%), labour productivity (-0.08%) and agriculture (-0.05%).

The Northern Europe losses 0.53% of its GDP, with the adaptation process alleviating the impact to -0.41%. The components' impacts are estimated at: -0.45% from changes in energy demand, -0.18% from SLR, -0.12% from labour productivity reduction and 0.22% increase in GDP from agricultural impacts.

Out of the -1.22% GDP reduction in Central Europe North, the largest impact is from SLR (-0.51%), followed by energy demand (-0.46%) and, almost identical, impacts from agriculture (-0.13%) and labour productivity (-0.12%). The regional GDP impact is reduced with the adaptation process to -1.27%.

The GDP effects in Central Europe South are relatively small compared to the other regions and add up to -0.75% reduction in the regional GDP, reduced to -0.73% by the adaptation. The largest constituent impact is due to changes in energy demand (-0.35%), followed by SLR (-0.14%), and agriculture and labour productivity (-0.13%, both).

Finally, the Southern Europe observed the largest overall GDP effect of -1.56%, reduced to -1.50% due to the market adaptation. Most of the overall impact is due to the changes in energy demand (-0.73%) and to agricultural impacts (-0.56%). Changes from labour productivity and SLR are computed at -0.16% and -0.11%, respectively.

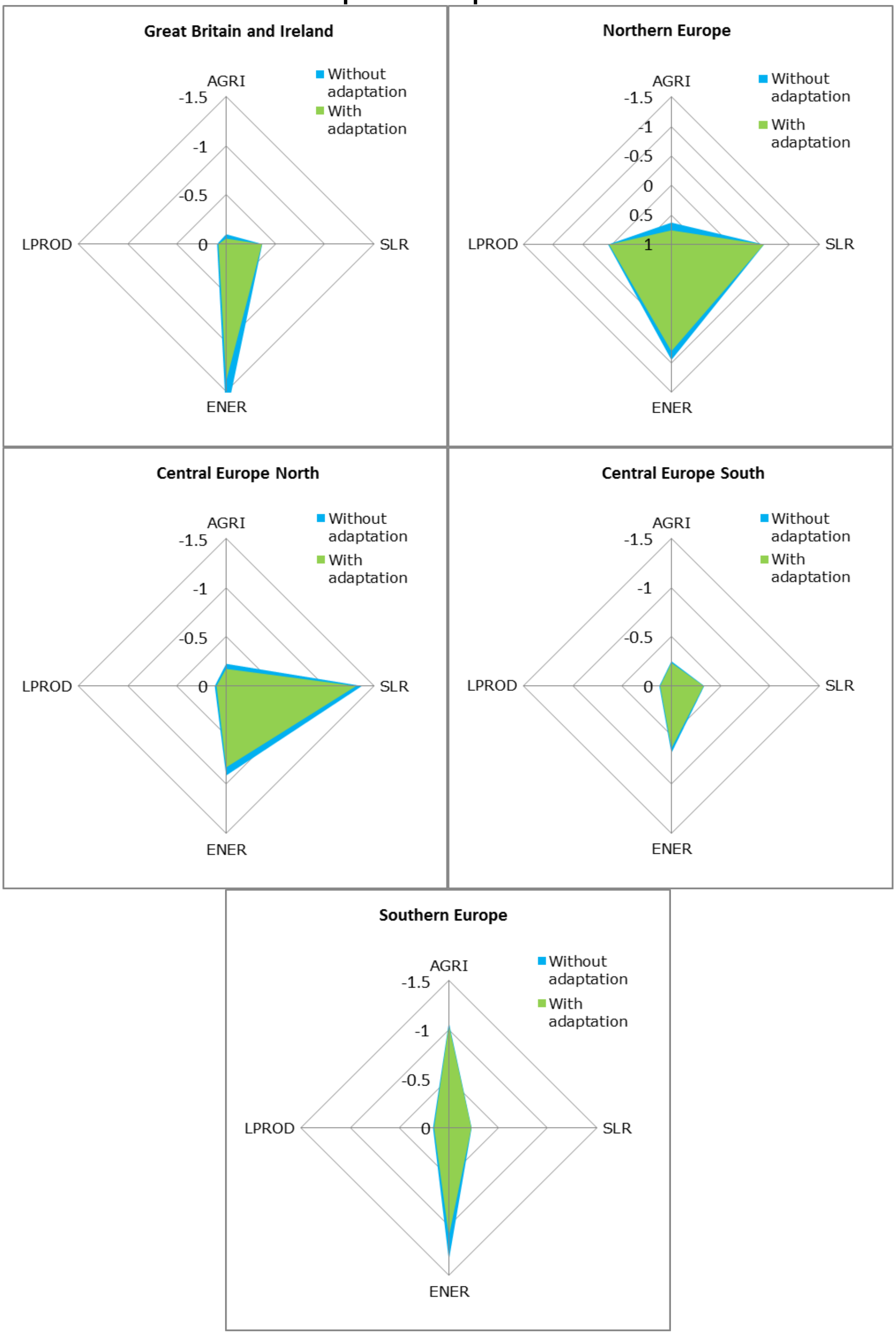
4.2. Welfare effects of the market adaptation

Welfare results of climate impacts with and without market adaptation

The set of graphs in **Figure 5** is analogous to that in **Figure 4** but is shows changes in welfare (EV) rather than GDP. It is worth noting that in all cases the adaptation improves the welfare, even in case of impacts/regions where the GDP was not necessarily higher. An example is impact of agriculture in Southern Europe, which results in further reduction of GDP from -0.56% to -0.62%, but the EV increases from -0.23% to -0.22%. This differential effect results from the fact that adaptation allows, among others, for greater flexibility in changing trade patterns and, in this case, to increase imports of products for substituting of domestic production which, due to climate impacts, became scarce or expensive. In this case the higher imports have negative impact on the GDP identity, although it benefits welfare through lower consumption prices.

The graphs in **Figure 5** are all plotted on the same scale ranging to -1.5% EV reduction, which allows to compare the size of total impact and the adaptation-induced change across the regions.

Figure 5: Change in the EU regions' EV from the climate impacts with and without the private adaptation



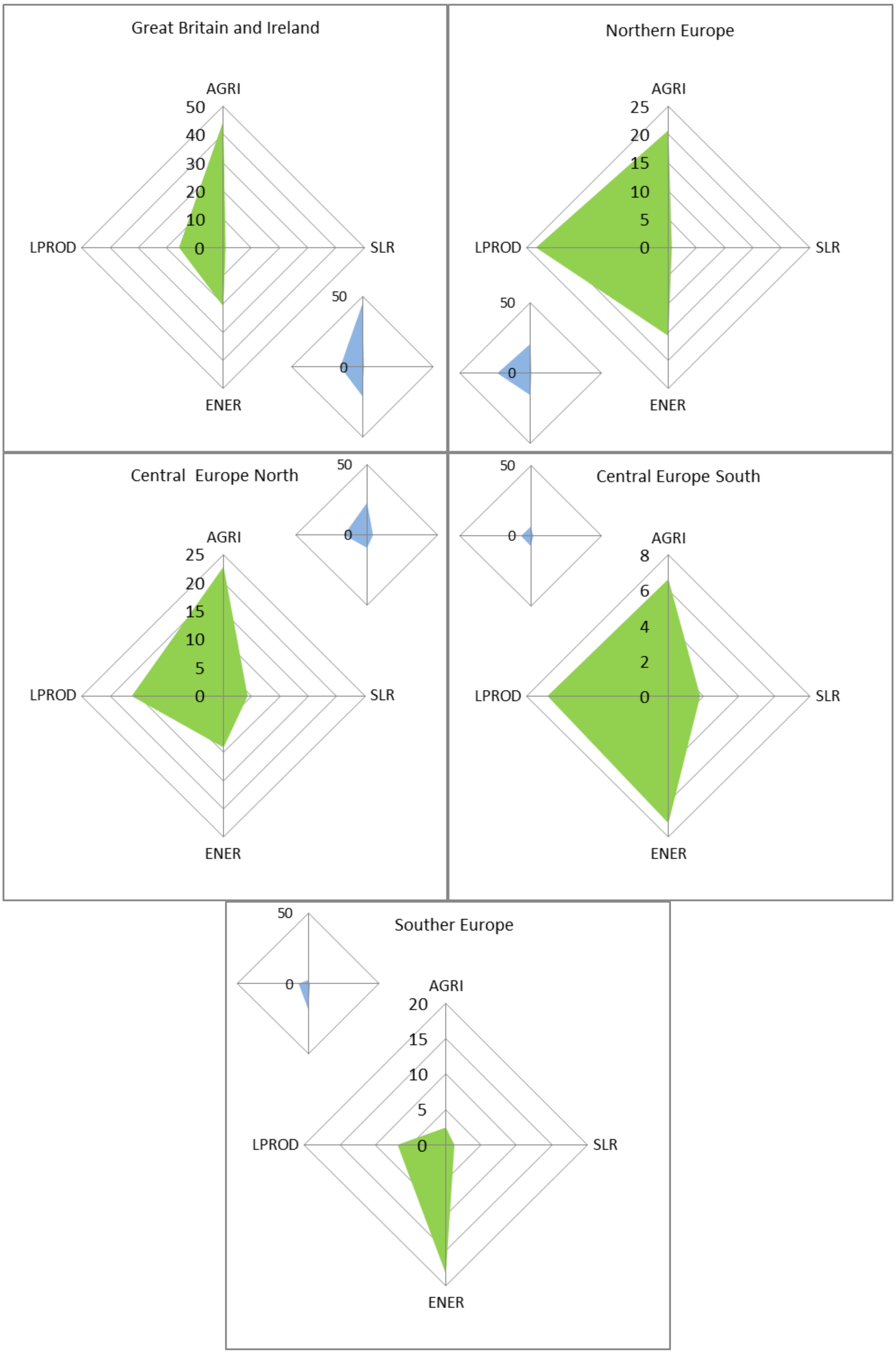
The overall proportional change from climate impacts without and with the adaptation and measured by the Equivalent Variation (EV) reflects the proportional change in the GDP change terms. For example the adaptation process alleviates the United Kingdom and Ireland's GDP impact by about 18% (from -1.34% to -1.10%), similarly as the welfare impact measured by the EV (from -2.32% to -1.90%). These proportional changes at the regional level are relatively consistent between the GDP and the EV effects, although they vary if analysed for the specific impacts. For example, the impact of agricultural shock in the United Kingdom and Ireland is almost entirely attenuated in GDP terms (from -0.05% to 0%) but the negative welfare impact remains (reduced from -0.10% to -0.06%). The analysis of proportional changes in welfare across different impacts is further explored in the next section.

Proportional change in adaptation-induced welfare

Further perspective considered in this section analyses magnitude of the adaptation process in proportion to the impacts of climate estimated without the adaptation process allowed. The set of graphs in **Figure 6** shows change in welfare generated by the adaptation response as percentage of welfare change originating from the climate impacts without the market adaptation accounted for. For example, the change in EV in United Kingdom and Ireland due to agricultural impacts without the adaptation is -0.1% with the subsequent adaptation process adding 0.044%, which is approximately a 44% improvement.

Each regional graph in **Figure 6** shows an additional small blue diagram which is based on the same data as the large green surface but they are imposed on the common scale for all regions (0 to 50%). This series of 'blue' graphs allows for direct comparison of the magnitude of adaptation-induced welfare gain by contrasting area and shape of the diagrams.

Figure 6: Value of the adaptation response as percentage of the climate impacts without the private adaptation



Comparing the overall welfare–enhancement effect of the adaptation (small blue charts in **Figure 6**) it is apparent that the effect diminishes when moving to lower latitudes. The largest relative effect is noted in the United Kingdom and Ireland region, followed by Northern Europe and Central Europe North, and with Central Europe South and Southern Europe showing the lowest welfare returns on the market adaptation process. A summary discussion of the market adaptation mechanisms is provided below for the different climate impact categories.

Agriculture

The largest welfare gains from the adaptation process are estimated for EU-Northern regions. The reason behind this layout is relatively mild or positive impacts of climate changes on domestic agricultural crops production (see **Table 2**), so the initial welfare reduction under rigid market conditions is due to higher import prices passed on by trading partners whose agricultural crops production is more affected. Subsequently, the value of adaptation reflects the degree into which these regions can substitute away from the highly priced imports towards more competitive imports and/or domestic production.

The effect of substituting expensive imports with domestic production is emphasised in Northern Europe region (24% improvement in crops' production productivity) where adaptation via lowering imports and increasing domestic production leads to 20% improvement in welfare. In United Kingdom and Ireland the benefit of domestic crops' productivity gain (6%) is dominated by loss from increasing price of imports under the rigid market assumptions. The adaptation process allows to reorient the composition of imports to reduce the welfare loss from the climate impact to zero.

A somehow opposite mechanism is observed in the EU-Southern regions where, following the climate shock, the domestic prices of agricultural crops rise more than the price of imports, and the adaptation process reflects the regions' ability to substitute *towards* the relatively low-priced imports. The Southern Europe region experiences a 20% decline in agricultural crops productivity which leads to substantial increase in their domestic prices and significant welfare loss. With the adaptation process occurring, lowering domestic production and increasing imports leads to lower consumer prices and increase in welfare by 2.4%.

Sea Level Rise

The market adaptation potential to effects of SLR is very small across all of the EU regions. The main channels of impact of the SLR are, firstly, a direct impact on households' budgets through higher, non-welfare creating expenditures related to migration and, secondly, via loss of capital in the business sector. While the markets can adapt, and to extend, to changes in capital supply, the forced migration costs are constant irrespective of degree of market adaptiveness, hence offer no possibility of adaptation.

The Central Europe South region shows the largest adaptive capacity (4.2%) to the SLR impacts, because it faces the largest capital loss (1.3%) which is 3 to 4 times larger than in other EU regions.

For other EU regions the benefits from market adaptation are very small. To explain this it is worth to recall how the physical impacts from SLR are represented in the macroeconomic model (see also section 2.3). The economic representation of SLR is incorporated via loss in capital uniform across all the sectors, and via increase in obliged consumption of households. Apart from Central Europe North, the capital loss is very small (Table 2 and Figure 8) for other EU regions and, since all the sectors are subjected to the same capital loss there are no large inefficiencies which could be corrected with the market adaptation mechanisms. The second channel of SLR impact – increase in obliged consumption –

affects directly the welfare (via reduction in welfare-creating consumption), and it remains the same irrespective of the degree of economic adaptation.

Energy Demand

There are two main channels through which changes in energy demand affect the regional performance. The first one relates to changes in private energy demand which directly affects households' welfare via a higher expenditure share spent on energy and, thus, lower share available for welfare-creating consumption. The second channel relates to changes in service sector energy demand which has an indirect impact on welfare via changes in the distribution of labour, wages and prices. Because the use of energy by the service sector is in general far larger than the use by households, the change in electricity demand of the business sector has the highest impact on welfare change.

For all EU regions the market adaptation to changes in energy demand is almost entirely realised through flexibility in labour market and substitution between the factors of production, while the adaptation via trade is very limited. The changing pattern of demand for energy and electricity requires a flexible labour market in which labour can move from sectors that face lowering demand for their output (energy sectors) to sectors which expand (e.g. electricity). Limited labour mobility maintains inefficiencies resulting in lower overall wage bill available to households.

The degree of adaptation to changes in energy demand via labour mobility depends mainly on the magnitude of the sectoral changes. For example, the United Kingdom and Ireland region faces an almost 140% increase in electricity demand, which has significant impact on the welfare level, but which can also be significantly alleviated if the markets are able to adjust. In another example, the Central Europe South region when subjected to relatively lower increase in demand for electricity, by 47%, faces much smaller welfare reductions, but it also has less capacity to adjust.

Labour productivity

The degree of benefit realised from the adaptation to reduced labour productivity appear to be inversely proportional to the magnitude of the labour productivity reduction. The Northern EU regions which experienced relatively smaller economic effects from this climate impact gain between 16% (United Kingdom and Ireland, and Central Europe North) and 23% (Northern Europe) of additional welfare from the adaptation process, while in the Southern EU regions which were subjected to more severe labour productivity reductions the adaptation process brings less than 7% of additional welfare gain.

The reasons for this differential degree of adaptation (as explored in detail in section 5.4) lie in the size of the labour productivity shock and in its international trade linkages. The Northern EU regions do not experience much of their 'own' labour productivity reduction, and most of the negative economic effects are passed on via trans-boundary effects: increase in price of imports and reduced demand for exports. For this reason the trade-related adaptation which allows for change in international trade pattern eliminates very significant portion of the GDP and welfare reductions, when the adaptation though mobility of labour, while still beneficial, adds considerably less to the overall effect.

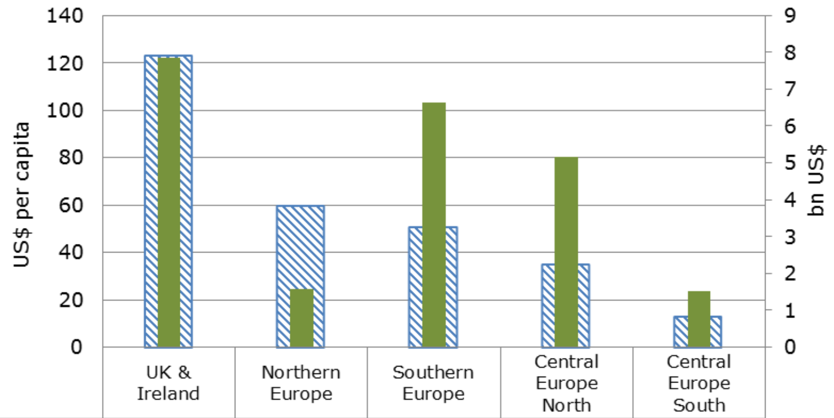
In contrast, in the Southern EU regions the bulk of the negative economic effects is caused by the labour productivity reduction which is internal to their economies, and the trans-boundary effect has only a small contribution to the overall reduction in GDP and welfare. This explains why adaptation via trade brings almost no effect to the degree of GDP and welfare reductions in these regions. On the other hand, and differently to the Northern EU regions, their Southern counterparts benefit mostly through adaptation via mobility of factors of production which enables adjustment of the economy to the new climatic situation.

Welfare value of the market adaptation

Since the welfare metric (EV) is estimated based on the change in real consumption above the subsistence level, it is possible to derive a money-metric as an additional quantification of the value of adaptation.

Figure 7 below shows the value of adaptation (measured as the difference between the welfare reductions for rigid and for adaptive markets) for aggregate regional value of the additional consumption (green bars), and for the average, per-capita value of additional consumption (blue, diagonally-filled bars) enabled by the market adaptation mechanism.

Figure 7: Welfare value of the market adaptation measured as difference between welfare reductions for rigid and for adaptive markets.



	UK & Ireland	Northern Europe	Southern Europe	Central Europe North	Central Europe South
EV change per capita US$	122.7	59.4	50.4	34.9	12.7
Regional EV change bn US$	7.8	1.6	6.6	5.2	1.5

In absolute aggregate terms, the region that capitalises the most on the adaptation process is United Kingdom and Ireland, where the autonomous adaptation provides almost 8bn US$ worth of additional consumption. Southern Europe's regional welfare gains an additional 6.6bn US$, while the adaptation process in the Central Europe North region results in further 5.2bn US$ spent by consumers. The welfare gains in Northern Europe and Central Europe South fall into the lower end of the absolute welfare change resulting from the adaptation process. Northern Europe's additional, adaptation-induced welfare is estimated at 1.6bn US$ and its relatively low value (in spite of high agricultural productivity improvement) stems from small size of this economy. In contrast, a large region, Central Europe South, gains only 1.5bn US$ of adaptation-induced welfare because of relatively mild climate impacts in this region (**Table 2**).

The second series in **Figure 7** (blue, diagonally-filled bars) depicts the value of adaptation-induced welfare per consumer in each of the EU regions. Hence this measure accounts for the differences in the population sizes of the EU economies. United Kingdom and Ireland gains the most from the adaptation process at over 120 US$ per capita. The Northern Europe region's welfare gain is approximately half of the highest gain and it is estimated at 60 US$ per each consumer in the region, closely followed by Southern Europe where each consumer gains about 50 US$ worth of additional consumption from the market adaptation process. The adaptation process in the Central Europe North region brings additional 35 US$ for each consumer, while the welfare gain in Central Europe South region is 13 US$ approximately.

5. Detailed EU analysis by impact category

This section presents an overview of how the market adaptation mechanisms affect the economic performance of the EU regions. The analysis is presented for three levels of market adaptation: normal, semi-rigid (with mobile labour but rigid trade), and rigid (sluggish labour and rigid trade); the details of the implementation of the different degrees of adaptation were discussed in section 2.2.

The main indicators used for describing the socio-economic effects of climate impacts are GDP and Equivalent Variation (EV). The EV represents change in real consumption (above subsistence level) and is interpreted as a measure of welfare change experienced by people in the respective regions. The two indices not necessarily correlate and, as will be further illustrated, can indeed move in different directions.

5.1. Agriculture

The climate impacts on agricultural crops production, as presented in **Table 2**, are most severe in Southern Europe, whose crops production productivity is reduced by 24%. Central Europe South and Central Europe North experience a relatively mild reduction in the productivity by -4% and -2%, while UK and Ireland are simulated to gain 6% in terms of crops productivity. The largest beneficent of the A1B scenario is crops production in Northern Europe with 24% increase in the productivity.

The overall magnitude of changes in GDP and EV (**Figure 8** and **Table 5**) is broadly reflecting the size of the simulated productivity shocks to Agricultural Crops. The largest gain is noticed in Northern Europe, while the GDP and EV declined most in Southern Europe whose crops productivity reduces by 24%. The exception is United Kingdom and Ireland which, although subjected to a 6% crops' productivity improvement, records small reduction in GDP and EV terms.

Figure 8: Change in GDP (left) and Welfare (EV, right) from climate impacts for Agriculture for the EU regions under 3 market adaptation scenarios, %

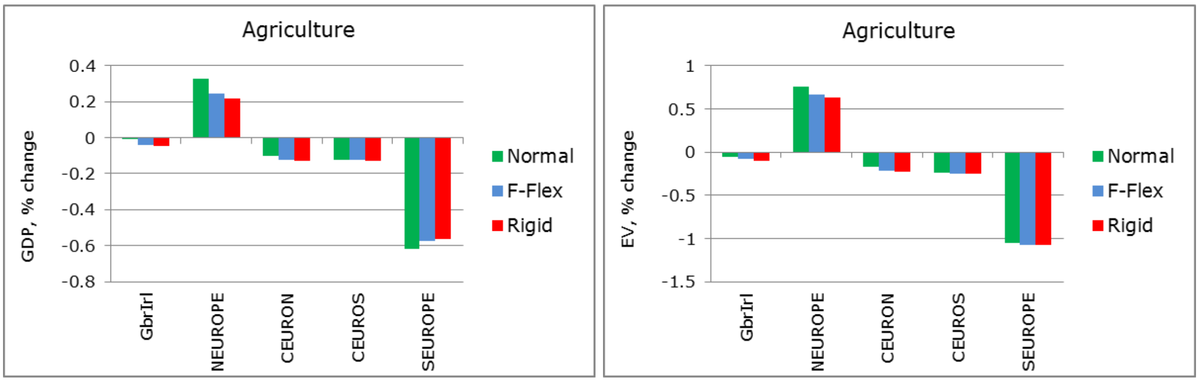


Table 5: Change in GDP and EV from climate impacts for Agriculture for the EU regions under 3 market adaptation scenarios, %

Measure	Adaptation level	GbrIrl	NEUROPE	CEURON	CEUROS	SEUROPE
GDP	Normal	-0.003	0.326	-0.101	-0.121	-0.615
	Semi-Flex	-0.040	0.247	-0.124	-0.123	-0.575
	Rigid	-0.048	0.219	-0.128	-0.127	-0.564
EV	Normal	-0.055	0.759	-0.174	-0.235	-1.048
	Semi-Flex	-0.083	0.664	-0.214	-0.249	-1.070
	Rigid	-0.100	0.629	-0.226	-0.252	-1.074

For most regions the introduction of market rigidities or, in other words, lower adaptive capacity of the markets, reduces the benefits from positive climate impacts (Northern Europe), or pushes further down reductions in GDP and EV from negative climate shocks (Central Europe North and Central Europe South). Sothern Europe's GDP improves with increase in the rigidity, however the welfare declines further.

The next sections provide explanation and discussion of these results for selected representative cases.

United Kingdom and Ireland

As noticed in the previous section United Kingdom and Ireland region records GDP and EV reductions in spite of the improvement of 6% in their productivity of crops production. This phenomenon is a combination of two effects. Firstly, the region produces only about 45% of crops it consumes, the remaining 55% being imported, which makes the region's market more dependent on import prices of crops than its own domestic production. Secondly, regions providing 55% of the imported crops products experience significant reductions in their crops' productivity, which affects their production prices and, via exports, translates into higher prices in United Kingdom and Ireland.

The first three columns of **Table 6** show the United Kingdom and Ireland's value of imports of crops from other regions, shares of imports from each region in total imports of crops, and change in price of imports originating in other regions due to region-specific climate impacts.[11]

[11] The change in price of imports also include effects of other general equilibrium effects such as demand and supply, however the climate shock impact dominates the price effect.

Table 6: Changes in volumes and prices of agricultural crops imported to United Kingdom and Ireland.

	Imports, bn US$	Import shares, %	Change in price of imports, %	Change in imports by source, %	
				Normal	Semi-rigid
China	0.151	1.3	-9	99	22
Japan	0.002	0.0	15	-32	-11
Korea	0.001	0.0	10	-16	-6
Indonesia	0.050	0.4	17	-37	-14
India	0.291	2.4	24	-52	-20
Australasia	0.175	1.5	7	-5	-2
South Asia	0.098	0.8	23	-50	-19
Rest of South-East Asia	0.206	1.7	24	-51	-20
Canada	0.239	2.0	-1	36	9
USA	0.479	4.0	12	-22	-7
Mexico	0.034	0.3	20	-45	-17
Brazil	0.608	5.0	2	19	5
Central America and Caribbean	0.501	4.2	9	-13	-4
Rest of South America	0.652	5.4	3	12	3
Middle East and North Africa	0.671	5.6	12	-23	-8
Sub-Saharian Africa	0.923	7.7	8	-9	-3
South Africa	0.478	4.0	13	-26	-9
Northern Europe	0.109	0.9	-13	150	31
UK & Ireland					
Central Europe North	2.746	22.8	5	4	1
Central Europe South	1.115	9.2	7	-4	-2
Southern Europe	2.460	20.4	22	-49	-19
Rest of Europe	0.026	0.2	16	-34	-12
Russia	0.007	0.1	-4	62	15
Rest of former USSR	0.041	0.3	-2	42	11

Most of the agricultural crops United Kingdom and Ireland imports from Central Europe North (23%), Southern Europe (20%), from Middle East, North Africa, Sub-Saharan Africa and South Africa (about 17% in total), and also from the USA (4%). All of these regions substantially increase their crops' supply price (see the third column in **Table 6**), which have significant impact on domestic prices and eventually is the reason for decline in GDP and EV in United Kingdom and Ireland in spite of its own improvement in productivity of crops production.

Adaptation via trade

Firms and all economic agents follow their cost minimising or utility maximising principles and react to change in prices: if a provider of particular good or service increases its supply prices the firms, when possible, aim to shift their purchases away from the more costly goods towards providers who offer a relatively lower price. The degree of this ability to shift trade pattern to substitute between various sources and products reflects the trade-related component of the market adaptation mechanism.

The two right-hand-side columns of **Table 6** show how the United Kingdom and Ireland's crops import pattern changes in response to its trade partner's changes in prices of crops products under two different degrees of market adaptation. Under 'normal', or full, adaptation the import flows which became most expensive are reduced the most: imports from Southern Europe carry a price rise by 22% and, in effect, their quantity reduces by almost a half (49%). Also imports from Middle East and North Africa and South Africa are being reduced by about a quarter (23% and 26%, respectively) following their price increase by 12% and 13%. On the other hand, some regions reduce their supply price of crops thanks to a positive, cost reducing productivity change. For example, Northern Europe supply crops products at 13% lower price so United Kingdom and Ireland increase the imports by 150% - a very large increase in percentage terms, although the relative value of the imports is low as it constitute less than 1% of the total crops imports. It is also important to remember that the change in import price taken into the firms' cost minimising decisions, is relative to an average import price that a region faces. If most of the trade partners increase their supply price then, relatively, a small increase can be lower than the average price and trigger an increase in import volumes. For the United Kingdom and Ireland this average price increase is about 6% so, for example, when price of imports from Central Europe North rises by 5% it still induces an increase in import volumes by about 4%.

The decrease in adaptive capacity related to trade reduces a region's ability to modify its trade pattern as a response to the price changes triggered by the climate shock. The changes in volumes imported under the rigid trade ("Semi-rigid" in **Table 6**) show significantly smaller changes in import volumes. For example the imports from the largest supplier of crops, Southern Europe, changes from 49% reduction to 19% reduction. The trade rigidity also limits the possibilities of additional imports as a response to the imports' price reduction: the previously discussed 150% increase in imports from Northern Europe is reduced to 31%.

The further move from 'semi-rigid' adaptation level to fully rigid markets by the introduction of reduced mobility of labour does not significantly alter the import patterns although it affects the GDP and EV impacts, the subject of the next section.

Adaptation via factor mobility and substitution

Limiting mobility of labour to move between sectors and reducing technical capacity for substitutions between labour and capital creates additional 0.008% reduction in GDP and 0.017% reduction in EV. These affects are relatively small although they are worth explanation to observe the underlying adaptation mechanisms.

Table 7 demonstrates selected sectoral information in United Kingdom and Ireland relevant to linking reduction in labour mobility with lowering of GDP and welfare. The employment change in the crops sector in the adaptive market with mobile labour increases by 4.8%, while limiting the labour mobility almost eliminates entirely this increase to 0.1%. Two main subsequent effects are reduction in the sectoral output and increase in the sectoral wage. Reduction in labour mobility clearly reduces crops' output from 11.7% to 7.1%, because the production in the sector becomes limited by the fixed endowment. Subsequently, immobility of labour does not allow for the wages to be equalised between sectors and wage in the crops sector increase by almost 12% compared to the increase of about 5% with the labour mobility allowed.

Table 7: Changes in output, wage, employment and wage bill for sectors in United Kingdom and Ireland with and without reduced mobility of labour.

	Output change, %		Wage change, %		Employement change, %		Total wage bill, bn US$ (change in wge bill, %)	
	Semi-rigid	Rigid	Semi-rigid	Rigid	Semi-rigid	Rigid	Semi-rigid	Rigid
Agriculture	0.3	-0.1	0.4	0.7	0.4	0.0	9 (0.76)	9 (0.7)
Crops	11.4	7.1	4.8	11.8	4.8	0.1	5.5 (9.82)	5.6 (11.92)
Forestry	0.2	0.0	0.1	0.3	0.2	0.0	0.5 (0.32)	0.5 (0.26)
Coal Mining	0.0	0.0	0.0	0.0	0.0	0.0	0.2 (-0.01)	0.2 (-0.05)
Crude Oil Extraction	-0.1	0.0	-0.1	-0.2	-0.1	0.0	1.2 (-0.23)	1.2 (-0.16)
Natural Gas	0.0	0.0	-0.1	-0.1	0.0	0.0	2.8 (-0.11)	2.8 (-0.09)
Refined Oil	0.0	0.0	-0.1	-0.1	0.0	0.0	2.2 (-0.09)	2.2 (-0.14)
Electricity	0.0	0.0	0.0	0.0	0.0	0.0	11.5 (0.02)	11.5 (-0.01)
Metals	0.0	0.0	0.0	0.0	0.0	0.0	32.6 (0.02)	32.6 (0.04)
Chemicals	0.0	0.0	0.0	0.1	0.0	0.0	37.9 (0.05)	37.9 (0.05)
Energy Intensives	0.0	0.0	0.0	-0.1	0.0	0.0	38.4 (-0.04)	38.4 (-0.06)
Electronic equipment	-0.1	0.0	-0.1	-0.1	-0.1	0.0	9.3 (-0.2)	9.3 (-0.12)
Transport Equipment	-0.1	0.0	-0.1	-0.2	-0.1	0.0	32.9 (-0.19)	32.9 (-0.16)
Other Equipment	0.0	0.0	0.0	0.0	0.0	0.0	60.4 (-0.06)	60.4 (-0.05)
Consumer Goods	0.3	0.0	0.3	0.6	0.3	0.0	58.8 (0.56)	58.8 (0.57)
Construction	0.0	0.0	0.0	-0.1	0.0	0.0	83.1 (-0.03)	83 (-0.06)
Transport	0.0	0.0	-0.1	-0.2	-0.1	0.0	58.2 (-0.12)	58.2 (-0.18)
Market Services	0.0	0.0	-0.1	-0.1	0.0	0.0	508.1 (-0.1)	507.9 (-0.15)
Non-market Services	0.0	0.0	0.0	-0.1	0.0	0.0	441.4 (-0.05)	441 (-0.13)
Total							*1393.8*	*1393.3*

The last column of **Table 7** provides the product of the changes in sectoral output, wage and employment. It shows the absolute value of the wage bill in each sector for the two market adaptation levels, and it also shows the percentage change (in brackets) in the wage bill from the full adaptation scenario. Although the changes do not appear large, they are dominated by the shocked sector (crops) and the sectors which have most trade interaction with the crops sector (e.g. agriculture and forest. The totals of the sectoral wage bills presented at the bottom of the table show that the wage bill in United Kingdom and Ireland is 0.5 bn US$ higher under the rigid market settings (immobile labour) than if the labour remains mobile across sectors. The 0.5 bn US$ represents about 0.02% reduction in households incomes, which corresponds to the 0.02% welfare (EV) reduction as presented in **Table 5**.

Northern Europe

Agricultural crop production in Northern Europe is the largest beneficiary of climate change in Europe. Its productivity of crop production is simulated to improve by 24% under the A1B scenario, which provide additional 0.33% GDP and 0.76% of welfare (EV) as shown in **Table 5** and **Figure 8**. The mechanisms which link different adaptation levels with change in GDP and EV is the same as illustrated above for the United Kingdom and Ireland, although benefits from the much larger positive domestic productivity increase outweighs the losses from higher import prices.

An important factor which allows the further leverage of improved productivity benefits is that the Northern Europe region consumes about 70% of the agricultural crops products it produces, compared to 45% for the United Kingdom and Ireland discussed before. The weight of this share is realised with the price of domestically produced crops dropping by 15%, while the average price of imports increasing by about 8% which, together, determine the domestic market price of crops products about 9% lower under the full adaptation scenario. Introduction of the rigidity in trade adaptation reduces the region's ability to trade away from high prices and affects both GDP and welfare.

The next two subsections look in more detail how flexibility in altering pattern of imports in response to varying import prices from different regions, and the degree to which mobility of labour can smooth out sectoral differentials affect the regional GDP and welfare.

Adaptation via trade

The imports of crops products by Northern Europe are mainly from Central Europe North, (41%), Southern Europe (19%), the USA (4.4%), and South America (about 10%), as illustrated in **Table 8**. All of these regions face decline in their crops productivity which translates into higher output prices. The output prices rise range from high (21% in Southern Europe), through medium (12% in the USA), to mild (4%-5% in South America).

Table 8: Changes in volumes and prices of agricultural crops imported to Northern Europe

	Imports, bn US$	Import shares, %	Change in price of imports, %	Change in imports by source, %	
				Normal	Semi-rigid
China	0.038	0.8	-9	51	17
Japan	0.008	0.2	17	-52	-17
Korea	0.001	0.0	11	-40	-11
Indonesia	0.018	0.4	18	-54	-18
India	0.040	0.8	25	-66	-25
Australasia	0.008	0.2	8	-31	-8
South Asia	0.055	1.1	25	-66	-25
Rest of South-East Asia	0.053	1.1	24	-64	-24
Canada	0.029	0.6	-1	2	4
USA	0.211	4.4	12	-42	-12
Mexico	0.008	0.2	21	-60	-21
Brazil	0.256	5.3	2	-12	-1
Central America and Caribbean	0.175	3.7	10	-36	-10
Rest of South America	0.194	4.1	4	-17	-3
Middle East and North Africa	0.145	3.0	13	-44	-13
Sub-Saharian Africa	0.212	4.4	9	-34	-9
South Africa	0.024	0.5	14	-47	-15
Northern Europe					
UK & Ireland	0.067	1.4	-1	4	4
Central Europe North	1.980	41.4	5	-22	-4
Central Europe South	0.224	4.7	7	-28	-7
Southern Europe	0.890	18.6	21	-61	-22
Rest of Europe	0.024	0.5	16	-51	-16
Russia	0.061	1.3	-4	21	10
Rest of former USSR	0.062	1.3	-2	7	5

The two right-hand-side columns of **Table 8** show how the crops' import volumes react to the change in import prices within a fully adaptive market and within a market with rigid trade (semi-rigid).

With full adaptation the import volumes from the main EU trade partners are reduced in reaction to the price increase: by 22% from Central Europe North, by 61% from Southern Europe, and by 28% from Central Europe South. Also limited are imports from the USA (by

42%) and South America (about 15%). Northern Europe increases the imports only from regions which can reduce the import price, although these regions constitute a very small share on the total crops imports by Northern Europe with the largest being Russia with 1.3% of the total imports and 7% increase in the imports volume.

The effect of limited adaptation can be observed by comparing the import response of the adaptive market with import response of the semi-rigid market in **Table 8**. The ability of the region to trade away from the high-price imports is clearly reduced by a factor of about 3 in case of Southern Europe, Central Europe South, and the USA.

In addition to the changing international trade pattern in crops products it is important to highlight the overall change in imports of crops in the region and the implications for the domestic production.

Table 9 shows that full trade adaptation allows for a substitution of the reduction in total imports of crops in Northern Europe by 32% with an increase in the domestic production by 44%. This effect of substitution between domestically produced and imported goods is greatly reduced with the increase in trade rigidity, where the overall imports decline by only 9% and the domestic production increases by 38%. In effect, the weight that the imported, high price has in the domestic market price faced by consumers increases leading to lower consumption with direct effect on GDP and welfare, and also resulting in an overall higher volume of imports which directly impacts the GDP measure.

Table 9: Change in total crops imports and production in Northern Europe, %

	Imports %	Domestic production, %
Semi-rigid	-9	38
Normal	-32	44

Adaptation via factor mobility and substitution

Reduction in adaptation capacity via limiting of the labour mobility and of substitution possibilities between labour and capital, bring an additional reduction to GDP of 0.03% and reduction to welfare (EV) by 0.04%, as presented in **Table 5** and **Figure 8**.

These reductions are due to inefficient allocation of labour between sectors which further generates lower aggregated household income and higher imports. The effects are further explored below with support of data from **Table 10**.

Table 10: Changes in output, wage, employment and wage bill for sectors in Northern Europe with and without reduced mobility of labour.

	Output change, %		Wage change, %		Employement change, %		Total wage bill, bn US$ (change in wge bill, %)	
	Semi-rigid	Rigid	Semi-rigid	Rigid	Semi-rigid	Rigid	Semi-rigid	Rigid
Agriculture	1.9	0.5	1.9	3.1	1.4	0.0	3.4 (3.4)	3.3 (3.08)
Crops	37.8	26.6	10.4	20.6	10.0	0.2	5 (21.38)	5 (20.79)
Forestry	0.3	0.0	0.7	0.5	0.2	0.0	1.4 (0.92)	1.4 (0.53)
Coal Mining	0.0	0.0	0.4	0.3	0.0	0.0	0 (0.4)	0 (0.28)
Crude Oil Extraction	-0.4	0.0	0.0	-0.1	-0.4	0.0	0.1 (-0.41)	0.1 (-0.14)
Natural Gas	-0.5	0.0	0.0	-0.1	-0.5	0.0	0.2 (-0.47)	0.2 (-0.06)
Refined Oil	0.1	0.1	0.5	0.4	0.0	0.0	0.4 (0.46)	0.4 (0.43)
Electricity	0.1	0.1	0.6	0.8	0.1	0.0	5 (0.66)	5 (0.75)
Metals	-0.4	0.0	0.1	-0.1	-0.4	0.0	13.5 (-0.33)	13.5 (-0.1)
Chemicals	-0.3	0.0	0.2	-0.1	-0.3	0.0	11 (-0.19)	11 (-0.06)
Energy Intensives	-0.3	0.0	0.1	-0.2	-0.3	0.0	16 (-0.19)	16 (-0.18)
Electronic equipment	-0.7	-0.1	-0.2	-0.5	-0.7	0.0	4 (-0.84)	4 (-0.5)
Transport Equipment	-0.4	0.0	0.1	-0.2	-0.4	0.0	7.6 (-0.32)	7.6 (-0.2)
Other Equipment	-0.4	0.0	0.0	-0.1	-0.4	0.0	26.8 (-0.4)	26.9 (-0.15)
Consumer Goods	1.0	0.2	1.2	1.7	0.8	0.0	20.1 (2.01)	20 (1.67)
Construction	0.0	0.0	0.4	0.1	-0.1	0.0	40.1 (0.37)	40 (0.11)
Transport	-0.2	0.0	0.3	-0.1	-0.2	0.0	20.3 (0.06)	20.3 (-0.08)
Market Services	0.0	0.0	0.4	0.3	-0.1	0.0	106.4 (0.34)	106.4 (0.31)
Non-market Services	0.0	0.0	0.5	0.4	0.0	0.0	162.4 (0.43)	162.2 (0.35)
Total (bn US$)							*443.6*	*443.3*

As discussed in the previous section, the increase in domestic production of crops products reduces to about 38% with the rigid trade assumption. This 38% increase is underpinned by a 10% increase in employment in the crops sector and about 10% higher wage. With immobile labour, however, the crops sector's production is limited by the fixed labour endowment, and the output increase is reduced further to about 27% and accompanied by 20% wage increase. The last columns of **Table 10** show the absolute value of the wage bill by sector and the percentage change from full adaptation scenario; the total wage bill for the Northern Europe, which constitutes most of the households' income, declines by about 0.3 bn US$, or 0.05% of the household income.

Furthermore, sectoral output limited with labour immobility forces higher imports (with downwards GDP pressure) and, as discussed in previous section, leads to increase in the domestic market price of crops products

Southern Europe

The Southern Europe region faces a very large decline in productivity of agricultural crops of 20% in the A1B scenario, see **Table 2** for details. This large shock results in 0.62% reduction in GDP and 1.05% reduction in welfare (EV) in the full adaptation scenario. High impact of domestically produced crops is realised via the share of 80% of domestically produced crops being consumed in the region.

Table 11 shows the main macroeconomic impacts for Southern Europe for the three adaptation levels scenarios of the agricultural crops impacts.

Table 11: Change in output and import volumes and prices for agricultural crops in Southern Europe from A1B scenario under three adaptation levels, %.

	Output, %	Price of output, %	Import, %	Price of imports, %
Normal	-21.1	23.5	26.9	5.8
Semi-rigid	-18.1	27.0	3.5	6.1
Rigid	-19.7	30.4	4.6	6.2

Under the full adaptation scenario the output of the crops sector declines by 21% and the price of domestically produced crops increases by 24%. To substitute for lower domestic production, the imports of crops increase by 27% at a 6% higher price.

Introduction of the trade rigidities drastically reduces the Southern Europe's ability to substitute relatively cheaper imports for domestic production, which effects in a smaller imports increase, from 27% to 3.5%. Correspondingly, the reduction in domestic crops production eases slightly from -21% to -18%.

The overall imports in Southern Europe change from 0.06% reduction in the full adaptation scenario to 0.27% reduction due to introduction of market rigidities. This reduction in decline of imports has two important implications: it improves GDP[12] but reduces welfare. The welfare reduction works through increase in domestic consumer prices by limiting share of imported goods which are relatively less expensive compared to domestically produced goods.

Adaptation via trade

As signalled above the trade-related adaptation mechanism in the Southern Europe allows to substitute the now-expensive domestic crops production with relatively cheaper imports. **Table 12** illustrates substantial increase in import volumes from regions which offer now competitive price for crops products. The rise is up to 230% from Northern Europe although such multi-fold increase is allowed by a very small initial value of imports (0.8% share of the total imports). A more substantial imports are provided by Central Europe North and Central Europe South (about 23% together), and the imports volumes increase by 31% and 21% respectively.

[12] Imports are subtracted from GDP in the expenditure identity: GDP = C+G+I+X-M

Table 12: Changes in volumes and prices of agricultural crops imported to Southern Europe

	Imports, bn US$	Import shares, %	Change in price of imports, %	Change in imports by source, %	
				Normal	Semi-rigid
China	0.214	1.1	-8	161	29
Japan	0.007	0.0	15	-17	-9
Korea	0.006	0.0	11	2	-3
Indonesia	0.070	0.4	18	-26	-11
India	0.293	1.5	25	-45	-19
Australasia	0.129	0.7	7	18	2
South Asia	0.149	0.8	25	-45	-19
Rest of South-East Asia	0.469	2.4	24	-43	-18
Canada	0.390	2.0	-1	76	15
USA	1.954	10.0	12	-4	-4
Mexico	0.115	0.6	20	-34	-14
Brazil	2.971	15.2	2	51	11
Central America and Caribbean	0.458	2.3	10	6	-1
Rest of South America	1.963	10.0	4	42	8
Middle East and North Africa	1.550	7.9	12	-4	-4
Sub-Saharian Africa	0.702	3.6	9	11	0
South Africa	0.133	0.7	14	-13	-7
Northern Europe	0.152	0.8	-13	233	40
UK & Ireland	0.462	2.4	-1	78	16
Central Europe North	2.217	11.3	5	31	5
Central Europe South	4.243	21.7	7	21	3
Southern Europe					
Rest of Europe	0.225	1.2	15	-17	-8
Russia	0.309	1.6	-4	110	21
Rest of former USSR	0.387	2.0	-2	83	17

Under rigid market conditions, i.e. without the market adaptation process, the ability of Southern Europe to shift its import pattern and to substitute between domestic production and imports is greatly reduced. Increase in imports of crops products from Central Europe North, Central Europe South and Northern Europe is reduced by a factor of about 7. Increase in imports from South America (including Brazil) which provide about 25% of the total imports, is reduced from about 47% to 10%. This limited ability of the Southern Europe region to adapt its trade pattern to the new economic situation results in reduction in increase in imports which has a positive impact on GDP. On the other hand, the regional market is deprived of ability to increase sourcing products at international market at competitive prices, which leads to higher prices faced by all the economic agents in the region and subsequent loss of welfare.

Adaptation via factor mobility and substitution

Reduction in adaptation capacity via limiting of the labour mobility and of substitution possibilities between labour and capital, bring increase of GDP by 0.011% and reduction to welfare (EV) by 0.004%, as presented in as presented in **Table 5** and **Figure 8**.

Table 13: Changes in output, wage, employment and wage bill for sectors in Southern Europe with- and without reduced mobility of labour.

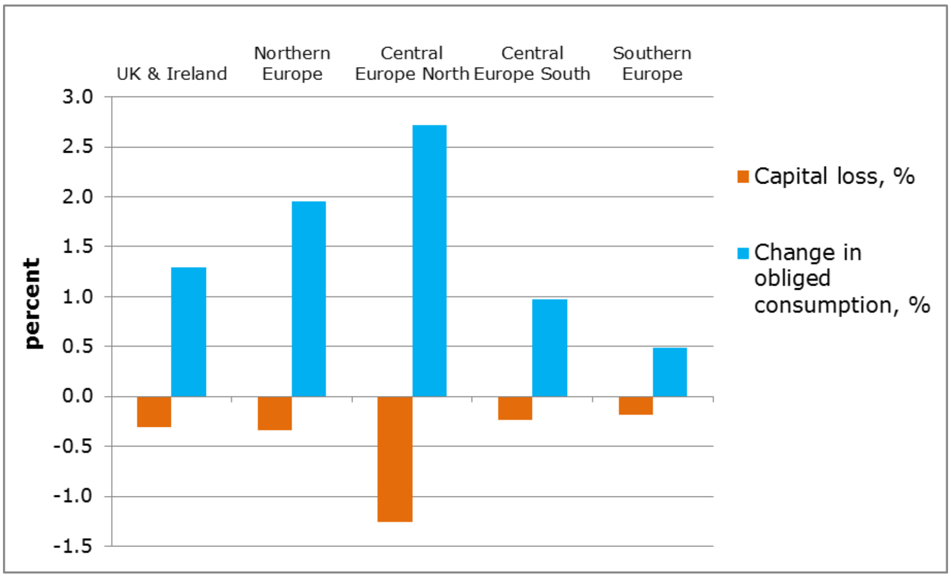
	Output change, %		Wage change, %		Employement change, %		Total wage bill, bn US$ (change in wge bill, %)	
	Semi-rigid	Rigid	Semi-rigid	Rigid	Semi-rigid	Rigid	Semi-rigid	Rigid
Agriculture	-2.0	-1.3	-1.7	-4.0	-1.0	0.0	11.7 (-2.7)	11.6 (-4.03)
Crops	-18.1	-19.7	1.5	5.0	2.2	0.1	44.5 (3.75)	45.1 (5.05)
Forestry	-0.1	0.0	-0.8	-0.7	-0.2	0.0	0.9 (-0.96)	0.9 (-0.67)
Coal Mining	0.1	0.0	-0.5	-0.4	0.1	0.0	0.6 (-0.43)	0.6 (-0.44)
Crude Oil Extraction	0.3	0.0	-0.4	-0.2	0.3	0.0	0.3 (-0.12)	0.3 (-0.22)
Natural Gas	0.4	0.0	-0.3	-0.2	0.4	0.0	0.4 (0.1)	0.4 (-0.17)
Refined Oil	-0.1	-0.1	-0.7	-0.8	0.0	0.0	1.8 (-0.66)	1.8 (-0.8)
Electricity	-0.1	-0.1	-0.7	-1.0	0.0	0.0	12.4 (-0.75)	12.4 (-1.02)
Metals	0.5	0.1	-0.2	0.3	0.5	0.0	50.1 (0.35)	50.1 (0.32)
Chemicals	0.4	0.1	-0.3	0.2	0.4	0.0	38.3 (0.15)	38.3 (0.17)
Energy Intensives	0.2	0.0	-0.5	-0.2	0.2	0.0	49 (-0.34)	49.1 (-0.18)
Electronic equipment	0.4	0.1	-0.3	0.1	0.4	0.0	8.8 (0.13)	8.8 (0.1)
Transport Equipment	0.3	0.0	-0.4	0.0	0.3	0.0	23.5 (-0.06)	23.5 (-0.04)
Other Equipment	0.4	0.0	-0.2	0.1	0.4	0.0	80.6 (0.17)	80.6 (0.14)
Consumer Goods	-1.3	-0.7	-1.5	-2.8	-0.8	0.0	91.3 (-2.32)	90.8 (-2.85)
Construction	0.0	0.0	-0.6	-0.4	0.0	0.0	120.5 (-0.63)	120.7 (-0.4)
Transport	0.0	0.0	-0.6	-0.5	0.0	0.0	25.6 (-0.61)	25.6 (-0.54)
Market Services	-0.2	-0.1	-0.8	-1.3	-0.2	0.0	373.1 (-0.99)	372.1 (-1.27)
Non-market Services	-0.1	0.0	-0.7	-1.0	-0.1	0.0	443.6 (-0.76)	442.7 (-0.97)
Total (bn US$)							*1377.1*	*1375.4*

As described in the previous sub-section, imposition of trade rigidity limits the region's ability to substitute imports for domestic production and leads to higher domestic production and lower imports (higher GDP) and higher domestic prices (lower welfare). Further introduction of rigidity into factor mobility leads to very high frictions in adjustments in employment for all the sectors, and the movement of labour from contracting sectors to expanding sectors is limited. In effect the shrinking sectors face excessive supply of labour and over-production, while the expanding sectors (mainly the agricultural crops production) face shortage of labour and lower output. These effects lead to further reduction in imports and increase in local prices which have negative impact on welfare.

5.2. Sea level Rise

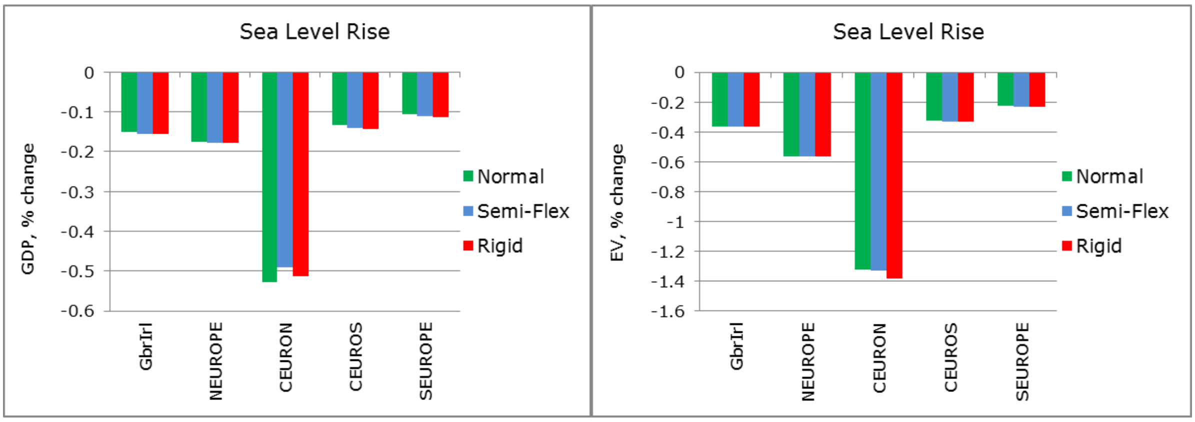
The SLR impact differs within the EU, with the largest share of capital loss (1.3%) and highest increase in subsistence expenditures related to migration (2.7%) estimated for the Central Europe North (**Table 2** and **Figure 9**). The increase in the subsistence budgets for Northern Europe and United Kingdom and Ireland are predicted at 2% and 1.3% respectively, while the capital loss in these regions could reach 0.35% and 0.3%, respectively. Central Europe South could face increase in the subsistence expenditure of 1% and capital loss of 0.2%. Finally, the Southern Europe's rise in the obliged consumption is about 0.5% with the capital loss estimated at 0.2%.

Figure 9: Capital loss and increase in expenditure due to SLR for the EU regions in A1B scenario.



An overall picture of effects of the SLR impacts on the EU regions' economy (**Figure 10** and **Table 14**) indicates that the change in GDP and welfare (EV) reflect the magnitudes of impacts across the EU regions. The Central Europe North records the largest loss (0.52% of GDP and 1.32% of EV), followed by Northern Europe (0.18% GDP and 0.56% EV), United Kingdom and Ireland (0.15% GDP and 0.36% EV), Central Europe South (0.14% of GDP and 0.33% of EV), and Southern Europe (0.11% of GDP and 0.23% of EV).

Figure 10: Change in GDP and EV from climate impacts for Sea Level Rise for the EU regions under 3 market adaptation scenarios, %



In general, market adaptation brings little benefit to the consequences of the SLR impacts. The GDP and welfare (EV) changes are at the tenth- and thousandth part of percent magnitude, for all the regions but Central Europe North where the GDP improves by 0.04% with increase in trade rigidity, but loosed further 0.02% with introduction of labour market rigidities.

In welfare terms introduction of rigidities reduces the consumption consistently for all the regions.

Table 14: Change in GDP and EV from climate impacts for Sea Level Rise for the EU regions under 3 market adaptation scenarios, %

Measure	Adaptation level	GbrIrl	NEUROPE	CEURON	CEUROS	SEUROPE
GDP	Normal	-0.150	-0.175	-0.528	-0.132	-0.106
	Semi-Flex	-0.154	-0.178	-0.490	-0.141	-0.112
	Rigid	-0.155	-0.179	-0.512	-0.143	-0.113
EV	Normal	-0.364	-0.563	-1.321	-0.327	-0.228
	Semi-Flex	-0.367	-0.565	-1.330	-0.332	-0.230
	Rigid	-0.367	-0.566	-1.379	-0.333	-0.231

In the next sections several representative examples of adaptation via trade and factors mobility and substitution are discussed in depth.

Central Europe North

Most of the economic impact in the Central Europe North region results from the significant reduction in private consumption. A decomposition of GDP change into contributions from two types of consumption (the subsistence and welfare-creating), exports and imports (**Table 15**) shows that, in the adaptive market, almost entire GDP loss (-0.53%) comes from the reduced consumption (-0.59%) with marginal addition from reduced exports (-0.04%), while reduction in imports (-0.11%) alleviate the negative GDP effect slightly. The welfare loss in the fully adaptive market is 1.32%.

Table 15: Decomposition of percentage GDP change and percentage change in welfare (EV) in the Central Europe North region.

Market assumption	GDP	=	Subsistence consumption	+	Welfare-creating consumption	+	Exports	—	Imports	Welfare
Rigid	-0.51		0.13		-0.74		-0.05		-0.15	-1.38
Semi-rigid	-0.49		0.13		-0.72		-0.05		-0.14	-1.33
Adaptive	-0.53		0.13		-0.72		-0.04		-0.11	-1.32

Adaptation via trade

Reduction of flexibility in shifting imports and exports preserves the existing trade pattern and does not allow for the region to substitute its imports towards more economically efficient arrangement. For the Central Europe North region the rigid trade implies reduction in imports (from -0.11% to -0.14%) which adds 0.03% to the GDP. On the other hand, however, the rigid trade results in slightly higher consumer prices which lead to reduction in welfare from -1.32% to -1.33% (**Table 15**).

Adaptation via factor mobility and substitution

Further elimination of adaptive capacity in the central Europe North via introduction of labour rigidity and reduction in technical substitution possibilities between capital and labour, leads to reduction in welfare to -1.38% and drop in GDP to -0.51%. As illustrated in **Table 15**, this reduction is due to further reduction in consumption in this region, and in spite of another reduction in imports by 0.01%.

The underlying reduction in consumption occurs due to inefficiencies in the labour market and the subsequent decrease in the household incomes. The first two columns in **Table 16** show the change in sectoral employment for the semi-rigid and rigid adaptation scenarios and it demonstrates how the changes in employment which were possible with adaptive labour market are hampered if the rigidity is introduced.

Table 16: Change in employment, wage and revenues for sectors in Central Europe North.

	Employement change, %		Total wage bill, bn US$ (change in wage bill, %)	
	Semi-rigid	Rigid	Semi-rigid	Rigid
Agriculture	-0.19	0.00	13.4 (-1.18)	12.3 (-9.36)
Crops	-0.16	0.00	18.9 (-1.13)	17.4 (-8.93)
Forestry	-0.17	-0.05	1.9 (-1.15)	1.6 (-13.1)
Coal Mining	-0.15	-0.04	4.2 (-1.11)	3.7 (-12.87)
Crude Oil Extraction	-0.48	-0.13	0.1 (-1.77)	0.1 (-20.11)
Natural Gas	-0.76	-0.11	2.2 (-2.32)	1.8 (-18.42)
Refined Oil	0.03	-0.06	1.7 (-0.75)	1.5 (-14.01)
Electricity	-0.08	-0.04	21.8 (-0.98)	19.2 (-12.82)
Metals	0.03	0.01	68.5 (-0.76)	63.6 (-7.79)
Chemicals	-0.05	0.00	65.9 (-0.92)	60.4 (-9.2)
Energy Intensives	-0.08	-0.02	51.1 (-0.97)	46.1 (-10.69)
Electronic equipment	-0.05	0.00	18.7 (-0.93)	17.2 (-8.79)
Transport Equipment	0.05	0.04	78.6 (-0.72)	75 (-5.33)
Other Equipment	0.08	0.03	153.8 (-0.66)	144.7 (-6.53)
Consumer Goods	-0.21	-0.02	76.4 (-1.23)	69.4 (-10.3)
Construction	0.27	0.01	120.5 (-0.29)	111.1 (-8.06)
Transport	-0.04	-0.01	61 (-0.91)	55.3 (-10.18)
Market Services	-0.12	-0.06	470.2 (-1.05)	407.7 (-14.21)
Non-market Services	0.07	0.04	542.5 (-0.67)	518.7 (-5.03)
Total (bn US$)			*1771.5*	*1626.9*

The two right-hand side columns of the **Table 16** show sectoral changes in the wage bill in absolute and percentage terms (in brackets). The regional total at the bottom informs that the total labour income is about 144bn US$ lower due to the rigid labour market when compared with the situation when the labour can more freely adjust to the changing economic situation.

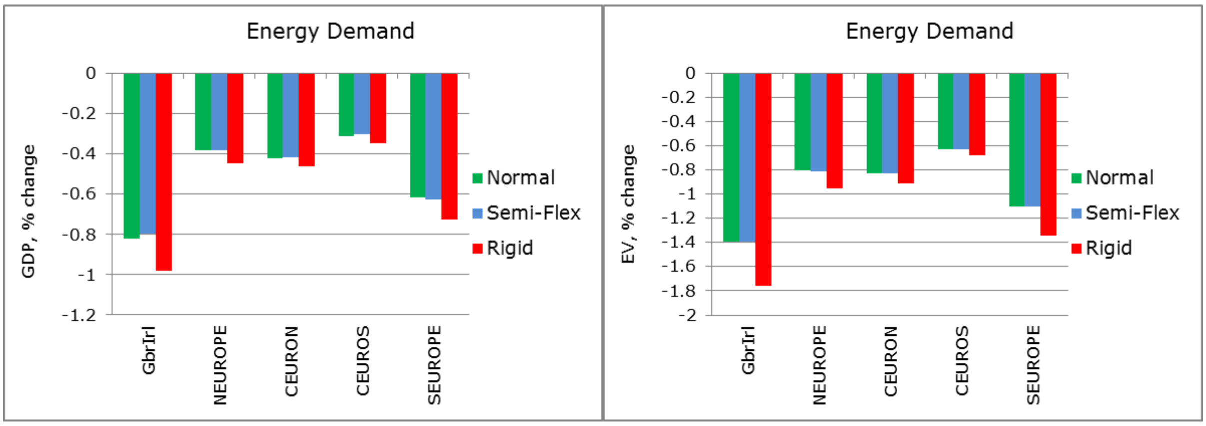
For other EU regions the benefits from market adaptation are very small. To explain this it is worth to recall how the physical impacts from SLR are represented in the macroeconomic model (see also section 2.3). The economic representation of SLR is incorporated via loss in capital uniform across all the sectors, and via increase in obliged consumption of households. Apart from Central Europe North, the capital loss is very small (**Table 2** and **Figure 9**) for other EU regions and, since all the sectors are subjected to the same capital loss there are no large inefficiencies which could be corrected with the market adaptation mechanisms. The second channel of SLR impact – increase in obliged consumption – affects directly the welfare (via reduction in welfare-creating consumption), and it remains the same irrespective of the degree of economic adaptation.

5.3. Energy Demand

The effect of the changes in energy demand on GDP depends mainly on the reduction in use of the energy fuels and increase in demand for electricity. Both types of changes have a negative impact on GDP because the energy fuels are relatively cheaper than electricity, so substituting electricity for energy fuels increases the cost for all affected sectors. Furthermore, as the use of energy by the service sector is in general far larger than the use by households, the same percentage increase for both users (e.g. **Table 2**) would imply a larger absolute increase for the service sector. Additional relative effects, discussed in more detail in the next section, also include changing in the relative competiveness of the countries and bilateral energy trade linkages between the regions.

The economic impacts from the changing demand for energy (**Figure 11** and **Table 17**) are largest in United Kingdom and Ireland, where they approach 1% loss in GDP and about 1.5% loss in welfare, whilst Southern Europe region follows with about 0.6% loss in GDP and 1.1% welfare reduction. The Northern Europe and Central Europe North experience similar reductions of 0.3%-0.4% in GDP and 0.8% in welfare. The least affected region is Central Europe South with 0.3% drop in GDP and 0.6% welfare reduction.

Figure 11: Change in GDP and EV from climate impacts for Energy Demand for the EU regions under 3 market adaptation scenarios, %



The results also clearly suggest that market adaptation via labour market is much more effective compared to adaptation via trade, which is almost insignificant in reducing negative effects of the changes in demand for energy. In fact, in some instances, the reduction in trade-related adaptive capacity effects in milder GDP reduction as observed in United Kingdom and Ireland, or in Central Europe South region. The welfare effects, however, consistently display reduction in real consumption with any increase in markets' rigidity.

Table 17: Change in GDP and EV from climate impacts for Energy Demand for the EU regions under 3 market adaptation scenarios, %

Measure	Adaptation level	GbrIrl	NEUROPE	CEURON	CEUROS	SEUROPE
GDP	Normal	-0.822	-0.381	-0.425	-0.314	-0.617
	Semi-Flex	-0.799	-0.384	-0.418	-0.302	-0.628
	Rigid	-0.982	-0.446	-0.461	-0.348	-0.726
EV	Normal	-1.395	-0.806	-0.829	-0.634	-1.101
	Semi-Flex	-1.397	-0.810	-0.827	-0.629	-1.107
	Rigid	-1.759	-0.955	-0.912	-0.683	-1.347

In the next sections several representative examples of adaptation are discussed in depth, with focus on adaptation via factors mobility and substitution.

United Kingdom and Ireland

The analysis of sources of reduction in GDP points to decline in consumption as the single main responsible component. **Table 18** presents decomposition of GDP change in United Kingdom and Ireland and it shows that, in the semi-rigid market, the 0.8% GDP decline comprises contributions from reduced consumption (0.84%) and lower exports (-0.06%), alleviated with smaller imports (-0.09%). With reduction in market adaptive capacity through introduction of sluggish labour, the GDP drops further to -0.99% which is driven, almost exclusively, by additional reduction in consumption to -1.05%. Also, the overall consumer prices (CPI) increase from 0.2% to 0.56%.

Table 18: Decomposition of percentage GDP change and percentage change in welfare (EV) in the United Kingdom and Ireland region.

Market assumption	GDP	=	Subsistence consumption	+	Welfare-creating consumption	+	Exports	—	Imports	Welfare	CPI
Rigid	-0.99		-0.01		-1.05		-0.05		-0.12	-1.76	0.56
Semi-rigid	-0.80		-0.01		-0.83		-0.06		-0.09	-1.40	0.20

The significant reduction in consumption in effect of reduction of cross-sectoral labour mobility results in inadequate employment in expanding sectors and over-employment in sectors facing lowering demand. For example, **Table 19** illustrates that increased demand for electricity stimulates employment by 18.6% in this sector. Under the sluggish labour assumption (labour not able to change the sector of employment), however, the Electricity sector can increase the employment by 0.7% only. Similarly, the Coal Mining sector which supplies fuels to the electricity generating sectors increases its employment by almost 13%, however, with sluggish labour it is able to attract only 0.26% more employees. These rigidities result in higher output prices for the Electricity and Coal Mining sectors, and much higher wages which, in spite of very limited increase in employment, drastically inflate the total wage bill for these sectors: the Electricity sector with mobile labour spends on its 18% larger employment additional 40% more on their wages, while with the rigid labour market the 0.73% larger employment consumes 105% more in wages. Although this effect is definitely beneficial for the employees at these two sectors, other sectors in the economy face opposite mechanics.

Table 19: Changes in sectoral employment, output prices and imports in United Kingdom and Ireland region.

	Employement change, %		Total wage bill, bn US$ (change in wage bill, %)	
	Semi-rigid	Rigid	Semi-rigid	Rigid
Agriculture	-0.37	-0.02	8.8 (-1.55)	8.7 (-2.69)
Crops	-0.57	-0.03	4.9 (-1.96)	4.8 (-3.63)
Forestry	-0.34	-0.03	0.4 (-1.49)	0.4 (-3.38)
Coal Mining	12.64	0.26	0.3 (25.68)	0.3 (28.52)
Crude Oil Extraction	0.34	0.01	1.2 (-0.15)	1.2 (-0.43)
Natural Gas	3.03	0.04	3 (5.25)	2.9 (3.24)
Refined Oil	-0.20	-0.03	2.2 (-1.22)	2.2 (-3.86)
Electricity	18.61	0.73	16 (39.28)	23.6 (105.37)
Metals	0.05	-0.04	32.4 (-0.73)	31.2 (-4.33)
Chemicals	-0.07	-0.02	37.5 (-0.97)	36.6 (-3.29)
Energy Intensives	-0.14	-0.03	38 (-1.1)	37.1 (-3.38)
Electronic equipment	-0.03	-0.01	9.2 (-0.89)	9.1 (-1.67)
Transport Equipment	-0.13	-0.01	32.6 (-1.08)	32.3 (-1.96)
Other Equipment	0.10	-0.01	60.1 (-0.63)	59.4 (-1.65)
Consumer Goods	-0.47	-0.02	57.4 (-1.75)	56.6 (-3.12)
Construction	0.17	0.01	82.7 (-0.5)	82.8 (-0.34)
Transport	-0.22	-0.02	57.5 (-1.26)	56.8 (-2.45)
Market Services	-0.38	-0.02	500.7 (-1.57)	495.8 (-2.52)
Non-market Services	0.05	0.00	438.4 (-0.73)	439.2 (-0.54)
Total (bn US$)			*1383.1*	*1381.0*

The sectors which face falling demands are able to scale down their operations to maintain competitiveness only if the redundant labour can find employment in other (expanding) sectors. For these sectors to maintain the current employment levels is necessary to lower the wages.

The net effect of changing employment and wages across all the sectors in United Kingdom and Ireland is provided in the *Total* row in **Table 19**. With reduced labour mobility the regional wage bill add up to 2bn US$ less when compared to the total with full labour mobility, which constitutes about 0.15% of the total household income from labour. With additional increase in consumer prices the welfare declines by 1.76%.

Central Europe South

The GDP and welfare effects in Central Europe South are smaller compared to the previously discussed United Kingdom and Ireland case. The two regions, however, are in line with the dominant effect of reduced consumption on the GDP and EV. In Central Europe South region the effect of lower consumption (by 0.34%, semi-rigid market) makes up the bulk of 0.31 reduction in GDP. The effect of introducing rigidity to the labour market pushes the GDP and welfare further down (to -0.36% and -0.68%), although the change is smaller than in case of United Kingdom and Ireland.

Table 20: Decomposition of percentage GDP change and percentage change in welfare (EV) in the Central Europe South region.

Market assumption	GDP	=	Subsistence consumption	+	Welfare-creating consumption	+	Exports	—	Imports	Welfare	CPI
Rigid	-0.36		-0.01		-0.37		-0.05		-0.08	-0.68	0.08
Semi-rigid	-0.31		-0.01		-0.34		-0.03		-0.07	-0.63	0.11

The reason for smaller negative effects are different changes in energy anticipated for the two regions (**Table 2**), particularly change in demand for electricity in the business sector, which dominates the electricity consumption. While in the Central Europe South the business sector demand for electricity is to increase by 47%, the corresponding figure for United Kingdom and Ireland is almost 139%.

Table 21: Changes in sectoral employment, output prices and imports in Central Europe South region.

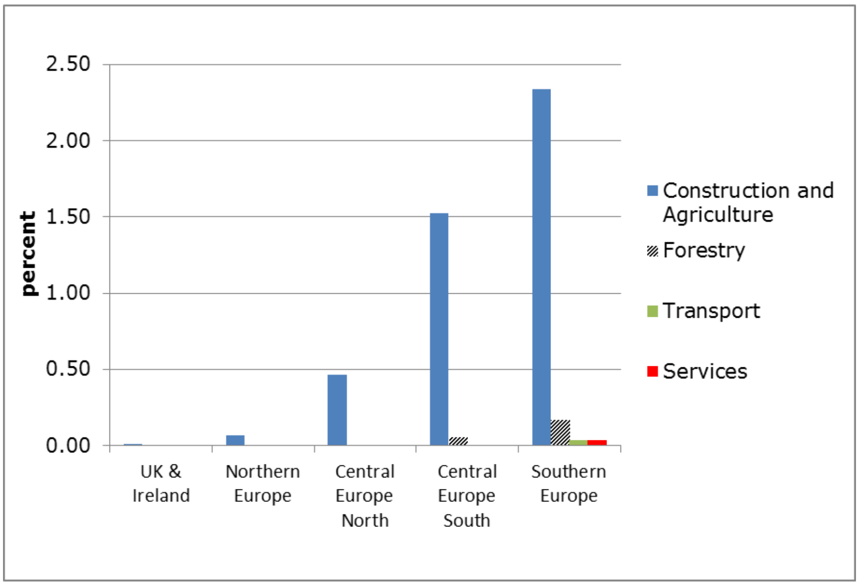
	Employement change, %		Total wage bill, bn US$ (change in wage bill, %)	
	Semi-rigid	Rigid	Semi-rigid	Rigid
Agriculture	-0.37	-0.01	7.8 (-0.93)	7.8 (-1.06)
Crops	-0.38	-0.01	25 (-0.95)	25 (-1.01)
Forestry	-0.33	-0.01	1.9 (-0.84)	1.9 (-0.89)
Coal Mining	4.15	0.05	0.3 (8.21)	0.3 (4.92)
Crude Oil Extraction	-0.13	-0.01	0.4 (-0.45)	0.4 (-0.84)
Natural Gas	0.44	-0.01	1.1 (0.68)	1.1 (-1.07)
Refined Oil	-0.37	-0.02	1.1 (-0.92)	1.1 (-2.22)
Electricity	7.96	0.23	18.2 (16.25)	19.7 (25.77)
Metals	0.05	0.00	39.8 (-0.09)	39.6 (-0.59)
Chemicals	-0.14	-0.01	32.6 (-0.48)	32.5 (-0.83)
Energy Intensives	-0.13	-0.01	34.5 (-0.44)	34.4 (-0.8)
Electronic equipment	-0.25	0.00	9.3 (-0.7)	9.3 (-0.57)
Transport Equipment	-0.35	-0.01	27.8 (-0.88)	27.8 (-0.96)
Other Equipment	-0.11	0.00	58.4 (-0.42)	58.4 (-0.42)
Consumer Goods	-0.41	-0.01	56.6 (-1.01)	56.6 (-1.15)
Construction	0.05	0.00	95.6 (-0.1)	95.7 (-0.07)
Transport	-0.21	-0.01	36.7 (-0.62)	36.6 (-0.98)
Market Services	-0.19	-0.01	284.7 (-0.58)	283.6 (-0.99)
Non-market Services	0.01	0.00	374.4 (-0.18)	374.4 (-0.18)
Total (bn US$)			*1106.4*	*1106.0*

Since the market adaptation to changes in energy demand occurs almost entirely through the factors market flexibility and movement of labour between affected sectors, the lower magnitudes of shifts in energy demand induce less of the negative economic effects on one side, but on the other side lower impacts also imply less adaptation. **Table 21** produces the respective changes in the demand for labour and change in wage bills for all sectors and the totals. Comparing with the sectoral effects for the changes in employment in Central Europe South they are less than half of those in United Kingdom and Ireland (**Table 19**). With the rigid labour market the regional wage bill is reduced by 0.4 bn US$, which is about 0.04% of the household income from labour.

5.4. Labour productivity

The reduction in labour productivity in the EU regions is relatively small when compared to reductions in regions around the tropical belt (**Table 2**). The Southern regions of the EU are relatively more affected (**Table 22** and **Figure 12**).

Figure 12: Reduction in labour productivity in the EU regions by sector, %



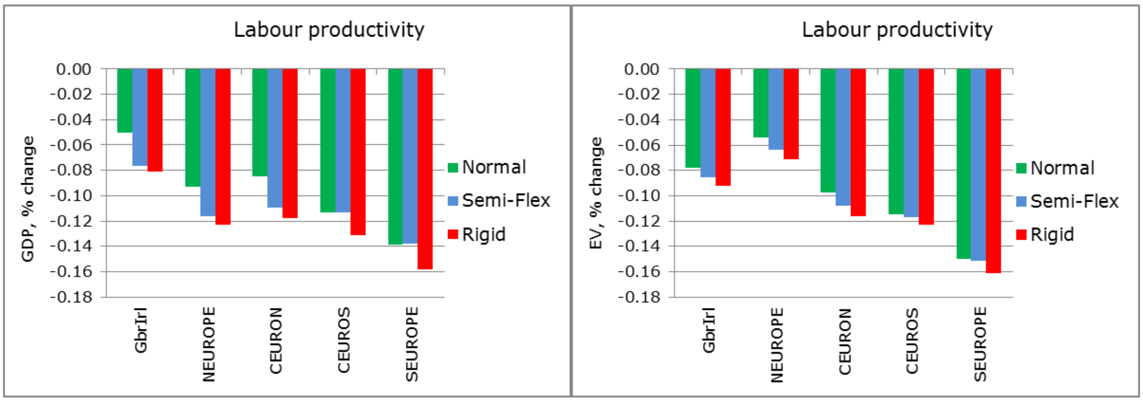
Across the sectors, the most affected is labour in the outdoor sectors such as construction and agriculture, which loses between 2.3% of productivity in Southern Europe, through 1.5% loss in Central Europe South, 0.5% in Central Europe North, to 0.07% and 0.01% in Northern Europe and United Kingdom and Ireland. Forestry is less affected with labour productivity loss of 0.17% in the Southern Europe, and 0.06% and 0.01% in Central Europe South and in Central Europe North, respectively. Transport and Service are affected only in the Southern Europe by 0.04% approximately.

Table 22: Reduction in labour productivity in the EU regions by sector, %

	Construction and Agriculture	Forestry	Transport	Services
UK & Ireland	0.01	0	0	0
Northern Europe	0.07	0	0	0
Central Europe North	0.46	0.01	0	0
Central Europe South	1.52	0.06	0.00	0.00
Southern Europe	2.34	0.17	0.04	0.04

The sizes of reductions in the labour productivity are broadly reflected in the magnitude of changes in GDP and welfare, presented in **Figure 13** and in **Table 23**. The most affected is the Southern Europe region subjected to largest labour productivity shocks, which loses about 0.14% of its GDP in the full-adaptation scenario. Central Europe South's GDP drops by 0.11%, while Central Europe North and Northern Europe both have their GDP reduced by about 0.09%. Finally, the United Kingdom and Ireland's GDP contract by 0.05%.

Figure 13: Change in GDP and EV from climate impacts for Energy Demand for the EU regions under 3 market adaptation scenarios, %



Across all the EU regions the introduction of market rigidities is accompanied by a welfare reduction. Comparing the labour productivity impact on GDP with the impact on welfare, it is noticeable that the Northern Europe region (which had the second-highest GDP reduction among the EU regions) records the lowest welfare reduction (0.05% in fully adaptive market).

Table 23: Change in GDP and EV from climate impacts for labour productivity for the EU regions under 3 market adaptation scenarios, %

Measure	Adaptation level	GbrIrl	NEUROPE	CEURON	CEUROS	SEUROPE
GDP	Normal	-0.050	-0.093	-0.085	-0.113	-0.139
	Semi-Flex	-0.076	-0.116	-0.110	-0.113	-0.138
	Rigid	-0.081	-0.123	-0.118	-0.131	-0.158
EV	Normal	-0.078	-0.054	-0.097	-0.114	-0.150
	Semi-Flex	-0.085	-0.064	-0.108	-0.117	-0.151
	Rigid	-0.092	-0.071	-0.116	-0.123	-0.161

In the next sections several representative examples of adaptation via trade and factors mobility and substitution are discussed in depth.

Northern Europe

GDP in in the Northern Europe region declines more than caused by reduction in its internal, marginally affected, labour productivity (**Figure 12** and **Table 22**). The largest component of the GDP reduction in the Northern Europe comes from reduction in exports, which decline by 0.28%. Under adaptive market conditions, the GDP loss is 0.09%, which can be decomposed into 0.03% loss from reduced consumption, 0.09% loss from lower exports, and 0.03% benefit from lower imports.

Table 12 below shows the Northern Europe export shares to other regions presented aside GDP changes in the other regions. The reduction in exports will be most towards the regions which are significant trading partners of the Northern Europe and are significantly affected by the climate incudes labour productivity reduction. The data bars facilitate reading the pattern.

Figure 14: Export shares by region in total North Europe's exports, and change in GDP in the importing region.

	Export share by the destination region, %	GDP change in importing region, %
China	5.6	-1.1
Japan	9.4	-0.5
Korea	5.0	-0.5
Indonesia	1.1	-2.4
India	2.0	-2.8
Australasia	2.1	-1.1
South Asia	1.4	-2.0
Rest of South-East Asia	8.3	-1.2
Canada	2.3	-0.1
USA	23.2	-0.3
Mexico	1.2	-0.4
Brazil	1.0	-0.8
Central America and Caribbean	0.7	-0.7
Rest of South America	1.4	-0.8
Middle East and North Africa	4.9	-0.6
Sub-Saharian Africa	1.6	-2.2
South Africa	0.6	-0.1
Northern Europe		
UK & Ireland	4.6	-0.1
Central Europe North	8.5	-0.1
Central Europe South	4.1	-0.1
Southern Europe	4.7	-0.1
Rest of Europe	1.1	-0.1
Russia	2.3	-0.1
Rest of former USSR	1.1	-0.2

It is clear from **Table 12** that some of the economies which are significant importers of goods and services from the Northern Europe are also seriously affected by climate change. Examples include China which absorbs almost 6% of Northern Europe's exports but its economy contracts by 1.1%; Rest of South East Asia imports over 8% of the exports with its GDP losing 1.2%, the USA's GDP impact is relatively lower at 0.3%, but it is leveraged through very high share of exports set at 23%.

The reduction in exports is further decomposed into specific sector-destination matrix in **Table 24** below. The Table shows how the total reduction in exports (-0.28%) is distributed across the exporting sectors. In the first column the Table shows that almost two-thirds of the exports reduction is due to lower demand for Consumer Goods (28.9%) and for Market Services (29.5%).

Table 24: Shares of total change in exports from Northern Europe by sector and by the destination regions in adaptive market scenario. Only figures larger than 1% are displayed.

Region	Share of change in total export by sector, %	Share of change in exports by destination region, %																								
		China	Japan	Korea	Indonesia	India	Australasia	South Asia	Rest of South-East Asia	Canada	USA	Mexico	Brazil	Central America and Caribbean	Rest of South America	Middle East and North Africa	Sub-Saharian Africa	South Africa	Northern Europe	UK & Ireland	Central Europe North	Central Europe South	Southern Europe	Rest of Europe	Russia	Rest of former USSR
Agriculture	-4.0	-3																								
Crops	-3.8																				-2					
Forestry	0.0																									
Coal Mining	0.0																									
Crude Oil Extraction	0.3																									
Natural Gas	0.0																									
Refined Oil	0.4																									
Electricity	-0.3																									
Metals	0.1																									
Chemicals	-5.3																									
Energy Intensives	1.0																									
Electronic equipment	-5.4															-1										
Transport Equipment	-4.2																									
Other Equipment	-7.9	-2														-1										
Consumer Goods	-28.9		-2								-2					-1				-5	-7	-2	-3	-2		
Construction	-3.5																									
Transport	-5.6																									
Market Services	-29.5	-6			-2	-5	-1		-3							-2	-2							-1	-1	
Non-market Services	-3.2																									
Total exported, %	*-100*	*-13*	*-4*	*-1*	*-3*	*-6*	*-4*	*-2*	*-6*	*0*	*-5*	*-1*	*-1*	*-1*	*-2*	*-9*	*-5*	*0*	*0*	*-6*	*-12*	*-3*	*-5*	*-5*	*-5*	*-1*

The rest of **Table 24** shows how the share of reduction in sectoral exports distributes across the importing regions (only shares larger than 1% are displayed). For example, the table shows that out of the 29.5% share of the Market Services in total export decline from Northern Europe, 6pp (percentage points) is due to lower exports of market services to China, 5pp due to exporting to India, 3pp to the Rest of South East Asia, etc.

The bottom row of **Table 24** shows the column total which represents percentage share of the total reduction in Northern Europe's exports summed across the sectors. The data indicates that the largest reduction comes from lower export demand in China (-13%) and Central Europe North (-12%).

The adaptation impact is mainly realised through lower imports for both, trade and primary factor-related adaptation types. As illustrated in **Table 25**, the reduction in exports remains constant with different levels of adaptation, consumption is reduced with increase in market rigidity, while reduction in decrease in imports makes the most of the GDP impact change.

Table 25: GDP change and contributions from Consumption, Exports and Imports, %

Market	Consumption	Exports	Imports	GDP
Rigid	-0.034	-0.099	-0.009	-0.123
Semi-rigid	-0.030	-0.099	-0.013	-0.116
Adaptive	-0.026	-0.099	-0.032	-0.093

Adaptation via trade

In parallel to the reduction in export demand following climate shock to labour productivity in other regions, there is also observed reduction in imports from these regions stemming from increase in import price. **Table 26** shows change in import price faced by Northern Europe, and subsequent reduction in import volumes with and without the trade-related adaptation.

The largest price increase comes with imports of the most affected sectors: construction, crops and agriculture (2.1%, 2% and 0.7% respectively). In the adaptive market the Northern Europe substitutes away from the more expensive imports toward domestic production. The imports of construction products are reduced by 3.7%, the crops by 2.4% and agricultural products by 0.2%.

Table 26: change in price of imports in Northern Europe, and change import volumes in adaptive and semi-rigid market settings.

Sector	Change in import price %	Change in import volume %	
		Adaptive market	Semi-rigid market
Agriculture	0.7	-0.20	0.04
Crops	2.0	-2.42	-0.96
Forestry	-0.1	0.41	0.26
Coal Mining	-0.6	0.29	0.09
Crude Oil Extraction	-0.8	0.21	0.11
Natural Gas	-0.5	0.09	0.03
Refined Oil	-0.7	0.17	0.10
Electricity	-0.3	0.48	0.15
Metals	-0.2	0.08	0.04
Chemicals	-0.3	0.11	0.06
Energy Intensives	-0.2	0.11	0.05
Electronic equipment	-0.2	-0.03	-0.05
Transport Equipment	-0.2	-0.02	-0.03
Other Equipment	-0.1	0.01	0.00
Consumer Goods	0.3	-0.40	-0.16
Construction	2.1	-3.66	-1.18
Transport	-0.3	0.04	0.03
Market Services	-0.2	0.06	0.00
Non-market Services	0.2	-0.47	-0.17

With the trade flexibility removed, however, the Northern Europe's ability to adjust its trade pattern is greatly reduced and the region is 'stuck' with the pricy imports. The imports of construction are now reduced by 1.2%, the crops products by less than 1% and the agricultural good by 0.04%.

Adaptation via factor mobility and substitution

Introduction of further rigidity to the Northern Europe's economy does not allow labour to move from the contracting to expanding sectors, as illustrated in **Table 27**. In effect the sectoral ability to adjust output to changes in international markets (both imports and exports) is reduced and leads to sub-optimal allocation of resources. The further decrease in imports leads to lower GDP and reduction in welfare via higher consumer prices.

Table 27: Change in labour demand for Northern Europe from reduction in labour mobility.

Sector	Change in labour demand, %	
	Semi-rigid market	Rigid market
Agriculture	0.8	0.02
Crops	1.2	0.03
Forestry	0.2	0.00
Coal Mining	-0.3	-0.01
Crude Oil Extraction	-0.5	-0.01
Natural Gas	-0.5	-0.01
Refined Oil	-0.1	0.00
Electricity	-0.1	0.00
Metals	-0.1	0.00
Chemicals	-0.2	0.00
Energy Intensives	0.0	0.00
Electronic equipment	-0.2	0.00
Transport Equipment	-0.1	0.00
Other Equipment	-0.1	0.00
Consumer Goods	0.3	0.00
Construction	0.2	0.01
Transport	-0.1	0.00
Market Services	-0.1	0.00
Non-market Services	0.0	0.00

In summary, almost all of the GDP and welfare effects observed in the Northern Europe are passed with international trade via changes in price of imports and demand for exports. This situation, where the direct climate impacts are 'outside' of the region provides high adaptation capacity realised via shift in trade patterns towards more economically viable solutions. For this reason the adaptation via trade brings more effect in the described situation when compared with benefits of adaptation through factors mobility.

Southern Europe

In contrast to the Northern Europe scenario where most of the direct climate effects are 'outside' of the region and the perturbations were passed via import and export linkages, in the Southern European region the direct impacts are mainly observed 'within' the region which is subjected to more substantial labour productivity losses.

Adaptation via trade

Exposure to trans-boundary effects of reduced labour productivity in other regions is very low in case of the Southern Europe regions. Such trans-boundary effects would be a product of degree of climate impact in trading partners' economies and of the intensity of trade between the partners' economies and Southern Europe, in this case. **Table 28** shows Southern Europe's export and import shares with each other region (as a measure of intensity of trade) aside change in GDP in each region (as a measure of degree of climate change impact).

Table 28: GDP impact of labour productivity by region and Southern Europe's international trade pattern

	GDP change	Export share, %	Import share, %	Imports change, %		
				Adaptive market	Semi-rigid market	Rigid market
China	-1.1	2.6	5.6	-0.38	-0.19	-0.14
Japan	-0.5	1.7	1.8	-0.14	-0.09	-0.04
Korea	-0.5	1.0	1.3	-0.38	-0.17	-0.08
Indonesia	-2.4	0.3	0.5	-1.09	-0.43	-0.37
India	-2.8	1.0	1.3	-2.14	-0.76	-0.72
Australasia	-1.1	1.2	0.6	-0.96	-0.38	-0.32
South Asia	-2.0	0.8	1.3	0.48	0.17	0.21
Rest of South-East Asia	-1.2	2.3	2.6	-0.75	-0.30	-0.25
Canada	-0.1	1.0	0.7	-0.01	-0.07	0.00
USA	-0.3	7.8	5.0	-0.44	-0.19	-0.13
Mexico	-0.4	1.0	0.5	-0.70	-0.23	-0.17
Brazil	-0.8	1.0	1.3	-1.17	-0.51	-0.43
Central America and Caribbean	-0.7	0.8	0.5	-1.59	-0.60	-0.56
Rest of South America	-0.8	1.3	1.9	-0.99	-0.41	-0.33
Middle East and North Africa	-0.6	8.7	9.5	0.78	0.27	0.31
Sub-Saharian Africa	-2.2	1.7	1.7	-0.59	-0.24	-0.20
South Africa	-0.1	0.5	0.5	-0.07	-0.08	-0.01
Northern Europe	-0.1	3.4	3.2	0.18	0.01	0.06
UK & Ireland	-0.1	11.2	8.3	0.23	0.02	0.07
Central Europe North	-0.1	21.7	25.5	0.11	-0.02	0.04
Central Europe South	-0.1	20.1	16.6	0.06	-0.04	0.01
Southern Europe						
Rest of Europe	-0.1	5.6	4.6	0.08	-0.03	0.03
Russia	-0.1	2.4	3.2	-0.39	-0.13	-0.08
Rest of former USSR	-0.2	1.0	1.9	-0.41	-0.15	-0.10

It is evident from **Table 28** that Southern Europe avoids trading with the regions which are most affected by reduction in labour productivity (mainly Asian regions, Sub-Saharan Africa and part of South America), and it's trade mainly concentrates within Europe, Middle East and North Africa. The changes following the climate shocks under the adaptive market conditions are rather marginal and barely exceed 1% change in import volumes. For this reason, the subsequently imposed higher rigidity in the international trade does not trigger significant changes in the import volumes and, in effect, does not have much effect on the Sothern Europe economy.

There is, however, further increase in imports after reducing labour mobility. Indeed, imports from main trading partners which were reduced due to the increase in the trade-rigidity increase again after sluggish labour is assumed. For example, imports from Central Europe North increase initially by 0.11% (adaptive market), then decrease by 0.02% (trade rigidity) to finally, increase again by 0.04% in effect of introduction of labour rigidity. The underlying mechanism is explored in the next section.

Adaptation via factor mobility and substitution

The intermediate connections within the link between rigid labour market and higher imports identified in the previous section include change in sectoral employment and sectoral price of output. The relevant data for the state of economy with and without the reduced labour mobility is presented in **Table 29**.

Table 29: Changes in sectoral employment, output prices and imports in Southern Europe region.

	Employement change %		Price of output change, %		Import volumes change, %	
	Semi-rigid	Rigid	Semi-rigid	Rigid	Semi-rigid	Rigid
Agriculture	0.7	0.1	1.0	1.9	-0.5	-0.3
Crops	1.1	0.1	1.6	2.5	-1.0	-0.8
Forestry	0.0	0.0	0.0	0.0	0.0	0.0
Coal Mining	-0.4	0.0	-0.2	-0.5	0.1	0.1
Crude Oil Extraction	-0.7	0.0	-0.5	-0.8	0.1	0.1
Natural Gas	-0.7	0.0	-0.5	-0.6	0.0	0.0
Refined Oil	-0.2	0.0	-0.8	-0.8	0.1	0.1
Electricity	-0.2	0.0	-0.3	-0.4	-0.1	-0.1
Metals	-0.2	0.0	-0.1	-0.2	0.0	0.1
Chemicals	-0.3	0.0	-0.2	-0.3	0.0	0.0
Energy Intensives	-0.1	0.0	-0.1	-0.1	0.0	0.2
Electronic equipment	-0.3	0.0	-0.2	-0.2	0.0	0.0
Transport Equipment	-0.2	0.0	-0.1	-0.2	-0.1	0.0
Other Equipment	-0.2	0.0	-0.1	-0.2	0.0	0.0
Consumer Goods	0.0	0.0	0.2	0.2	-0.3	-0.3
Construction	0.9	0.2	0.7	2.8	-0.8	0.3
Transport	-0.1	0.0	-0.4	-0.4	0.0	0.0
Market Services	-0.2	0.0	-0.1	-0.2	0.0	0.0
Non-market Services	0.0	0.0	0.1	0.0	-0.1	-0.1

As identified from the change in employment figures, although the labour moves from shrinking to growing sectors if it is given certain degree of mobility, this movement is restricted in the rigid scenario. This leads to under-employment in the sectors affected by the labour productivity reduction, and to over-employment in sectors which would reduce their employment in the adaptive market settings. The resulting inefficiencies lead to increase in cost of production and higher price of output which, in turn, encourages more imports which became relatively more competitive in the southern Europe regions. For example, the Construction sector's labour productivity is reduced by 2.3% (**Figure 12**) which leads to increase in demand for labour by 0.7%. However, if the labour is not mobile enough to meet the sector's demand, the employment in this sector increases by 0.1% only. In effect, the lower output and higher costs of production generate 0.9pp higher price of output. The imports of construction products react with an increase in volume of imports by 0.2pp (from -0.5% to -0.3%).

The final effect of reduced labour mobility in Southern Europe is increase in imports and increase in consumers' prices, both having negative effects on GDP and welfare.

6. Conclusions and further research

The main purpose of this study is to explore the role market adaptation can play in determining the order of magnitude of climate impact estimates. Autonomous or market adaptation is defined as the reaction of market prices when faced with climate shocks. Four climate impact categories are considered in this study: agriculture, sea level rise, energy demand and labour productivity.

A computable general equilibrium model is used to assess how much climate impacts could rise due to additional market rigidities. In particular, three kinds of market rigidities are considered: lower labour mobility across sectors within a region, lower substitutability between capital and labour, and lower substitutability between imported goods and domestic production.

It is found that if markets can autonomously adapt to climate shocks the potential climate damages can be substantially reduced. In global terms, it is estimated that the rigid case increases the climate impacts by a third (compared to a case with market adaptation), approximately, both regarding the GDP and welfare losses. Thus the GDP loss could be 1.4% instead of 1% under more rigid markets. Most of the additional damages due to market rigidities would come associated with the labour market rigidity, rather than more restricted substitution possibilities in international trade. Moreover, concerning the share of the additional losses under rigid markets, most of the additional impacts are due to climate effects on labour productivity and energy demand.

Regarding the regional decomposition of the absolute damages, the region that absorbs most of the avoided damages thanks to market adaptation is the UK and Ireland region, followed by Southern Europe and the Central Europe North regions. In general, it seems that the welfare-enhancement effect of adaptation diminishes relatively when moving to lower latitudes. Related to the population, the UK and Ireland region would have an additional 120 US$ gain in per capita terms thanks to adaptation. The Northern Europe region would be 60 US$ and that of the Southern Europe region being 50 US$.

It should be noted that this study is subject to a number of limitations. Firstly, the quantitative estimates are derived from a set of mathematical equations and specific values of key parameters, which represent de facto the idealised functioning of the market economies, yet ignoring the many rigidities and inertia distorting markets. It is anyhow a useful framework against which to assess the question of interest in this study. Secondly, it would be interesting to test the robustness of the findings to alternative characterisations of the market rigidities. Furthermore, a formal decomposition of the climate impacts distinguishing between partial and general equilibrium adjustments would be also valuable to understand the relative importance of the general equilibrium effects, which relate to the indirect autonomous adaptation process.

7. References

Aaheim, Asbjorn, and Marianne Aason (2008). “What do we know about the economics of adaptation?” CEPS Policy Brief No. 150, January 2008.

Barslund Mikkel, Busse Matthias, Schwarzwälder Joscha (2015). Labour Mobility in Europe: An untapped resource? CEPS Policy Brief. No. 327, March 2015, https://www.ceps.eu/system/files/Labour%20Mobility%20PB%20joint%20Bertelsmann%20FINAL%20mb.pdf

Bosello, Francesco, and Ramiro Parrado (2014), Climate Change Impacts and Market Driven Adaptation: the Costs of Inaction Including Market Rigidities. FEEM Note di Lavoro 2014.064

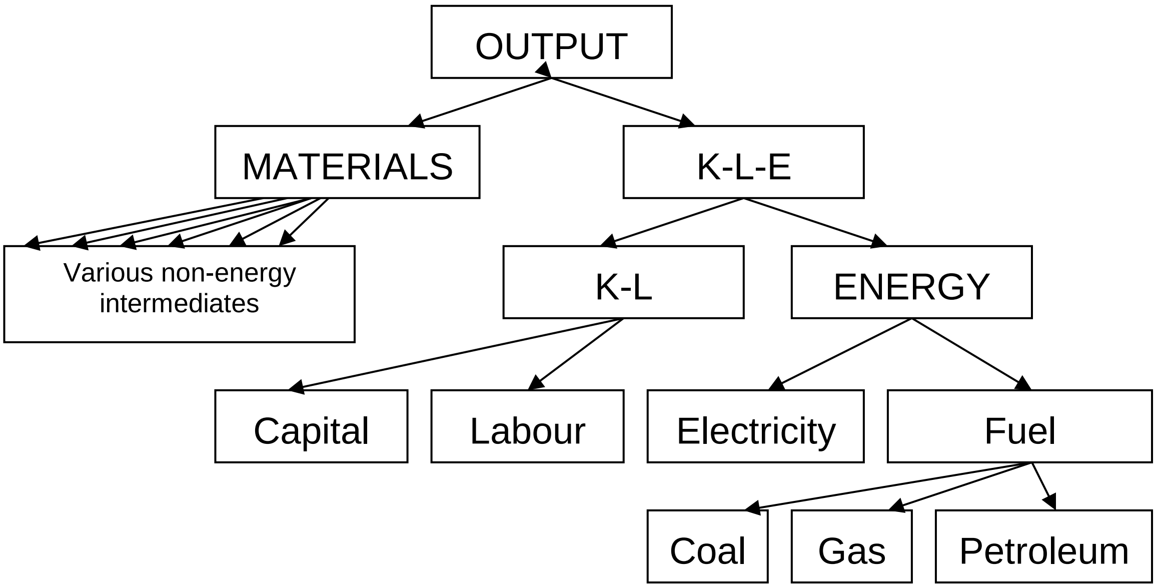
IPCC (2007) Intergovernmental Panel on Climate Change. Climate Change 2007: Impacts, Adaptation and Vulnerability (Working Group II contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change). Cambridge University Press, February 2008. ISBN 0521880106.

Malik Arun, Qin Xin, Stephen C. Smith (2010). Autonomous Adaptation to Climate Change: A Literature Review, Institute for International Economic Policy Working Paper Series Elliott School of International Affairs. The George Washington University

Annex A - Description of the CAGE-GEME3 model

Producers seek to maximise profits subject to their production technology and the cost of inputs. The production technology is modelled using a nested constant elasticity of substitution (CES) function which is summarised in below.

Figure 15: Production structure in the CAGE model



NOTE: K-L-E REFERS TO THE CAPITAL-LABOUR-ENERGY BUNDLE AND K-L TO THE CAPITAL-LABOUR BUNDLE.

As shown, output is produced by combining capital (K) and labour (L) with energy (E) and other intermediate inputs. All combinations of inputs are treated as imperfect substitutes, as governed by CES functions (though some are given low elasticity values to reflect low levels of substitutability).

All commodities enter the marketplace. Production from each country can be sold either within that country or exported. Similarly, the purchase of goods and services can be either of domestic production or imports. Total domestic demand consists of that from households, government, investment, intermediate inputs, and inputs for transport margins used for trade. The extent to which this domestic demand is satisfied by imports or domestic production is governed by a two-level constant elasticity of substitution function reflecting the imperfect substitutability at both levels. On the lower level, imports from different regions are combined, and on the upper level, the composite import commodity is combined with domestic production (the Armington function, Armington, 1969).

The economic institutions included in the model are households, government, firms and the rest of the world. Households purchase marketed commodities at market prices, meaning that the prices include commodity taxes. Households maximise their utility or well-being based on their preferences and the relative prices of goods and services, subject to their income constraints. Household consumption also has a nested structure, with households first choosing between energy and non-energy commodities and then on consumption within these categories. Substitutability within each nest is determined by a constant elasticity of substitution function.[13]

There are general constraints to the system (which are not directly considered by any of the particular economic agents). The zero profit constraint in production is imposed as firms are assumed to operate in a competitive environment. There are also zero profit constraints on domestic economic institutions – households, governments and investment – which mean that all income to institutions must be accounted for with either spending or saving. With respect to imports and transport margins, the zero profit conditions imply that their prices are also constrained to match their costs, inclusive of margins and taxes, as appropriate.

The macroeconomic closure rules govern the savings-investment behaviour, aggregate government finances, the behaviour of factor markets and the trade balance between each country and the rest of the world. The savings-investment closure maintains a constant volume of investment, and any change in the price of investment goods is adjusted for by changing the value of household savings. The government closure allows public consumption to be flexible in terms of quantity, then any additional revenue to government raises government income, and hence raises government expenditure. In that case, government consumption is modelled with a Leontief function, i.e. an increase (fall) in government expenditure proportionally increases (decreases) consumption of all commodities. The factor-market closure fixes the aggregate volume of both capital and labour at the regional level. Both capital and labour can move between sectors, however capital and labour are immobile across regions. Thus, returns to capital and wage rate of labour adjust to clear the market, and the wage and capital prices are region specific. The rest-of-the-world closure fixes the current account balance between regions at the benchmark level, with prices adjusting to ensure that all production from each region is either consumed domestically or exported.

---

[13] The structure of household consumption and the elasticity values are chosen with reference to the MIT EPPA model (Paltsev et al. 2005).

Table 30: List of region-codes and geographical aggregation.

Country code used	Description	List of countries
CHN	China	China
JPN	Japan	Japan
KOR	Korea	Korea
IDN	Indonesia	Indonesia
RUS	Russia	Russia
IND	India	India
USA	USA	USA
CAN	Canada	Canada
MEX	Mexico	Mexico
BRA	Brazil	Brazil
ZAF	South Africa	South Africa
GBIRL	UK & Ireland	UK, Ireland
NEU	Northern Europe	Denmark, Estonia, Finland, Lithuania, Latvia, Sweden
CEUN	Central Europe (North)	Poland, Netherlands, Luxembourg, Germany, Belgium
CEUS	Central Europe (South)	Austria, Czech Republic, France, Hungary, Romania, Slovakia, Slovenia, Croatia
SEU	Southern Europe	Bulgaria, Cyprus, Spain, Greece, Italy, Malta, Portugal
AUZ	Australasia	Australia, New Zealand, rest of Oceania
SAsia	South Asia	Bangladesh, Iran, Sri Lanka, Nepal, Pakistan, rest of South Asia
SSA	Sub-Saharan Africa	Botswana, Cote d'Ivore, Cameroon, Ethiopia, Ghana, Kenya, Madagascar, Mozambique, Mauritius, Malawi, Namibia, Nigeria, Senegal, Tanzania, Uganda, South Central Africa, Central Africa, rest of Eastern Africa, Rest of South African Customs Union, Rest of Western Africa, Zambia, Zimbabwe
RoEUR	Rest of Europe	Albania, Switzerland, Norway, Rest of Eastern Europe, Rest of EFTA, Rest of Europe
RoSEAsia	Rest of South-east Asia	Cambodia, Laos, Mongolia, Malaysia, Philippines, Singapore, Thailand, Taiwan, Vietnam, Rest of East Asia, Rest of Southeast Asia, Rest of the World
RoFSU	Rest of Former USSR	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Ukraine, Rest of Former Soviet Union
MENA	Middle East & North Africa	United Arab Emirates, Bahrain, Egypt, Israel, Kuwait, Morocco, Oman, Qatar, Saudi Arabia, Tunisia, Turkey, Rest of North Africa, Rest of Western Asia
CAMCAR	Central. America & Caribbean	Costa Rica, Guatemala, Honduras, Nicaragua, Panamá, El Salvador, Rest of Central America, Caribbean, Rest of North America
SAmer	Rest of South America	Argentina, Bolivia, Chile, Colombia, Ecuador, Peru, Paraguay, Uruguay, Venezuela, Rest of South America

Table 31: List of sector codes and sectoral aggregation

AGR	Agriculture	Bovine cattle, sheep and goats, horses, animal products nec, raw milk, wool, silk-worm cocoons, fishing
Crops	Crops	Paddy rice, wheat, cereal, grains nec, vegetables, fruit, nutsv oil seeds, sugar cane, sugar beet, plant-based fibers, crops nec
Forest	Forestry	Forestry
COA	Coal Mining	Coal
CRU	Crude Oil Extraction	Oil
GAS	Natural Gas	Gas, gas manufacture, distribution
P_C	Refined Oil	Petroleum, coal products
ELE	Electricity	Electricity
MET	Metals	Ferrous metals, metals nec, metal products
CHE	Chemicals	Chemical, rubber, plastic products
EINT	Energy Intensives	Minerals nec, paper products, publishing, mineral products nec
EEQU	Electronic equipment	Electronic equipment
TEQU	Transport Equipment	Motor vehicles and parts, transport equipment nec
OEQU	Other Equipment	Machinery and equipment nec, manufactures nec
CONC	Consumer Goods	Bovine meat products, meat products nec, vegetable oils and fats, airy products, processed rice, sugar, food products nec, beverages and tobacco products, textiles, wearing apparel, leather products, wood products
CNS	Construction	Construction
TRN	Transport	Transport nec, water transport, air transport
MSER	Market Services	Water, trade, communication, financial services nec, insurance, business services nec, dwellings
NMSER	Non-market Services	Recreational and other services, public administration, Defense, Education, Health

Annex B – Values of parameters used for simulation of autonomous adaptation

Table 32: Values of substitution elasticity between imports from various regions (*sigma M*) used in the experiments

	Rigid market					Adaptive market				
Sector	*GbrIrl*	*NEUROPE*	*CEURON*	*CEUROS*	*SEUROPE*	*GbrIrl*	*NEUROPE*	*CEURON*	*CEUROS*	*SEUROPE*
Coal Mining	1.83	1.83	1.83	1.83	1.83	6.10	6.10	6.10	6.10	6.10
Natural Gas	9.66	10.24	7.66	9.07	9.37	32.19	34.12	25.53	30.22	31.24
Refined Oil	1.26	1.26	1.26	1.26	1.26	4.20	4.20	4.20	4.20	4.20
Electricity	1.68	1.68	1.68	1.68	1.68	5.60	5.60	5.60	5.60	5.60
Construction	1.14	1.14	1.14	1.14	1.14	3.80	3.80	3.80	3.80	3.80
Chemicals	1.98	1.98	1.98	1.98	1.98	6.60	6.60	6.60	6.60	6.60
Agriculture	1.06	0.80	0.88	0.96	1.08	3.55	2.68	2.94	3.20	3.61
Crops	1.40	1.42	1.49	1.38	1.51	4.66	4.74	4.97	4.60	5.02
Forestry	1.50	1.50	1.50	1.50	1.50	5.00	5.00	5.00	5.00	5.00
Crude Oil Extraction	3.12	3.12	3.12	3.12	3.12	10.40	10.40	10.40	10.40	10.40
Metals	2.29	2.10	2.15	2.17	2.13	7.64	6.99	7.18	7.23	7.09
Energy Intensives	1.46	1.41	1.38	1.61	1.44	4.87	4.70	4.61	5.37	4.80
Electronic equipment	2.64	2.64	2.64	2.64	2.64	8.80	8.80	8.80	8.80	8.80
Transport Equipment	1.90	1.82	1.83	1.86	1.84	6.32	6.08	6.09	6.20	6.12
Other Equipment	2.40	2.42	2.41	2.41	2.41	8.00	8.06	8.02	8.05	8.05
Consumer Goods	1.91	1.87	1.91	1.94	1.95	6.36	6.23	6.35	6.47	6.50
Transport	1.14	1.14	1.14	1.14	1.14	3.80	3.80	3.80	3.80	3.80
Market Services	1.14	1.14	1.14	1.14	1.14	3.80	3.80	3.80	3.80	3.80
Non-market Services	1.14	1.14	1.14	1.14	1.14	3.80	3.80	3.80	3.80	3.80

Table 33: Values of substitution elasticity between domestic and imported goods and services (*sigma A*) used in the experiments

	Low					Normal				
Sector	*GbrIrl*	*NEUROPE*	*CEURON*	*CEUROS*	*SEUROPE*	*GbrIrl*	*NEUROPE*	*CEURON*	*CEUROS*	*SEUROPE*
Coal Mining	0.92	0.92	0.92	0.92	0.92	3.05	3.05	3.05	3.05	3.05
Natural Gas	2.70	4.62	3.25	3.88	4.36	8.99	15.40	10.85	12.94	14.52
Refined Oil	0.63	0.63	0.63	0.63	0.63	2.10	2.10	2.10	2.10	2.10
Electricity	0.84	0.84	0.84	0.84	0.84	2.80	2.80	2.80	2.80	2.80
Construction	0.57	0.57	0.57	0.57	0.57	1.90	1.90	1.90	1.90	1.90
Chemicals	0.99	0.99	0.99	0.99	0.99	3.30	3.30	3.30	3.30	3.30
Agriculture	0.68	0.66	0.70	0.67	0.59	2.26	2.21	2.35	2.23	1.96
Crops	0.75	0.80	0.79	0.84	0.78	2.49	2.65	2.62	2.79	2.59
Forestry	0.75	0.75	0.75	0.75	0.75	2.50	2.50	2.50	2.50	2.50
Crude Oil Extraction	1.56	1.56	1.56	1.56	1.56	5.20	5.20	5.20	5.20	5.20
Metals	1.11	1.06	1.08	1.08	1.08	3.71	3.54	3.61	3.60	3.59
Energy Intensives	0.82	0.80	0.81	0.82	0.82	2.73	2.68	2.69	2.75	2.73
Electronic equipment	1.32	1.32	1.32	1.32	1.32	4.40	4.40	4.40	4.40	4.40
Transport Equipment	0.99	0.94	0.91	0.97	0.95	3.28	3.13	3.05	3.23	3.16
Other Equipment	1.19	1.21	1.20	1.20	1.20	3.98	4.02	4.01	4.01	3.99
Consumer Goods	0.84	0.90	0.86	0.89	0.91	2.79	2.99	2.88	2.97	3.05
Transport	0.57	0.57	0.57	0.57	0.57	1.90	1.90	1.90	1.90	1.90
Market Services	0.57	0.57	0.57	0.57	0.57	1.90	1.91	1.91	1.91	1.91
Non-market Services	0.57	0.57	0.57	0.57	0.57	1.90	1.90	1.90	1.90	1.90

Table 34: Change in GDP and EV for the EU regions from climate impact scenarios, %

	Market adaptation level	GDP					EV				
		All impacts	Agriculture	SLR	Energy	Labour productivity	All impacts	Agriculture	SLR	Energy	Labour productivity
UK & Ireland	Rigid	-1.27	-0.05	-0.16	-0.98	-0.08	-2.32	-0.10	-0.37	-1.76	-0.09
	Semi-rigid	-1.07	-0.04	-0.15	-0.80	-0.08	-1.93	-0.08	-0.37	-1.40	-0.09
	Fully adaptive	-1.02	0.00	-0.15	-0.82	-0.05	-1.90	-0.06	-0.36	-1.39	-0.08
Northern Europe	Rigid	-0.53	0.22	-0.18	-0.45	-0.12	-0.96	0.63	-0.57	-0.96	-0.07
	Semi-rigid	-0.43	0.25	-0.18	-0.38	-0.12	-0.76	0.66	-0.56	-0.81	-0.06
	Fully adaptive	-0.32	0.33	-0.18	-0.38	-0.09	-0.64	0.76	-0.56	-0.81	-0.05
Central Europe North	Rigid	-1.22	-0.13	-0.51	-0.46	-0.12	-2.63	-0.23	-1.38	-0.91	-0.12
	Semi-rigid	-1.14	-0.12	-0.49	-0.42	-0.11	-2.47	-0.21	-1.33	-0.83	-0.11
	Fully adaptive	-1.14	-0.10	-0.53	-0.43	-0.08	-2.44	-0.17	-1.32	-0.83	-0.10
Central Europe South	Rigid	-0.75	-0.13	-0.14	-0.35	-0.13	-1.39	-0.25	-0.33	-0.68	-0.12
	Semi-rigid	-0.68	-0.12	-0.14	-0.30	-0.11	-1.32	-0.25	-0.33	-0.63	-0.12
	Fully adaptive	-0.68	-0.12	-0.13	-0.31	-0.11	-1.31	-0.24	-0.33	-0.63	-0.11
Southern Europe	Rigid	-1.56	-0.56	-0.11	-0.73	-0.16	-2.82	-1.07	-0.231	-1.35	-0.16
	Semi-rigid	-1.45	-0.57	-0.11	-0.63	-0.14	-2.56	-1.07	-0.230	-1.11	-0.15
	Fully adaptive	-1.48	-0.62	-0.11	-0.62	-0.14	-2.54	-1.05	-0.228	-1.10	-0.15

Annex C - Linking climate and labour productivity

The assessment analyses daily climate data[14] for the 30 year reference period (1980-2010) and for the future period (2069-2099). The change in the heat stress index (Wet Bulb Globe Temperature, WBGT[15]) is computed at the grid cell level[16] for over 50,000 cells covering the Earth landmass. The increase in temperature determines how labour productivity will change in each of the grid cells and, once compounded with the population data, for each region and country. Such regional labour productivity changes are then input to the CAGE model to derive further economic implications of the climate-induced labour productivity change.

Table 35 shows the annual average WBGT for the regions considered in this study under the RCP8.5 scenario, and the consequent changes in labour productivity for three levels of work intensity (heavy, moderate and light). It should be noted that the WBGT values are annual averages, which can mask significant volatility at different times of the year. The annual average is presented in this report for informative purposes. The analysis of the actual impact on labour productivity is actually undertaken with daily WBGT data so the productivity is affected only for days in which WBGT exceeds a threshold value.

---

[14] The methodology (following Kjellstrom et al. 2014) only considers the average temperature increase, therefore not accounting for the effects of heat waves, which require the analysis of a series of consecutive days.

[15] WBGT is a composite index representing temperature, humidity, heat radiation and wind speed. It captures and quantifies physical conditions of the environment relevant to human performance.

[16] The cells are 0.5°x0.5°.

Table 35. Base WBGT temperature with (outdoor) and without (indoor) sun radiation, and WBGT increase from 1980-2010 to 2069-2099 (RCP8.5 scenario)

	Temperature (WBGT)		Work intensity		
	Reference (outdoor)	Future increase	Heavy	Moderate	Light
China	18.1	3.8	-0.107	-0.034	-0.016
Japan	17.6	3.4	-0.085	-0.018	-0.005
Korea	16.5	3.6	-0.089	-0.016	-0.004
Indonesia	27.2	3.2	-0.327	-0.050	-0.006
India	25.0	3.8	-0.244	-0.079	-0.038
Australasia	24.1	2.9	-0.194	-0.024	-0.002
South Asia	23.9	3.9	-0.232	-0.097	-0.051
Rest of South-East Asia	23.2	3.5	-0.231	-0.058	-0.018
Canada	12.2	4.2	-0.014	0.000	0.000
USA	17.1	3.7	-0.061	-0.007	-0.001
Mexico	21.3	3.4	-0.086	-0.016	-0.004
Brazil	24.2	3.4	-0.187	-0.025	-0.004
Central America and Caribbean	23.8	3.2	-0.132	-0.007	0.000
Rest of South America	21.3	3.1	-0.121	-0.026	-0.008
Middle East and North Africa	19.3	3.4	-0.070	-0.007	-0.002
Sub-Saharian Africa	23.6	3.7	-0.188	-0.032	-0.005
South Africa	19.8	3.2	-0.038	-0.001	0.000
Northern Europe	12.6	3.2	-0.001	0.000	0.000
UK & Ireland	14.6	2.5	0.000	0.000	0.000
Central Europe North	14.5	3.1	-0.023	-0.002	0.000
Central Europe South	15.5	3.3	-0.015	-0.001	0.000
Southern Europe	17.4	3.1	-0.023	-0.002	0.000
Rest of Europe	14.5	3.3	-0.011	0.000	0.000
Russia	11.9	3.6	-0.007	0.000	0.000
Rest of former USSR	14.5	3.3	-0.015	-0.002	-0.001

Human productivity begins to be affected at a WBGT of 26 degrees (following the exposure-response function of Kjellstrom et al., 2014). The change in labour productivity will depend on both the initial WBGT level and its increase projected for the future periods. Although the largest absolute increase in the WBGT index is projected in the northern Hemisphere regions (e.g. Canada, Northern Europe or Russia), the reference temperature values there are relatively low[17], and well below the 26 degrees threshold. Hence, even after a significant increase of as much as 10 degrees in the WBGT scale, the future level of the index might not be high enough to affect labour productivity. In fact, there are many areas in the world where the high historical WBGT levels have already limited work capacity (e.g. Indonesia or India).

Furthermore, the magnitude of the reduction in labour productivity will depend on the specific type of labour considered according to its work intensity. For example, the work capacity of a

[17] In the higher Northern latitudes temperature can be negative for some grid cells. Even if there is a significant increase in WBGT, starting from a close to zero value would not affect much to labour productivity.

person performing heavy physical labour outdoors will be relatively more affected by the same increase in temperature when compared to the work capacity of a person carrying out indoors office tasks.

The specific base for the selection of sectors most prone for heat stress impacts is formed by NIOSH[18] standards. For this study, four types of labour are considered with respect to the degree of impact of the temperature change on productivity:

- Intensive physical work performed outdoors and possibly exposed to direct sun heat radiation (e.g. work on a construction site);
- Moderate physical work performed indoors or in full shade (e.g. work in industry);
- Light work performed indoors (e.g. administrative office work);
- Work not affected by surface temperature change (e.g. work in longwall mining)[19].

Table 35 lists the values of the labour productivity shock in each region for type of labour. The productivity reductions are higher for more labour intense occupations by construct, although the magnitude of the specific occupations being affected depends on the region-specific circumstances. For example, the most affected performance of heavy labour is in Indonesia; however the moderate work is most affected in South Asia. The heavy labour sectors are most affected in Indonesia (over 30%), India, South and South-East Asia, Australia, New Zealand, Sub-Saharan Africa, South America (about 20%).The largest reduction in labour productivity is simulated to occur in the tropical belt where the initial (historical) temperatures are above 26 degrees WBGT in the reference, so every increase in temperature contributes negatively to the productivity.

Looking at reductions in labour productivity at the grid cell level, beyond the spatial resolution of the CAGE model, the highest reduction in labour productivity (of as much as 45%) is simulated in regions of northern South America, central Africa and South East Asia. These regions have already recorded reduced labour productivity due to high temperatures in the past. The labour productivity in the future period will decrease by up to 45% to the level of about 20% in the most affected regions and the most affected type of (heavy) labour.

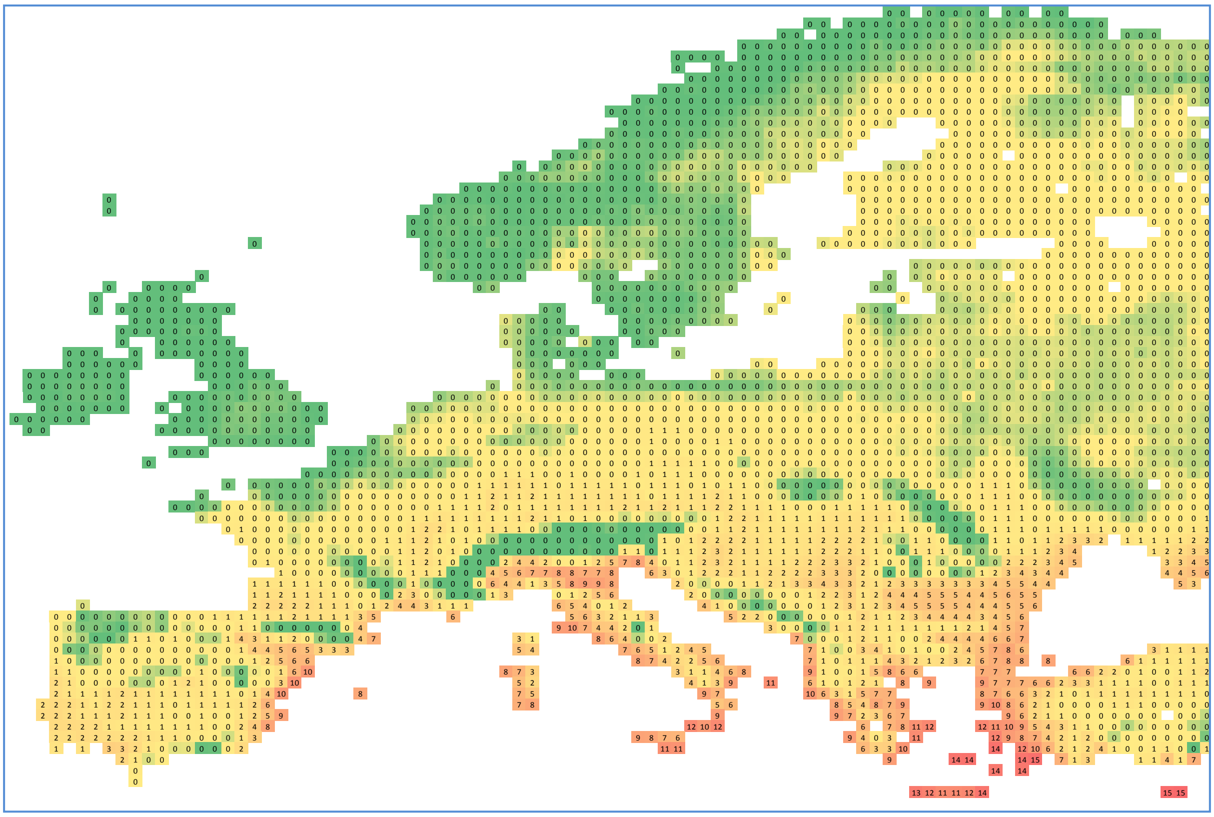
The direct impact of increase in temperature on labour productivity in the EU regions is relatively small when compared to the impacts projected for the tropics, although the reductions are still significant. From the grid cell perspective (see **Figure 16**) the highest impacts within the EU for the most intensive work are projected for the southernmost regions in the Mediterranean, and they gradually ease when moving north. The largest reduction is noted for Cyprus (-15%), the parts of Greece around the Aegean Sea (10-13%), southern parts of Italy (9-12%), and Valencia coast in Spain (9-10%).

---

[18] NIOSH (1986). *Working in Hot Environments*. National Institute for Occupational Safety and Health, 86-112

[19] Grouping of sectors by impact: (i) heavy workload (400W) outdoors in the sun (agriculture, crops, construction), (ii) moderate workload (300W) indoors or in full shade (forestry, metals, energy intensives, transport equipment, other equipment, chemicals, crude oil extraction, refined oil), (iii) light workload (200W) indoors (consumer goods, non-market services, transport , market services, electronic equipment, natural gas, electricity), and (iv) no impact (coal mining). Detailed sectoral composition is listed in **Table 31** .

Figure 16: Productivity reduction for intense work outdoors for EU, percent.



Annex D – The concept of adaptation

Planned adaptation is the result of deliberate policy decision, resulting from recognition that the conditions are expected to change or are already changing, and that some form of action is required to maintain a desired state. The scale and complexity of the planned adaptation projects is usually large (e.g. building dikes) with only a public sector having capacity for their planning and implementation, hence it is often called public adaptation.

Autonomous adaptation is the complement to the planned adaptation and relies on mechanisms which constitute the market economy, hence often called private or market-based adaptation. It is undertaken by individual institutions, enterprises or communities independently adjusting to the changing climate conditions.

Closely linked to the two types of adaptation mentioned above is the issue of degree of proactiveness in their development and implementation. Depending on the timing, goal and motive of its implementation, adaptation can be either reactive or anticipatory. Reactive adaptation occurs after the initial impacts of climate change become evident, while anticipatory adaptation occurs before the impacts are obvious.

An example of categorisation of adaptation types is shown in **Figure 17**.

Figure 17: Adaptation options

		Anticipatory	**Reactive**
Natural systems			Changes in length of growing Changes in ecosystem composition Wetland migration
Human systems	*Private*	Purchase of insurance Construction of house on stilts Redesign of oil-rigs	Changes in farm practices Changes in farm insurance premiums Purchase of air-conditioning
	Public	Early warning system New building codes, design standards Incentives for relocation	Compensatory payments, subsidies Enforcement of building codes Beach nourishment

Based on IPCC (2001)

In practice, the border lined between different adaptation types may be blurred, and adaptation cases in the real world are often a combination of the different adaptation types. Examples include a private, bottom-up adaptation project responding to incentives provided by the government, or government responding to community's concerns by providing policies and taking action. Malik et al. (2010) proposes to view the adaptation process as a *continuum*: pure spontaneous adaptation undertaken by private agents at one end, and pure planned adaptation (big infrastructure projects led by the government and regulations) by government at the other side of the continuum.

Autonomy is also a matter of perspective. Adaptation may appear autonomous to an observer, A, who takes no actions but sees the results of actions that others, B, have taken. From B's perspective the actions are not autonomous. For example, people may migrate from hazardous areas. From government's point of view, that is autonomous (no government action), though the migrants took deliberate action in their movements.[20]

[20] Adaptation Working Group, William Walker et al

ECONADAPT

The Economics of Adaptation

Funded by the European Union

Deliverable 8.2.2: "The implications of irrigation as a planned adaptation measure on an economy wide context"

Ramiro Parrado (CMCC), Francesco Bosello (CMCC) and Anna Dellarole (Milan University)

Deliverable number	D8.2.2
Work Package Number	WP8
Submission date	April 2016
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

Document information

Title:	Deliverable 8.2.2 "The implications of irrigation as a planned adaptation measure on an economy wide context"
Authors:	Ramiro Parrado (CMCC), Francesco Bosello (CMCC) and Anna Dellarole (Milan University)
Other Contributors	Other Contributors
Date:	April 2016
Contact details	Ramiro Parrado, ramiro.parrado@feem.it
Work Package Number	WP8
Deliverable number	D8.2.2
Filename:	D8.2.2-Planned-Adaptation-Agriculture.docx
Document history:	Version 1
Type of Activity	RTD
Nature	R = Report, O = Other
Dissemination / distribution level	PU = Public
Citation:	Deliverable 8.2.2 of the ECONADAPT Project.
Copyright:	

The ECONADAPT project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 603906.

To find out more about the ECONADAPT project, please visit the web-site:
www.econadapt.eu

For further information on the ECONADAPT project contact Alistair Hunt at:
ecsasph@bath.ac.uk

.

Table of Contents

1 Introduction

The economic relevance of the agricultural sector varies widely between countries. In OECD economies agriculture accounts today for less than 1.6 % of overall economic output and employs less than 6% of the population. By contrast, in many least developed countries more than 25 % of gross domestic product (GDP) is derived from agriculture and in some countries, more than 50 % of workers are employed in this sector (WDI, 2012). Furthermore, 70 % of extremely poor people (1.4 billion living below the poverty level of US$1.25-a-day) live in rural areas and depend mostly on agriculture for their livelihood (IFAD, 2010).

Projected high population growth is one important stressing factor for agricultural production. According to the latest IPCC (the Intergovernmental Panel on Climate Change) socio-economic scenarios[21] the world's population is expected to reach 8.5 to 9.9 billion by 2050 with developing countries, especially in Sub-Saharan Africa, depicting the highest population growth during the next 40 years. To feed a world population of more than 9 billion, food production has to rise by 70 % globally and agricultural production to double in developing countries (FAO, 2009).

Changing climatic conditions are a further stress on agriculture production. The consequences of these changes are various and include among others: changes in agricultural productivity with associated changes in regional distribution and intensity of food production (Fellmann, 2012).

Therefore, adaptation actions are necessary. Some adaptation responses can be driven by self-regulatory mechanisms (the so-called autonomous reaction), other by planned policy intervention. Examples of autonomous adaptation at the farm level are changes in crop management, (cultivation and planting date adjustment), irrigation and fertilizer optimization, research and development. Typical examples of autonomous adaptation at the national and international level are changes in agents' behaviour adjusting/adapting to new price conditions. These autonomous responses can be strengthened by planned strategies. Governments may promote specific practices, such as crop switching, local seed banks, rain storage, adoption of new technologies, irrigation projects, early seasonal weather forecast, the development of new markets and the improvement of trade flows, etc.

In developing countries agricultural production is highly dependent on rainfall. In Sub-Saharan Africa in particular approximately 97% of total cropland is rainfed (Calzadilla et al., 2013). Accordingly, seasonal rainfall variability would strongly affect their crop production and reverberate throughout their economies. Given that water is a major factor to guarantee agricultural production, the development of irrigation can be a key to promote climate change adaptation.

This deliverable aims to assess the economy-wide effects of an increased demand for irrigation services to reduce the adverse effects of climate change, using a computable general equilibrium (CGE) framework. More specifically, an explicit irrigation module is implemented into the ICES model (Eboli et al. 2010; Parrado and De Cian, 2014) a multi-country, multi-sector, recursive dynamic CGE model. In the new specification farmers can switch from rainfed to irrigated land bearing additional capital, operational and maintenance costs (costs for irrigation services). With the enhanced model we assess the impacts of climate change with and without adaptation for the world agricultural sector and the propagation of such effects to the whole economy.

[21] Five new socio-economic scenarios, called Shared Socioeconomic Pathways (SSPs), have been developed for the Fifth assessment report by IPCC (AR5, 2014).

2 Water and irrigation in economic models

Few examples of global CGE models consider explicitly water resources and irrigation as production factors in agriculture.[22] One among the first global studies along this stream is Berrittella et al. (2005) applying the GTAP-W1 model. Water input is treated as a non-marketed (zero cost) productivity augmenting factor combined with primary and intermediate inputs to produce crops at the top of the nested CES production function. Perfect input complementarity is assumed (i.e. substitution possibilities are not allowed). Water is perfectly mobile amongst different agricultural sectors, while it is immobile between agriculture and the water distribution services sector.

The GTAP-W1 model has been used to analyse the economic costs of restricted water supply[23] (Berrittella et al., 2005; Berrittella, Hoekstra, Rehdanz, Roson and Tol, 2007); water price policy[24] (Berrittella et al., 2005; Berrittella, Rehdanz, Roson and Tol, 2008); agricultural trade liberalization policy on water-intensive sectors (Berrittella et al., 2005; Berrittella, Rehdanz, Tol and Zhang, 2008); and investment in irrigation projects in China to increase water supply (Berrittella et al., 2006). The GTAP-W1 approach has some shortcomings. Firstly, water is treated as a sort of technology parameter rather than a proper primary factor, and thus water substitutability with other inputs cannot be fully captured. Secondly, investments in irrigation are set exogenously, and therefore it is not a farmers' decision. Finally, GTAP-W1 is a static model; hence the adjustment path towards the long-run equilibrium cannot be properly described.

Some of these limitations have been addressed by GTAP-W2 (Calzadilla et al., 2011), which introduces three different kinds of land inputs: rainfed, irrigated, and pasture land. This immediately allows for substitution possibilities between irrigated land and other primary inputs in crops production. In that approach, water combines with irrigable land in an input composite, which is on its turn combined with rainfed land, natural resources, labour and capital-energy into the value-added nest through a CES structure. Irrigated land is more valuable than rainfed land because yields per hectare are higher and because irrigation development is costly while rainfall is free.

The GTAP-W2 model has been used to analyse the economy-wide impacts of water saving through increased irrigation efficiency (Calzadilla et al. 2011),[25] and the effects of expanding irrigation and increasing agricultural productivity in Sub Saharan Africa (Calzadilla et al. 2013).[26] Still the cost of investments in irrigation expansion and efficiency, improvements in agricultural productivity are not incorporated into the model. Therefore, benefits from irrigation could be overestimated. Moreover, limits on water availability and accessibility are not

[22] Because of data requirements, more studies of water resources have been done with regional or national CGE models. For example, Decaluwé et al. (1999), Roe et al. (2005) and Diao et al. (2008) presented a CGE model for Morocco; Gomez et al. (2004) for the Balearic Islands; Letsoalo et al. (2007), Van Heerden et al. (2008) and Juana et al. (2011) for South Africa; Dudu et al. (2010) for Turkey; Strzepek et al. (2008) for Egypt; Lennox and Diukanova (2011) for the Canterbury region in New Zealand; You and Ringler (2010) for Ethiopia; Peterson et al. (2004) and Dixon et al. (2009) for Australia.
[23] From a modelling perspective, water scarcity is guaranteed either with an increase in economic rents of water resource or with a decrease in agricultural production (drop in productivity in water demanding industries). The former is modelled by water tax with lump sum recycling, while the latter by water tax without recycling.
[24] The water saving policy is obtained through a water price tax.
[25] Water productivity is used as a proxy of irrigation efficiency.
[26] The expanded irrigation scenario is obtained doubling both irrigated areas and water endowment, while the increased agricultural productivity scenario is determined by improvements in productivity, for both rainfed and irrigated land, through agricultural R&D investments.

considered. Finally, the transformability of rainfed land into irrigated land is not allowed, since they are treated as two separate stocks.

A slightly different approach has been followed by Ponce (2013) in the ICES-W model where in the crops' production function, irrigated land is obtained combining land and irrigation capital. The productivity of irrigation capital and of rainfed land then depends on the level of a water reservoir and precipitation, respectively. ICES-W is a recursive dynamic model and captures the evolution of investments in irrigation projects which however remain exogenous while the transformability of rainfed land into irrigated land is not allowed. Finally, Ponce uses the share of area actually irrigated over the total land to disaggregate irrigated and rainfed land. This amounts to assume that the average price per hectare of irrigated and dry land is the same. This is not realistic, as better land conditions are usually required for irrigation, which translates into higher prices for irrigable land.

A different approach has been followed by Taheripour et al. (2013) in the GTAP-BIO-W model. The authors distinguish between irrigated and rainfed activities, by using different production functions. Moreover, they account for different levels of water scarcity and of land productivity within national borders considering several river basins (RBs) per country serving different Agro Ecological Zones (AEZs). Supply of water is exogenously given at the RB level, and only irrigated crops can compete for it. Managed water is immobile between RBs, but mobile across AEZs within a given basin. As in the GTAP-BIO model, land supply is fixed at the AEZ level. Land is transformable among pasture, forest and cropland. However, in GTAP-BIO-W cropland is also convertible into irrigated or rainfed land, which are used by only irrigated crops or rainfed crops, respectively. The GTAP-BIO-W model has been used to study the impacts of water scarcity on food security and on international agricultural trade (Liu et al. 2013) and the economic implications of future irrigation shortfalls on regional and global food supplies (Liu et al.2014). Although the GTAP-BIO-W model gives a better representation of climate change impacts at a subnational level, it does not consider adaptation strategies.

Similarly to Taheripour et al. (2013), Baker (2011) distinguishes between irrigated and non-irrigated crop production and between irrigated and non-irrigated land in the EPPA-IRC model. Differently from GTAP-BIO-W, water is not considered explicitly as a primary factor in the crop production function, but in the value of the output produced with irrigated land and thus the value of irrigated land itself. In particular, the production structure of irrigation services includes a fixed factor on behalf of water resources. This is a subtle way to represent water availability constraints on land conversion. With this modelling approach Baker can capture the cost of land conversion. EPPA-IRC is a dynamic model and can represent trends in irrigation expansion where the stock of irrigable land, subject by a maximum potential increase (i.e. the theoretical limit to irrigation imposed by physical water resources) is progressively reduced, proportionally to the expansion of irrigation.

Many challenges still remain and there are many opportunities for future research. Firstly, gathering more data to improve water and irrigation modelling in the CGE framework. Secondly, more empirical studies have to be done to estimate the elasticity of transformation for the land supply structure, and to quantify the elasticity of substitution for both irrigated and rainfed crops' production functions. Finally, further modelling improvements are required to develop a better representation of adaptation strategies to assess climate change impacts on agriculture.

3 Methodology

Advancing the literature reviewed, this study allows for the endogenous transformability of rainfed land into irrigated land which becomes a decision variable for the farmer which compares its cost with benefits (lower yield losses).

Overview of the ICES-IRR model

The basic ICES model is a multi-region, multi-sector, recursive dynamic CGE model of the global economy, derived from the GTAP-E model (Burniaux and Truong, 2002), which in turn is the energy environmental extension of the standard GTAP model (Hertel, 1999). A detailed description of ICES can be found in Parrado and De Cian (2014). Other features of ICES are similar to most CGE models: domestic production is determined by a series of nested constant elasticity of substitution (CES) functions, which specify substitutability between primary factors, energy and non-energy intermediates. The demand side of the economy is characterized by a representative household, who receives income from primary factors, and allocates it across private consumption, public consumption and saving so as to maximize per capita aggregate utility, according to a Cobb-Douglas function. A global bank collects global net savings and allocates them amongst regions according to relative rates of return to capital. Bilateral trade is specified by assuming imperfect substitutability to consider product heterogeneity by country origin (Armington, 1969).

Regional aggregation

The current version of ICES-IRR is based the GTAP version 8 database (Narayanan et al., 2012), which represents the global economy in 2007. For the present exercise, the world is grouped into 22 regions, and 23 representative industries (**Table 36**).

Regions/countries	Production sectors
United States of America (USA)	Rice (Rice)
Northern Europe (North_Europe)	Wheat (Wheat)
North EU15 (North_EU15)	Other Grains including Maize (CerCrops)
Mediterranean EU15 (Med_EU15)	Oil Seeds Including Soy (VegFruits)
Mediterranean EU12 (Med_EU12)	Livestock (Livestock)
Eastern EU12 (East_EU12)	Coal (Coal)
Rest of Europe (RoEurope)	Oil (Oil)
Rest of Former Soviet Union (RoFSU)	Gas (Gas)
South Korea (SouthKorea)	Nuclear Fuel (NuclearFuel)
Australia (Australia)	Oil_Pcts (Oil_Pcts)
South Africa (SouthAfrica)	Nuclear Electricity (Ely_Nuclear)
Canada (Canada)	Renewable Electricity (Ely_Renew)
Japan (Japan)	Fossil Electricity (Ely_Other)
New Zealand (NewZealand)	Energy Intensive Industries (En_Int_ind)
North Africa (NAF)	Other industries (Oth_ind)
Middle East (MDE)	Construction (Construction)
Sub-Saharian Africa (SSA)	Road Transport (RoadTransprt)
Southern Asia (SASIA)	Other Transport (OthrTransprt)
India (India)	Trade (Commerce)
China (China)	Water (Water)
Eastern Asia (EASIA)	Irrigation Services (IRServ)
Latin and Central America (LACA)	Market Services (MServ)
	Public Services (PubServ)

Table 36: ICES-IRR regional and sector aggregation

New specification of the ICES model: ICES-IRR

The main innovation of the ICES-IRR model is related to the specification of the crop production function (**Figure 18**). Farmers decide first which combination of rainfed and irrigated land to use. The use of irrigable land requires capital and infrastructure. Hence, irrigated land is not only more productive, but also more costly. To account for this, a new intermediate factor, called “irrigation services”, is included. Irrigable land and irrigation services are aggregated to determine irrigated land, which in turn is an imperfect substitute[27] of rainfed land.

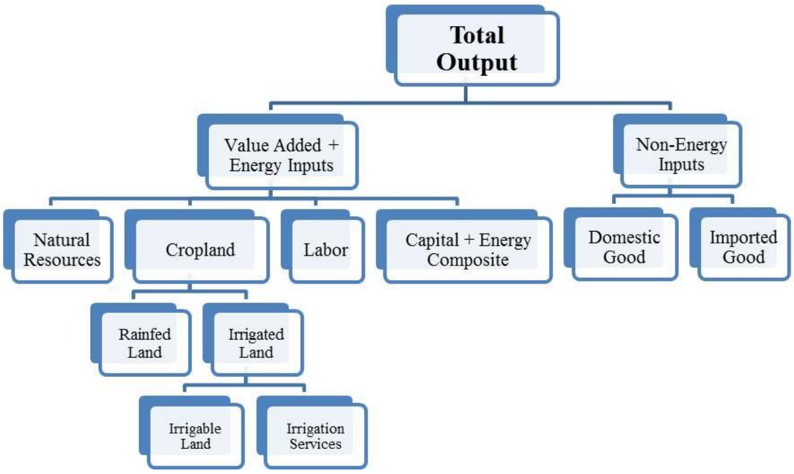


Figure 18: Crop production tree

Irrigation services are on their turn a new production sector that uses energy, water distribution services, capital and labour (Figure 19). To take into account constraints on the potential use of irrigation services imposed by water availability the supply of this sector is constrained by including a fixed factor. As usual it can be interpreted as the water (scarcity) rents.

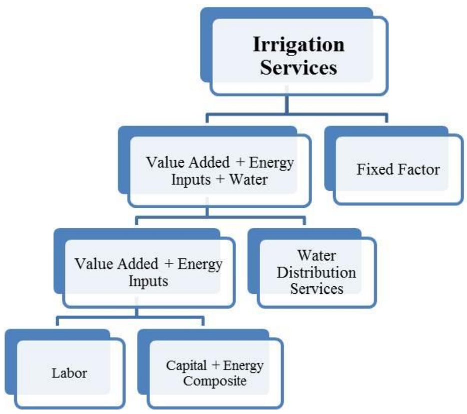


Figure 19: **Irrigation services production tree**

Another significant improvement in the ICES-IRR model is the new land supply structure. In the standard ICES model, a fixed land supply at the country level is imperfectly substitutable

[27] Due to the lack of empirical estimates, the elasticity of substitution between irrigated and rain-fed croplands has been set at the value of 10. This high value guarantees land substitutability from rain-fed to irrigated land if the former becomes relatively less profitable.

across different crops depending on relative crop prices and land rents. Imperfect land transformability is represented by a one-level Constant Elasticity of Transformation (CET) function. This specification implies to consider land equally and easily transformable across different activities (e.g., wheat, rice, millet, livestock, etc.) and land types (e.g. cropland, pasture land etc.).

This is not very realistic. In particular, irrigated cropland is usually more valuable and “less substitutable” because it should meet specific conditions in terms of slope, drainage, texture, soil depth, etc. (FAO, 1997). Therefore, following Taheripour et al. (2013), we develop a three-level CET function (
Figure **20**). At the bottom level, land in each region is assumed to be transformable among pasture and cropland, while at the second level cropland is allocated between irrigable land and dryland.[28] Finally at the top level, land supply among crops is treated as in the standard ICES model. Differently from Taheripour et al. (2013), where irrigable land is supplied only to irrigated crop production, in ICES-IRR both irrigable and rainfed land can be used by all crop-producing industries.

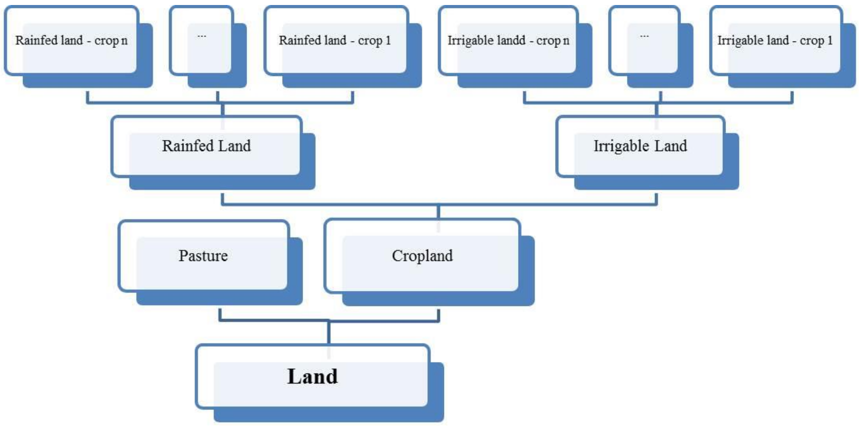


Figure 20: Land allocation tree

The extended database

The new model specification requires a new database. As a first step, the value of the original land endowment in ICES is split into the value of pasture land and cropland.[29] The former is given by the value of land used in the production of animals and animal products (Livestock sector), while the latter is given by land rents, paid in crops production (Rice, Wheat, Cereal Crops, Vegetables and Fruits).

Then, the value of cropland is split between rainfed and irrigable land. Because of the lack of data it was not possible to use directly prices and land areas to disaggregate the two components. The split has been done following Calzadilla et al., (2011) and Dellarole (2015) using the shares of each land type in total production. These shares are computed (**Table 38** in Appendix B) using the IFPRI database (Nelson et al., 2010), referring to data for 2010 under the “Baseline Perfect Mitigation” scenario. It is also assumed that the value of irrigable land includes the intrinsic value of water. Again, information on market price of water

[28] The procedure for calibrating the elasticity of transformation between rain-fed and irrigable land as well as a sensitivity analysis on this parameter is described in Appendix A.

[29] In the GTAP database, land disaggregation across different crops industries depends on rental land value and thus there is not a direct connection with physical quantity of land use in hectares.

used for irrigation are largely lacking. Following Baker (2011), it is thus imposed that water contributes the 10% of the value of irrigable land in the USA. Values for the other regions are adjusted, using the ratio of irrigated yield to rainfed yield as a proxy of land rents ratio (see **Table 39** in Appendix B). The final data estimated for the ICES regions are shown in **Table 37**.

Region	*Rainfed Land*	*Irrigable Land*	*Pasture Land*
USA	66%	11%	22%
North_Europe	37%	0%	62%
North_EU15	53%	1%	46%
Med_EU15	69%	11%	20%
Med_EU12	58%	10%	32%
East_EU12	62%	4%	34%
RoEurope	62%	7%	31%
RoFSU	64%	5%	31%
SouthKorea	77%	14%	9%
Australia	44%	2%	54%
SouthAfrica	70%	5%	25%
Canada	61%	5%	34%
Japan	73%	16%	11%
NewZealand	21%	4%	75%
NAF	51%	33%	16%
MDE	56%	20%	24%
SSA	86%	2%	12%
SASIA	38%	25%	37%
India	45%	26%	29%
China	38%	28%	35%
EASIA	54%	27%	20%
LACA	66%	4%	30%
World	54%	18%	28%

Table 37: Distribution of land rents in the ICES-IRR database

The value of irrigable land is however only one component of the actual value of irrigated land. Costs of irrigation services must be also considered. These costs vary quite a lot depending on many factors, e.g. irrigation system, water prices, operation and maintenance (O&M) costs, wages etc. For simplicity, we assume that the value of irrigation services in each crop industry is given by labour, capital, water services, energy costs and water scarcity rents.

Following crop budget data for the US, it is assumed that 60% of the irrigated land value is given by (irrigable) land and 40% by irrigation services.[30] Finally, the value of irrigation services is split into the value of labour, capital, water distribution services and energy, using the cost shares in crop production taken from the GTAP database. The value of primary factors and intermediates used in the irrigation services sector is the residual.

Model verification

To test the behaviour of the modified model we impose a hypothetical uniform 10% reduction of rainfed and irrigated land productivity in a fixed and in a flexible irrigation cases. The first is implemented preventing substitutability between irrigated and rainfed land in ICES-IRR. The second case allows for the expansion of irrigable land and therefore it is possible to substitute irrigated land for rainfed land. When comparing the two cases, the expected outcome is to observe lower negative impacts on agricultural production when farmers are allowed to

[30] We fixed that share based on available information in Southeast Missouri Crop Budgets 2015 from the University of Missouri Extension, and the Projected Budgets for Irrigated Crops from the North Dakota State University Extension service.

expand irrigation. To isolate as much as possible the feedback mechanisms triggered by price changes, the shock is imposed on just one region and crop at a time.

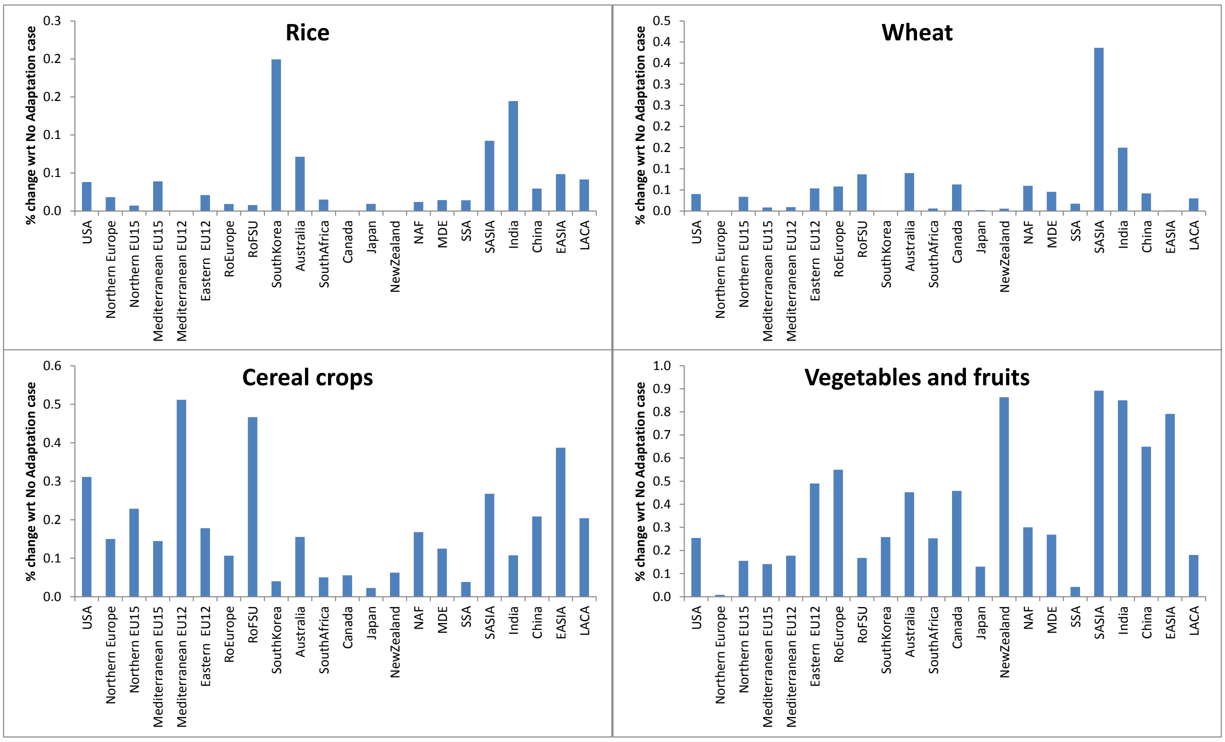


Figure 21: Effect of flexible irrigation as a response to a negative land productivity shock on crop production (% difference between the flexible and fixed irrigation cases)

As expected (see **Figure 21**), the expansion of irrigation allows farmers to reduce crops' production losses for each of the four crops modelled in ICES. It is important to stress however that when land productivities for all crops in all countries are shocked together, not all agricultural sectors report a positive effect from irrigation expansion. This is due to the interplay of mainly two effects. Firstly, within each country there is an increased competition for scarce irrigation services, which eventually prevents some crops from benefiting from irrigation use. Secondly, countries compete internationally in crop markets. Accordingly winners after the shock, crowd out production of the losers.

4 Simulation scenarios

Reference Scenario

Population and economic growth rates reference for this study are those of the OECD version of Shared Socioeconomic Pathway SSP2 (O'Neill et al., 2014). This is the “Middle of the Road” scenario, developed for the Intergovernmental Panel on Climate Change (IPCC) 5th assessment report. It assumes a prolongation of current economic development trends, with reductions in resource and energy intensity at historic rates and a slowly decreasing fossil fuel dependency.[31] Changes in irrigated and rainfed land productivity are taken from the IFPRI “Baseline Perfect Mitigation” scenario, where today's climate conditions are imposed for the future (Nelson et al., 2010).

Climate Change Scenarios

Climate change impacts on crops' yields derive from the Agricultural Model Intercomparison and Improvement Project (AgMIP, Rosenzweig et al., 2013) which provides several sets of climate change impacts using five crop models.[32] Specifically, we used yield impacts in the four Representative Concentration Pathways (RCP2.6, RCP4.5, RCP6, and RCP8.5), for four crops (maize, rice, soy and wheat) with and without irrigation. Data do not include growth-enhancing effects from CO_2 fertilization, which are subject to large uncertainties (Long et al., 2006; Tubiello et al., 2007) and are based on the output from the general circulation model HadGEM2-ES (Jones et al., 2011).

Crop models' output presents high spatial resolution. Yield changes are thus aggregated for the ICES-IRR regions using the AgMIP@GEOSHARE tool (Elliott et al., 2015; Rosenzweig et al., 2014; Villoria et al., 2014). Furthermore, yields data show strong yearly oscillations which could be a problematic input to be processed by a recursive dynamic CGE model. To smooth the variability, changes in rainfed and irrigated land productivity have been calculated as the difference between the 28-year moving average in each future year while the 1980-2007 average is taken as representative of the current climate. Finally, while for rice and wheat there is a perfect correspondence with the ICEs-IRR sectors, we used maize data as representative of other cereal crops, soy data for vegetable and fruits and the data on rainfed land for soy as a proxy for pasture land.[33]

Figure 22 shows the average and a 95% confidence interval for these changes by crop and region for RCP 8.5 in 2050 which features the strongest climate signal. Two results are worth noting: firstly, in 2050 climate change impacts can still affect positively yields in some regions;

---

[31] The benchmark scenario is described in Deliverable 8.1: Report on the ICES and the GEM-E3 model benchmark scenario for the subsequent analysis.

[32] From the ensemble of crop models, only five provided information for all RCP and crops that can be used in the ICES model. These models are: Environmental Policy Integrated Climate model - EPIC (Gassman PW, et al., 2004; Izaurralde RC, et al., 2006), the GIS-based EPIC model - GEPIC (Liu J, et al., 2007), the Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model - LPJmL (Bondeau et al., 2007), the Lund-Potsdam-Jena General Ecosystem Simulator with Managed Land - LPJ_GUESS (Bondeau et al., 2007; Smith et al., 2001), and the parallel Decision Support System for Agro-Technology Transfer - pDSSAT (Elliott et al., 2013; Jones et al., 2003).

[33] We acknowledge this is a simplification, but we choose to do so to include also a climate change impact on pasture land.

secondly, irrigated land is not necessarily affected less negatively than rainfed land. This occurs for cereal crops in most regions but not in Africa, Middle East, South Asia and India. In the case of wheat, in the USA, Canada, Middle East, South Asia, India, China and Latin America and the Caribbean rainfed land yield losses are lower than that of irrigated land. In the case of rice, the Rest of Former Soviet Union, Japan, South Asia and India show a higher negative impact on irrigated land. Finally, regarding vegetables and fruits, only Africa and India show a relative advantage for rainfed land.

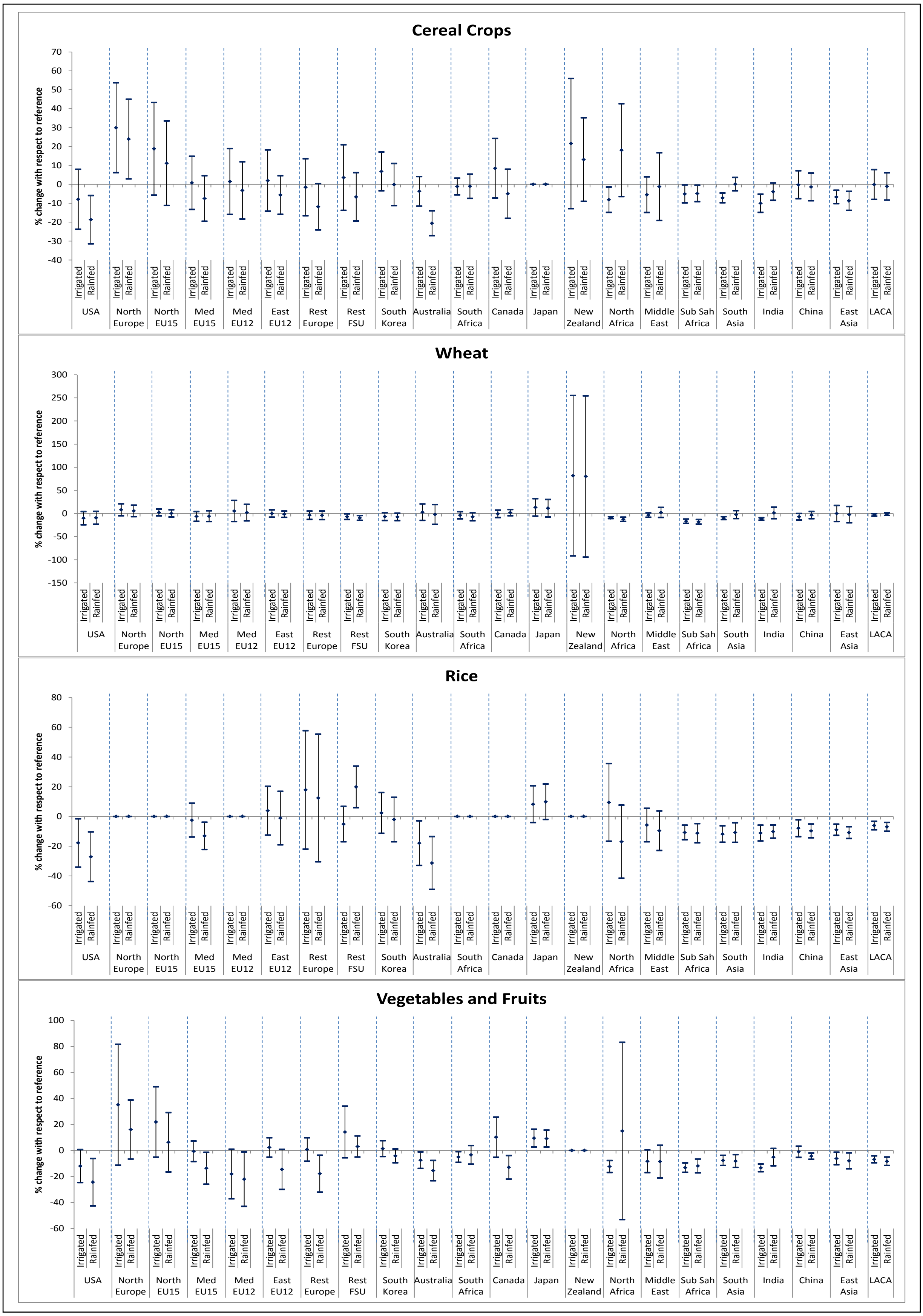


Figure 22: Impacts on land productivity by crop and region for RCP 8.5 in 2050 (irrigated and rainfed land)

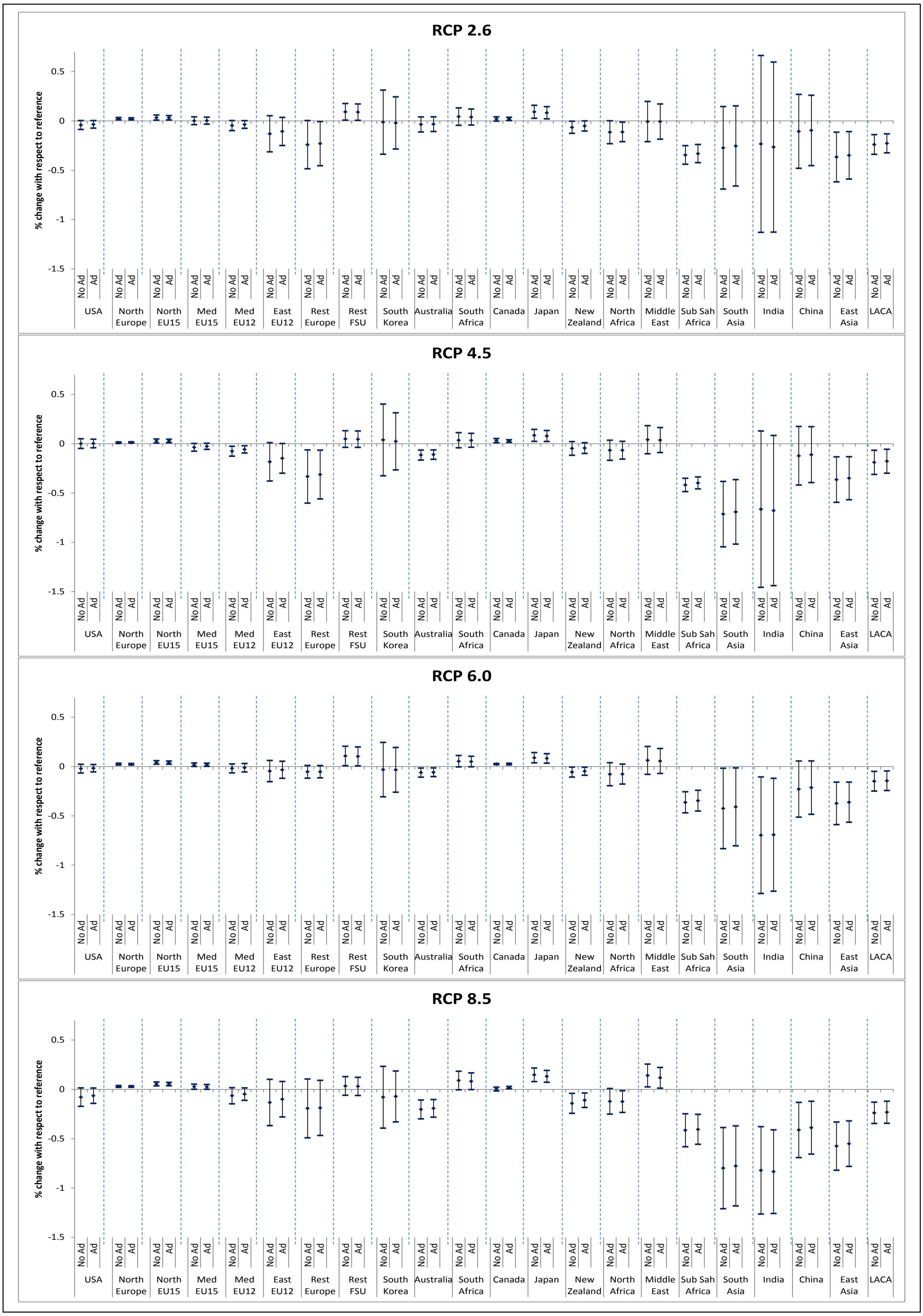


Figure 23: Impacts on real GDP by region and RCP in 2050 (with and without adaptation)

5 Simulation results

We run simulations for each RCP and each crop model considering two cases. The Adaptation case where farmers are allowed to expand irrigation and the No Adaptation case where there is no irrigation expansion. Simulation results are reported with (Ad case) and without (NoAd case) irrigation expansion for each RCP in deviations from the baseline (no climate change). The simulation period is 2008–2050, but comments will focus on 2050 unless otherwise specified. As in the case of initial impacts, we summarise results for each region in the model with the average and a 95% confidence interval computed using results from the five AgMIP crop models.

Figure 23 reports GDP impacts. Deviations are moderate and range between -1.45% and 0.66% with respect to the baseline with the highest GDP losses in South Asia and India and potential gains especially in the Former Soviet Union countries and the Middle East. In the No Adaptation case, results show lower variability for high latitude countries where climate change impacts are also lower or slightly positive. Conversely, low latitude (in particular Asian) countries show higher average negative impacts along with wider confidence intervals. This trend is reinforced as we move from a low (RCP2.6) to a high (RCP8.5) climate change impact scenario. When irrigation can be expanded in the Adaptation case, macroeconomic results do not differ much from the No Adaptation case, although tiny average GDP gains can be observed in many regions: Sub Saharan Africa, South Asia, China, East Asia, Mediterranean and East Europe, South Korea, Australia, USA and Canada, in particular in RCP 8.5.

Effects of climate change and of irrigation are more evident looking directly at changes in crop production, which include the endogenous market adjustments embedded in the ICES model (**Figure 24**). In the No Adaptation case cereal production change ranges between -1% and -0.2%, that of wheat between -0.7% and -0.3%, that of rice between -1.2% and -0.3%, that of vegetables and fruits between -1% and -0.3%. On average, there would be a slight world output decrease for the four crops considered. Production losses are concentrated in the USA, Australia, part of Europe and Asian countries (with a partial exception of East Asian wheat) and in Sub-Saharan Africa. Production contractions however are much smaller than the initial yield losses.

This has two explanations. On the one hand, irrespectively upon the lower land productivity, demand for agricultural commodities is sustained by increasing world population. The negative impact of climate change on yields thus translates mostly into higher crop prices, rather than lower production. **Figure 25** shows this for the pDSSAT crop model in RCP 8.5 where this effect is particularly evident.

On the other hand, the higher the crop price, the higher the amount of land farmers would allocate to the production of that crops. This occurs as crop prices are linked to land rents. This mechanism prevents huge disinvestment in the cultivation of the most negatively affected crops. **Figure 26** exemplifies this fact for North EU15 and Figure **27** for Latin America and the Caribbean. In both areas, vegetables and fruits are the crops most negatively affected by climate change (left panel in figure), and land demand increases more accordingly (right panel in figure).[34]

[34] In the North EU15, apparently, land demand to produce rice would increase even more, but in fact this large increase is simply due to the fact that total rice production in the area is extremely low which easily induces huge % changes in front of small perturbations.

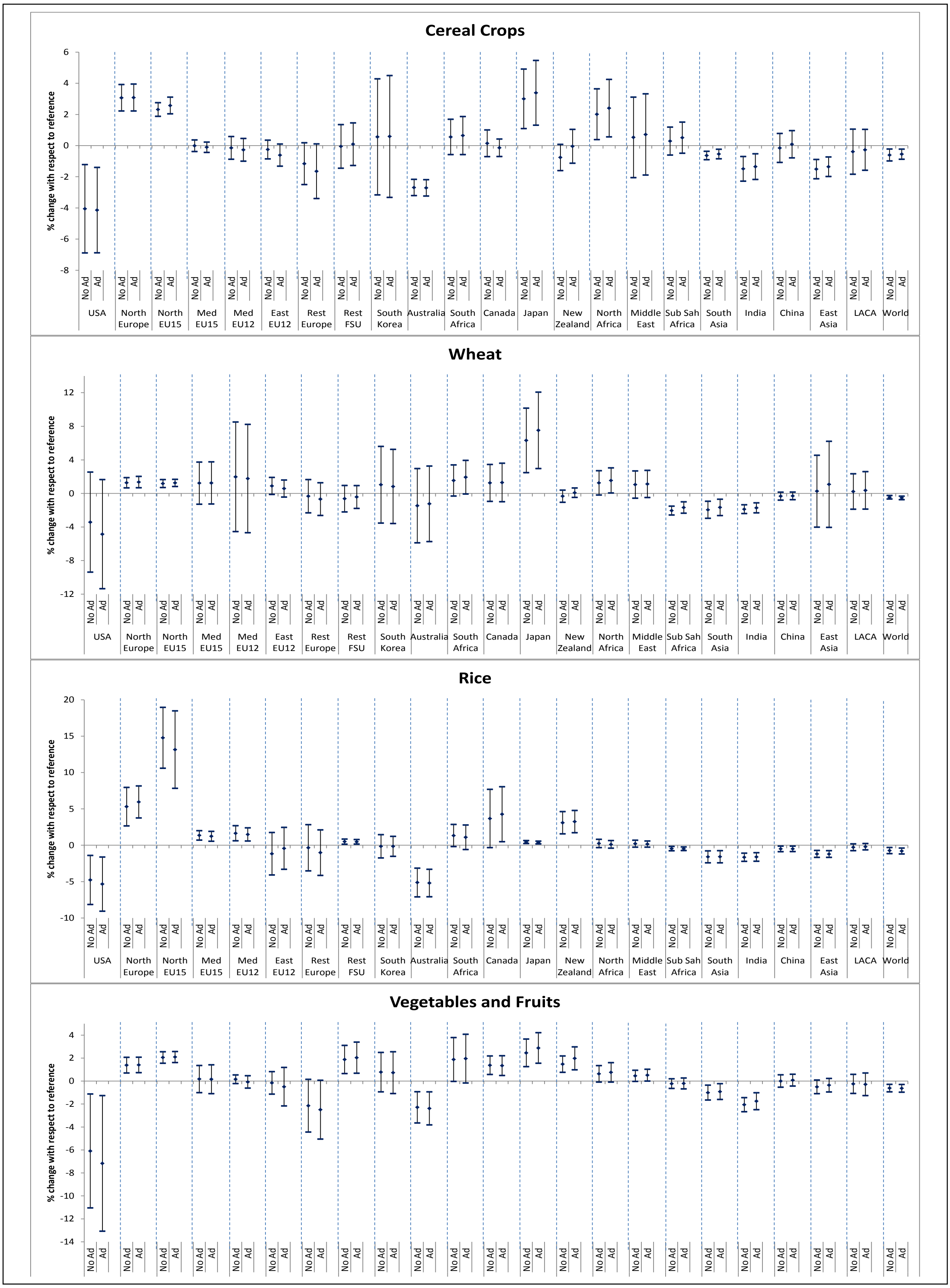
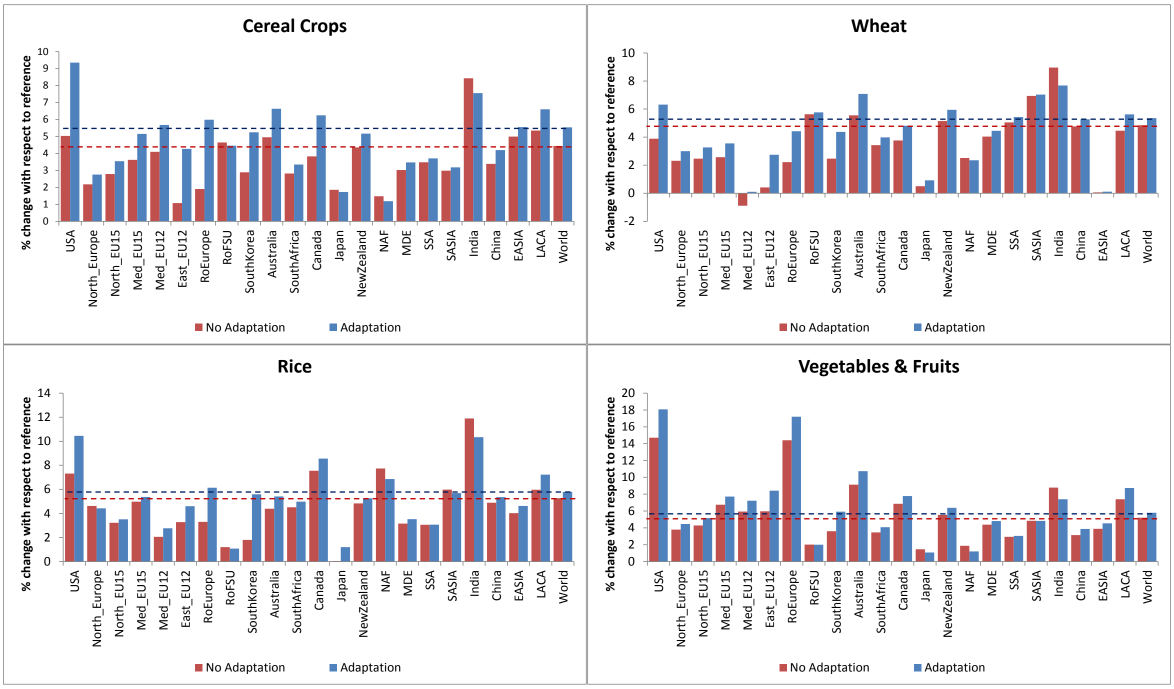


Figure 24: Impacts on crop production by region for RCP 8.5 in 2050 (with and without adaptation)



Note: CGE model results obtained using data from pDSSAT. The dashed lines show the change in world prices

Figure 25: Impacts on crop prices by region for RCP 8.5 in 2050 (with and without adaptation)

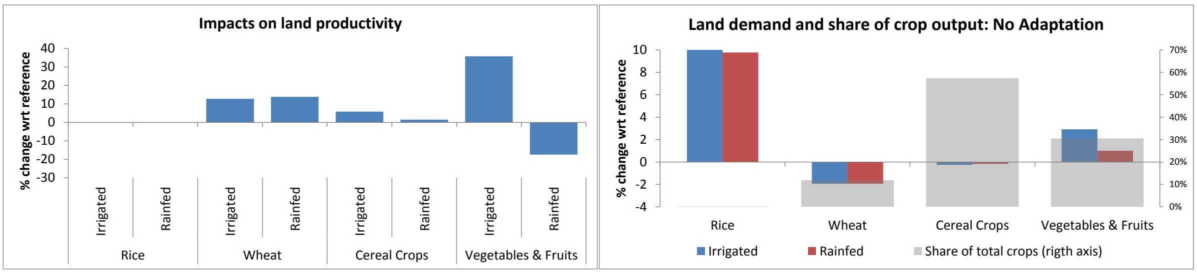


Figure 26: Impacts on land productivity and land demand for North EU15 (pDSSAT)

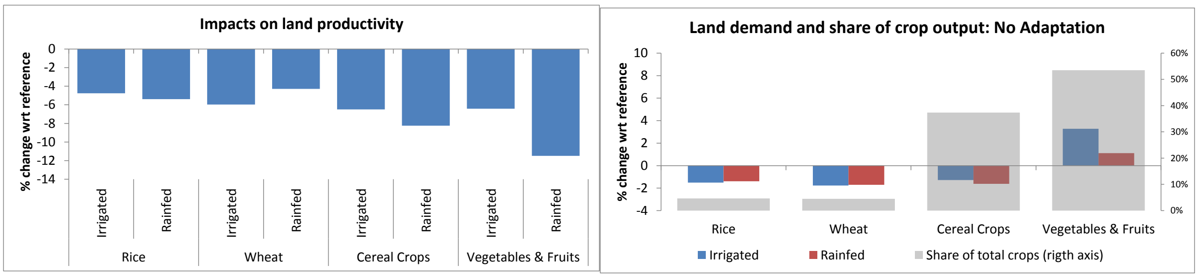


Figure 27: Impacts on land productivity and land demand for Latin America and the Caribbean (pDSSAT)

Finally, international trade also matters, influencing demand patterns. In general, regions with lower increases in domestic prices compared with world prices would also export more and vice versa. Climate change will thus reallocate agricultural production from most to less affected sectors and countries.

In the Adaptation case, only world cereal crops production is higher than with rigid irrigation. This does not apply however to each single region as the final outcome depends on the effects on international markets of agricultural commodities. The possibility to expand irrigation, which depends upon the initial level of irrigated and irrigable land and the cost of irrigation, not to mention obviously the initial climate impacts, determines eventually the winners and the losers of adaptation. Note in particular that, with few exceptions, agricultural prices are higher with than without irrigation expansion, as this option is particularly costly. In general, flexible irrigation (Adaptation), tends to increase crop production in developing countries and decrease that in developed countries, in particular the USA, witnessing more competitive production in the former than in the latter. But this very much depends on the crop and on the region.

6 Reduced-form impact functions

Taking advantage of the amount of information generated by the simulations, it is possible to estimate reduced-form functions linking the future changes in agricultural output produced by the ICES-IRR model at the world and regional level, to temperature increase. In the specific, we calibrate a cubic reduced-form damage functions for each crop in ICES-IRR as shown in equation (1):[35]

$$D_j = \alpha_1 dt + \alpha_2 dt^2 + \alpha_3 dt^3$$

Where *D* is the damage on output expressed as deviation from the baseline with *j=Adaptation, No Adaptation*; *dt* is the change in temperature and α_i are the coefficients of the cubic function. We first fit a curve for each crop model and then run a pooled estimation with all crop model results to represent the average damage function with and without adaptation for each RCP. An example of these reduced-form damage functions is shown in **Figure 28** for cereal crops at the World level.

The y-axis denotes changes in output with respect to the baseline case while the x-axis displays the changes in global temperature with respect to pre-industrial levels. Each crop model observation is represented by a single marker for every year in the simulation period showing the No adaptation (solid marker) and Adaptation (empty marker) cases. Therefore, we count on 43 observations for each case and 215 observations when pooling all simulation results to estimate the average damage function with and without adaptation. With the exception of LPJ-Guess, all crop models, and accordingly also the averaged pooled estimation, show a positive effect from expanding irrigation services in world cereal crops production.

The regional picture is however differentiated as shown by **Figure 29**. For instance, within the EU, only in Northern EU 15 irrigation increases the agricultural output according to the input from all the from five crop models, while the remaining three EU regions (Mediterranean EU15, Mediterranean EU12 and Eastern EU12) show the opposite outcome on average. South Asia would benefit from irrigation when temperature increases by more than 1.7°C, even though results for the adaptation and no adaptation cases are very close considering all crop models separately. Latin America and the Caribbean do not show noticeable differences between the two cases (on average) up to an increase of 2°C; then irrigation could improve cereal crop production after that temperature level considering in particular the inputs of pDSSAT, LPJ-GUESS, and EPIC.[36]

This naturally depends upon the yield impact stemming from the crop models, as for some the advantage of using irrigation is smaller than in other, but most importantly on the already commented effects on international trade of agricultural commodities.

[35] We estimated as well quadratic damage functions for all cases but we selected the cubic form since it provides a closer fit to the simulated data.

[36] For the other crops refer to **Figure 32, Figure 33,** and **Figure 34** of of Appendix C

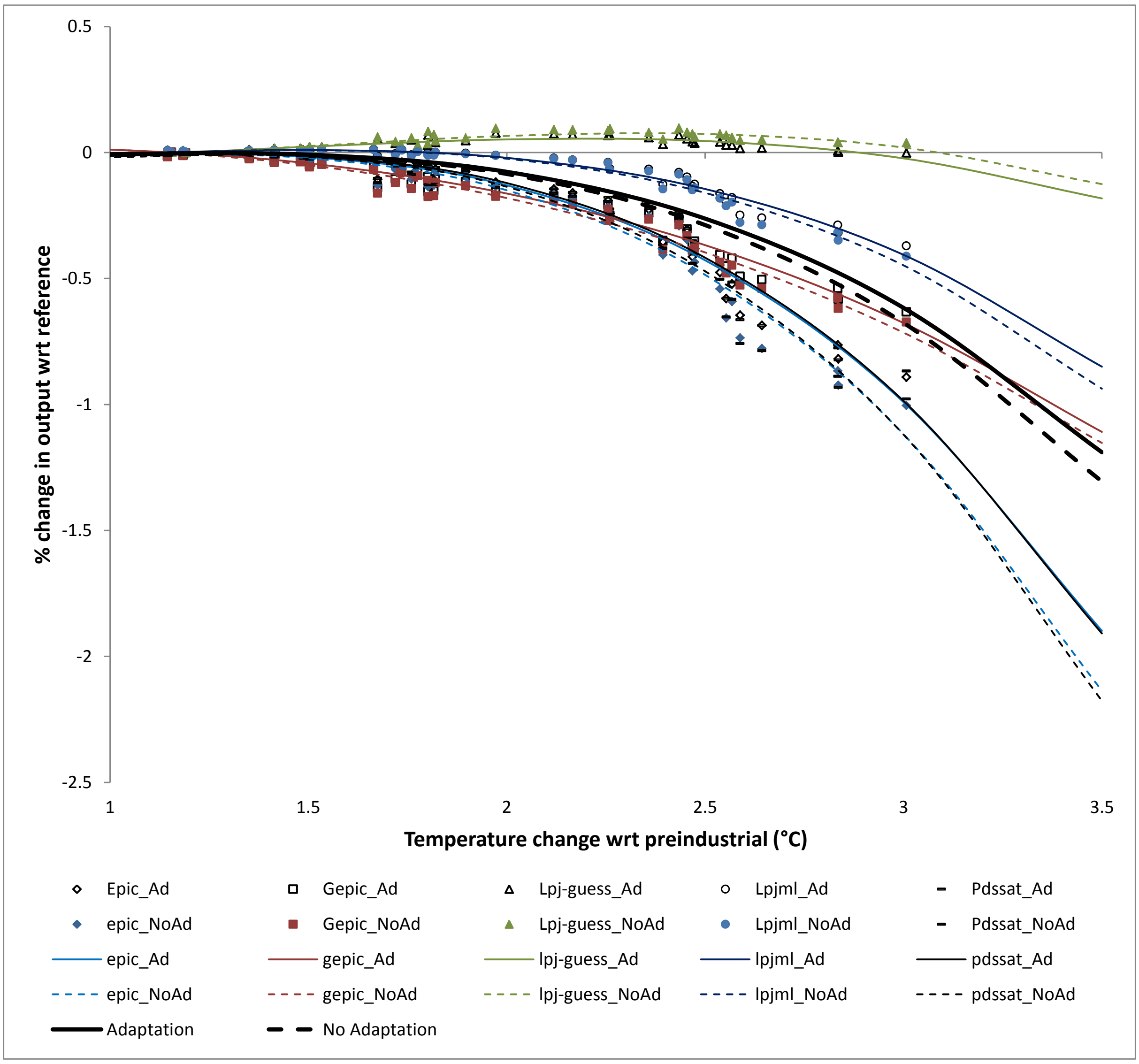


Figure 28: Impacts on World cereal crops production for RCP 8.5 (with and without adaptation)

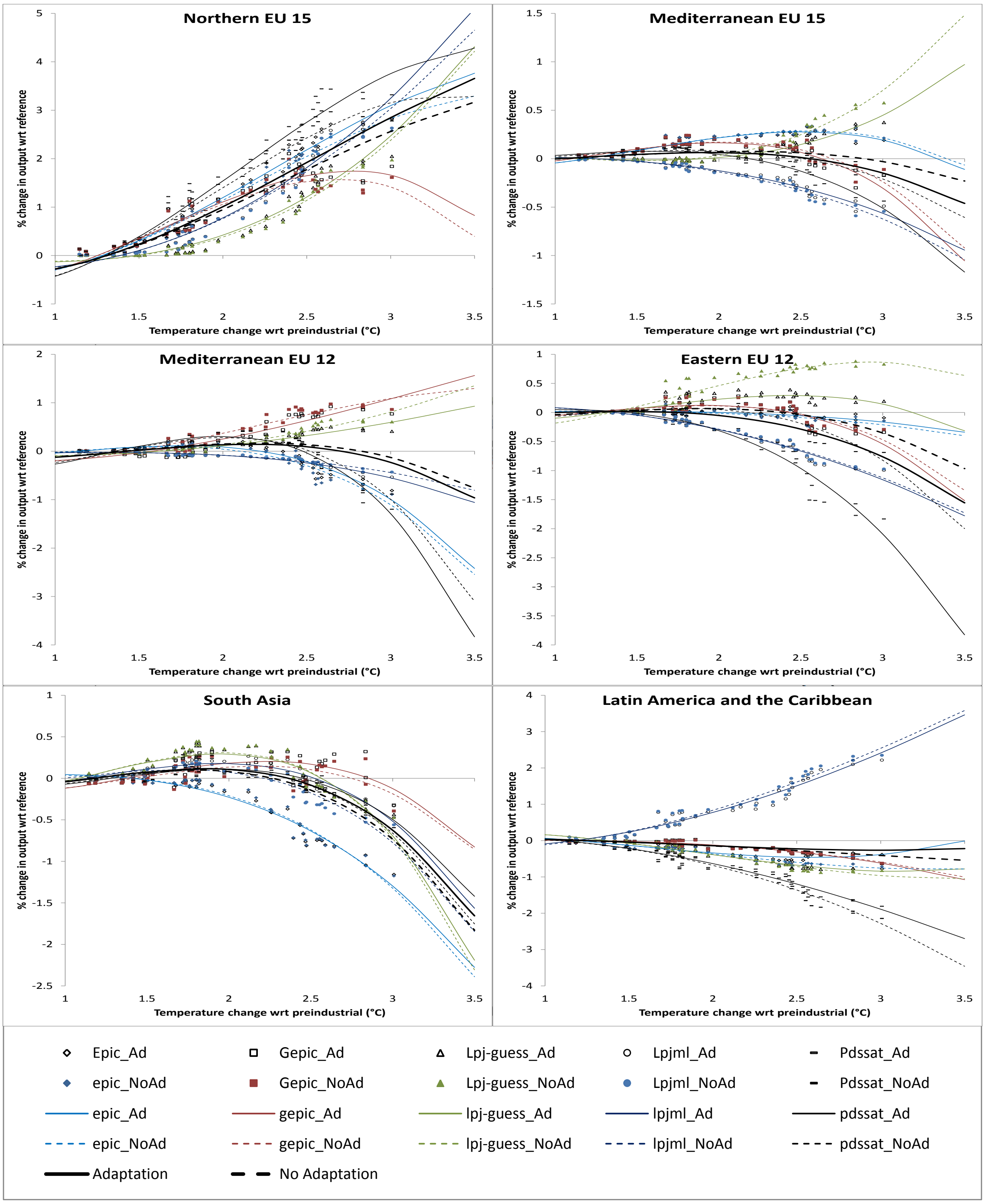


Figure 29: Impacts on cereal crops production in selected regions for RCP 8.5 (with and without adaptation)

Figure 28 and Figure **29** are good examples of the reduced-form damage functions that can be estimated considering the Adaptation and No Adaptation cases for RCP8.5. We use the same methodology to estimate reduced-forms for each crop in ICES-IRR by pooling all simulation results of the five crop models by RCP. This allows providing ranges for the economy-wide impacts of climate change on world agricultural output using the temperature increase from selected climatic models. In order to do so we selected the global mean average temperature change of two climate models to represent the minimum and maximum for

RCP2.6 (MRI-CGCM3[37] and MIROC-ESM-CHEM[38]) and for RCP8.5 (MIROC-ESM-CHEM and CNRM-CM5[39]).[40]

Figure 30 depicts the projections of those intervals for each crop on the ICES-IRR model, considering a range for RCP 2.6 and RCP 8.5 from 2010 to 2060.

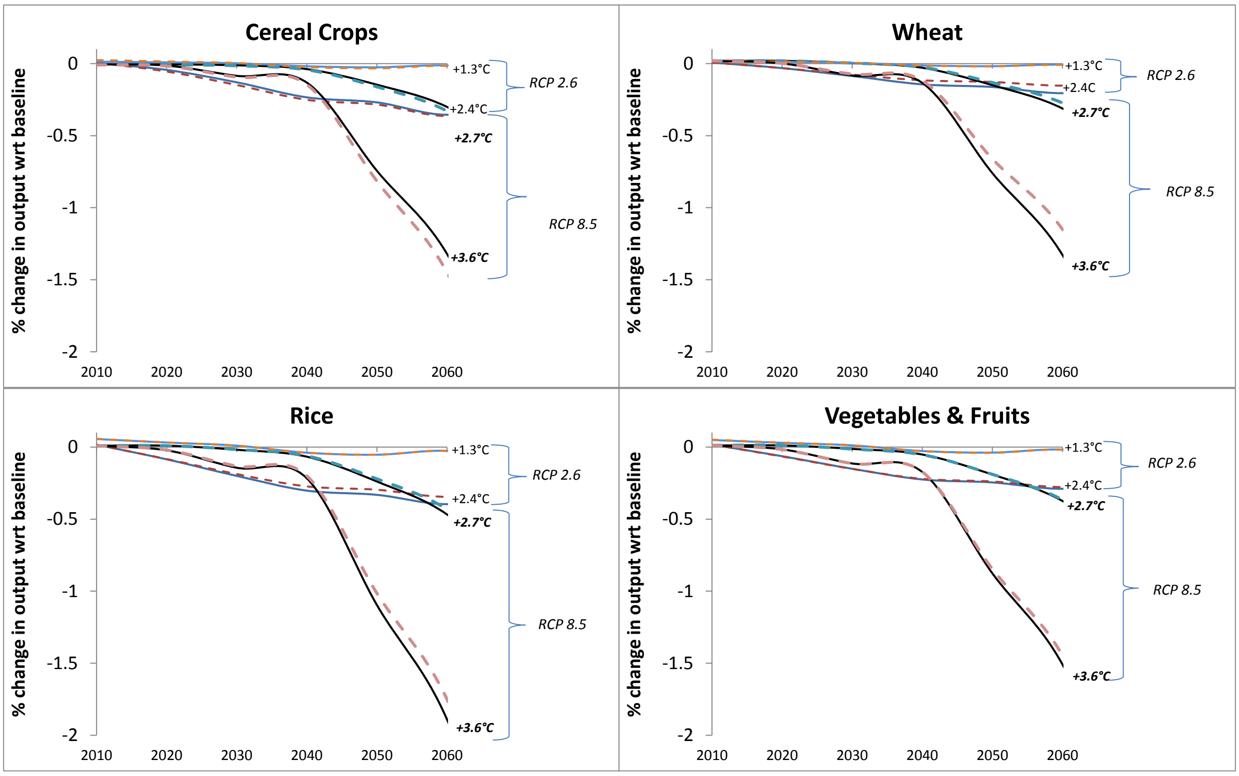


Figure 30: Impacts on World agricultural production for RCP 2.6 and RCP 8.5 (with and without adaptation)

As expected there is an overlapping of results during the first three decades, and after that the interval for RCP 8.5 becomes wider, while variation for RCP 2.6 are within a narrow interval given that it is a stabilization scenario.

Figure 30 highlights the fact that at the world level only cereal crops would increase output when irrigation is used worldwide as an adaptation measure. For wheat and rice world output would slightly reduce, while for vegetables and fruits both cases (adaptation and No Adaptation) show a very close outcome. We acknowledge that ICES-IRR simulations run until 2050 and projections of damage after this year should be analysed with care since they are an extrapolation of previous trends. Further research plans to extend the simulation horizon of ICES-IRR to address this limitation.

---

37 Yukimoto et al. (2012)
38 Watanabe et al. (2011)
39 Voldoire et al. (2011)
40 We are gratefully thankful to Clare Goodess and Colin Harpham from the School of Environmental Sciences at the University of East Anglia who provided a set temperature data for RCPs 2.6 and 8.5 from five Global Circulation Models that participated at the Coupled Model Intercomparison Project Phase 5 (CMIP5).

7 Conclusions

Agricultural activities are particularly sensitive to climatic variables such as temperature, precipitation, water availability and frequency/intensity of extreme weather events. Hence, it is expected that climatic changes, affecting all these variables, will increase the stress on agricultural production and potentially food security.

Sufficient water availability is obviously a major factor to guarantee a stable agricultural production, therefore, the expansion of irrigated areas or higher irrigation efficiency could play a key role in climate change adaptation in agriculture. At the same time, irrigation is particularly costly and its widespread use could trigger indirect effects due to higher costs and also due to an increased demand for irrigation services which could eventually turn irrigation into an expensive option. This paper describes a modelling approach to include irrigation as a planned adaptation strategy within the ICES model, a multi-country, multi-sector, recursive dynamic CGE model of the world economy. The new specification modifies the model land supply structure in order to consider different land rents and imperfect flexible land conversion between pasture and cropland, irrigable and rainfed land and among different crop industries. Moreover, it takes into account the additional capital, operational and maintenance costs that farmers face when they decide to expand irrigation.

This is a novelty compared to the existing literature, in which few studies analyse the role of irrigation as an adaptation strategy (Berittella et al., 2006; Calzadilla et al., 2013), and, most importantly, treat irrigation as an exogenous variable rather than as an autonomous farmers' decision.

More specifically, the present study compares a no-adaptation scenario, where climate change impacts are imposed assuming fixed amount of irrigated and rainfed land and an adaptation scenario, in which farmers are allowed to expand irrigated land to contrast yield losses from climate change.

In the no-adaptation scenario lower latitude countries are those most negatively affected either in terms of decreased crop production or lower GDP, that can reduce by -1.4% in Asian countries by mid-century. Some higher latitude countries, e.g. Northern EU and the Former Soviet Union could experience slight GDP gains as a consequence of higher crop yields. Against this background, irrigation expansion can be an effective adaptation option in particular for lower latitude countries enabling higher production and lower GDP losses. However, gains compared to the no adaptation case are tiny in percentage term. Converting rainfed into irrigable land and expanding irrigation services is costly and in the end increases further agricultural prices which compresses demand expansion. The final effect of flexible irrigation is a reallocation of crop production from developed to developing countries which are advantaged in relative terms by a combination of lower irrigation costs with the initial climatic impacts.

References

Armington, P. S. (1969). A theory of demand for products distinguished by place of production. IMF Staff Papers 16 (1), 159-178.

Baker, J. (2011). The impact of including water constraints on food production within a CGE framework. Thesis (S.M. in Technology and Policy). Available online at: http://hdl.handle.net/1721.1/68446, Massachusetts Institute of Technology, Engineering Systems Division, Technology and Policy Program.

Berrittella, M., A. Hoekstra, K. Rehdanz, R. Roson, and R. Tol (2007). The economic impact of restricted water supply: A computable general equilibrium analysis. Water Research 41 (8), 1799-1813.

Berrittella, M., K. Rehdanz, R. Roson, and R. Tol (2005). Virtual water trade in a general equilibrium analysis. Paper presented at 8th Annual Conference on Global Economic Analysis June 9-11, 2005, Lubeck, Germany.

Berrittella, M., K. Rehdanz, R. Roson, and R. Tol (2008). The economic impact of water taxes: A computable general equilibrium analysis with an international data set. Water Policy 10 (3), 259-271.

Berrittella, M., K. Rehdanz, and R. Tol (2006). The economic impact of the south-north water transfer project in China: A computable general equilibrium analysis. Working Papers FNU-117, Research Unit Sustainability and Global Change, Hamburg University and Centre for Marine and Atmospheric Science.

Berrittella, M., K. Rehdanz, R. Tol, and Y. Zhang (2008). The impact of trade liberalization on water use: A computable general equilibrium analysis. Journal of Economic Integration 23 (3), 631-655.

Bondeau, A., P. C. Smith, S. O. N. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Muller, and M. Reichstein (2007). Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology 13, 679-706.

Bosello, F., L. Campagnolo, and F. Eboli (2013). Climate change and adaptation: The case of Nigerian agriculture. Working Papers 2013.35, Fondazione Eni Enrico Mattei.

Bosello, F. and R. Parrado (2014). Climate change impacts and market driven adaptation: The costs of inaction including market rigidities. Working Papers 2014.64, Fondazione Eni Enrico Mattei.

Bosetti, V., E. De Cian, A. Sgobbi, and M. Tavoni (2009). The 2008 WITCH model: New model features and baseline. Working Papers 2009.85, Fondazione Eni Enrico Mattei.

Burniaux, J.-M. and T. P. Truong (2002). GTAP-E: An energy-environmental version of the GTAP model. GTAP Technical Paper 16, GTAP Technical Paper.

Calzadilla, A., K. Rehdanz, and R. S. Tol (2011). Water scarcity and the impact of improved irrigation management: A computable general equilibrium analysis. Agricultural Economics 42, 305-323.

Calzadilla, A., T. Zhu, K. Rehdanz, R. S. Tol, and C. Ringler (2013). Economy-wide impacts of climate change on agriculture in Sub-Saharan Africa. Ecological Economics 93, 150-165.

Decaluwé, B., A. Patry, and L. Savard (1999). When water is no longer heaven sent: Comparative pricing analysis in an AGE model. Cahiers de recherche 9908, Université Laval, Département d'économique.

Diao, X., A. Dinar, T. Roe, and Y. Tsur (2008). A general equilibrium analysis of conjunctive ground and surface water use with an application to Morocco. Journal of Agricultural Economics 38 (2), 117-135.

Dixon, P. B., M. T. Rimmer, and G. Wittwer (2009). Modelling the Australian government's buyback scheme with a dynamic multi-regional CGE model. Working Papers G-186, Victoria University, Centre of Policy Studies/IMPACT Centre.

Dudu, H., E. H. Cakmak, and S. Saracoglu (2010). Climate change and irrigation in Turkey: A CGE approach. Iktisat Isletme ve Finans 25 (286), 9-33.

Elliott, J., C. Muller, D. Deryng, J. Chryssanthacopoulos, K. J. Boote, M. Buchner, I. Foster, M. Glotter, J. Heinke, T. Iizumi, R. C. Izaurralde, N. D. Mueller, D. K. Ray, C. Rosenzweig, A. C. Ruane, and J. Sheffield (2015). The Global Gridded Crop Model Intercomparison: Data and modeling protocols for Phase 1 (v1.0). Geoscientific Model Development 8, 261-277.

Elliott J, Glotter M, Best N, Kelly D, Wilde M, Foster I (2013) The parallel system for integrating impact models and sectors (pSIMS). Proceedings of the Conference on Extreme Science and Engineering Discovery Environment: Gateway to Discovery (XSEDE '13), Association for Computing Machinery, 21:1–8.

Food and Agricultural Organization (FAO) (1997). Irrigation potential in Africa: A basin approach. Rome: Food and Agricultural Organization of the United Nations.

Food and Agricultural Organization (FAO) (2009). Global agriculture towards 2050. High level expert forum - How to feed the world in 2050. Rome: Food and Agricultural Organization of the United Nations.

Gassman PW, et al. (2004), Historical development and applications of the EPIC and APEX models. ASAE/CSAE meeting paper no. 042097. Available at www.card.iastate.edu.

Golub, A. and T. Hertel (2012). Modeling land-use change impacts of biofuels in the GTAP-BIO framework. Climate Change Economics 3(3).

Gomez, C., D. Tirado, and J. Rey-Maquieira (2004). Water exchange versus water work: Insights from a computable general equilibrium model for the Balearic Islands. Water Resources Research 40(10).

Gurgel, A., J. M. Reilly, and S. Paltsev (2007). Potential land use implications of a global biofuels industry. Journal of Agricultural and Food Industrial Organization 5(2), 1-36.

Hertel, T., A. Golub, A. Jones, M. O'Hare, R. Pelvin, and D. Kammen (2010). Effects of U.S. maize ethanol on global land use and greenhouse gas emissions: Estimating market-mediated responses. BioScience 60(3), 223-231.

Hertel, T. W. and M. Tsigas (1999). Structure of GTAP. In T. W. Hertel (Ed.), Global trade analysis: Modeling and applications. Cambridge University Press.

Izaurralde RC, et al. (2006), Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecol Modell 192(3-4):362–384.

Iglesias, A., S. Quiroga, and A. Diz (2011). Looking into the future of agriculture in a changing climate. European Review of Agricultural Economics 38(3), 427-447.

Iglesias, A., S. Quiroga, A. Diz, and L. Garrote (2011). Adapting agriculture to climate change. Economia Agraria y Recursos Naturales 11(2), 109-122.

International Fund for Agricultural Development (2010). Rural Poverty Report 2011. Rome: International Fund for Agricultural Development.

International Institute for Applied System Analysis (IIASA) (2015). SSP Database, Version 1.0. Available online at: https://tntcat.iiasa.ac.at/SspDb.

Jones, C.D., Hughes, J.K., Bellouin, N., Hardiman, S.C., Jones, G.S., Knight, J. Liddicoat, S., O'Connor, F.M., Andres, R.J., Bell, C., Boo, K.O., Bozzo, A., Butchart, N., Cadule, P., Corbin, K.D., Doutriaux-Boucher, M., Friedlingstein, P., Gornall, J.,Gray, L.,Halloran, P.R.,Hurtt, G., Ingram,W.J., Lamarque, J.F., Law, R.M., Meinshausen, M.,Osprey, S., Palin, E.J., Parsons Chini, L.,Raddatz, T., Sanderson, M.G., Sellar, A.A., Schurer, A.,Valdes, P.,Wood, N., Woodward, S., Yoshioka, M., Zerroukat, M., (2011), The HadGEM2-ES implementation of CMIP5 centennial simulations. Geosci. Model Dev. 4, 543–570.

Jones JW, et al. (2003) The DSSAT cropping system model. Eur J Agron 18(3-4):235–265.Fellmann, T. (2012). The assessment of climate change-related vulnerability in the agricultural sector: reviewing conceptual frameworks. In A. Meybeck, J. Lankoski, S. Redfern, N. Azzu, and V. Gitz (Eds.), FAO/OECD Workshop: Building Resilience for Adaptation to Climate Change in the Agriculture Sector, 37-61.

Juana, J., K. Strzepek, and F. Kirsten (2011). Market efficiency and welfare effects of inter-sectoral water allocation in South Africa. Water Policy 13(2), 220-231.

Koopman, J. F., O. Kuik, R. S. Tol, and R. Brouwer (2015). Water scarcity from climate change and adaptation response in an international river basin context. Climate Change Economics 06(01).

Lennox, J. and O. Diukanova (2011). Modelling regional general equilibrium effects and irrigation in Canterbury. Water Policy 13(2), 250-264.

Letsoalo, A., J. Blignaut, T. de Wet, M. de Wit, S. Hess, R. S. Tol, and J. Van Heerden (2007). Triple dividends of water consumption charges in South Africa. Water Resources Research 43(5), 1-32.

Liu J, et al. (2007), GEPIC—modeling wheat yield and crop water productivity with high resolution on a global scale. Agr Syst 94(2):478–493.

Liu, J., T. W. Hertel, F. Taheripour, T. Zhu, and C. Ringler (2013). Water Scarcity and International Agricultural Trade. 2013 Annual Meeting, August 4-6, 2013, Washington, D.C. 155248, Agricultural and Applied Economics Association.

Liu, J., T. W. Hertel, F. Taheripour, T. Zhu, and C. Ringler (2014). International trade buffers the impact of future irrigation shortfalls. Global Environmental Change 29, 22-31.

Long, S. P., E. A. Ainsworth, A. D. B. Leakey, J. Nosberger, and D. R. Ort (2006). Food for thought: Lowerthan-expected crop yield stimulation with rising CO2 concentrations. Science 312 (5782), 1918-1921.

Narayanan, B., A. Aguiar, and R. McDougall (Eds.) (2012). Global Trade, Assistance, and Production: The GTAP 8 Data Base. Purdue University: Center for Global Trade Analysis.

Nelson, G. C., M. W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. D. Robertson, S. Tokgoz, T. Zhu, T. B. Sulser, C. Ringler, S. Msangi, and L. You (2010). Food security, farming, and climate change to 2050: Food security, farming, and climate change to 2050. IFPRI Research Monograph. Washington, D.C.: International Food Policy Research Institute (IFPRI).

Oliva, R. (2013). Climate change, water scarcity in agriculture and their economy-wide impacts. A CGE model analysis. In Economic modeling of water resources in agriculture. Top-down and bottom-up approaches. PhD Thesis in Science and Management of Climate Change, Ca' Foscari University, Venice. Available online at: http://hdl.handle.net/10579/2244.

O'Neill, B., E. Kriegler, K. Riahl, K. Ebi, S. Hallegatte, T. Carter, R. Mathur, and D. van Vuuren (2014). A new scenario framework for climate change research: The concept of shared socio-economic pathways. Climatic Change 122, 387-400.

Parrado R. and De Cian E. (2014) " Technology spillovers embodied in international trade: Intertemporal, regional and sectoral effects in a global CGE framework", Energy Economics, 41(2014): 76-89.

Parry, M., C. Rosenzweig, A. Iglesias, M. Livermore, and G. Fischer (2004). Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change 14(1), 53-67.

Peterson, D. C., G. Dwyer, D. Appels, and J. Fry (2004). Modelling water trade in the southern Murray-Darling Basin. Staff Working Papers 31925, Productivity Commission.

Roe, T., A. Dinar, Y. Tsur, and X. Diao (2005). Feedback links between economy-wide and farm-level policies: With application to irrigation water management in Morocco. Journal of Policy Modeling 27(8), 905-928.

Rosenzweig, C., J. Elliott, D. Deryng, A. Ruane, C. Mueller, A. Arneth, K. Boote, C. Folberth, M. Glotter, N. Khabarov, K. Neumann, F. Piontek, T. Pugh, E. Schmid, E. Stehfest, H. Yang, and J. Jones (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proceedings of the National Academy of Sciences 111, 3268-3273.

Rosenzweig, C., J. Jones, J. Hatfield, A. Ruane, K. Boote, P. Thorburn, J. Antle, G. Nelson, C. Porter, S. Janssen, S. Asseng, B. Basso, F. Ewert, D. Wallach, G. Baigorria, and J. Winter (2013). The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. Agricultural and Forest Meteorology 170, 166-182.

Sands, R. D., H. Forster, C. A. Jones, and K. Schumacher (2014). Bio-electricity and land use in the Future Agricultural Resources Model (FARM). Climatic Change 123 (3-4), 719-730.

Smith B, et al. (2001), Representation of vegetation dynamics in the modeling of terrestrial ecosystems: Comparing two contrasting approaches within European climate space. Glob Ecol Biogeogr 10(6):621–637.

Schmitz, C., H. van Meijl, P. Kyle, G. C. Nelson, S. Fujimori, A. Gurgel, P. Havlik, E. Heyhoe, D. M. d'Croz, A. Popp, R. Sands, A. Tabeau, D. van der Mensbrugghe, M. von Lampe, M. Wise, E. Blanc, T. Hasegawa, A. Kavallari, and H. Valin (2014). Land-use change trajectories up to 2050: Insights from a global agro-economic model comparison. Agricultural Economics 45(1), 69-84.

Strzepek, K., G. Yohe, R. S. Tol, and M. Rosegrant (2008). The value of the high aswan dam to the Egyptian economy. Ecological Economics 66(1), 117-126.

Taheripour, F., T. Hertel, and J. Liu (2013a). Introducing water by river basin into the GTAP-BIO model: GTAP-BIO-W. GTAP Working Papers 77, Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University.

The World Bank (2012). World Development Indicators. Available online at: http://data.worldbank.org/.

Tubiello, F. N., J. S. Amthor, K. J. Boote, M. Donatelli, W. Easterling, G. Fischer, R. M. Gifford, M. Howden, J. Reilly, and C. Rosenzweig (2007). Crop response to elevated CO2 and world food supply: A comment on “Food for Thought... by Long et al., Science 312:1918-1921, 2006”. European Journal of Agronomy 26(3), 215-223.

van Heerden, J. H., J. Blignaut, and M. Horridge (2008). Integrated water and economic modelling of the impacts of water market instruments on the South African economy. Ecological Economics 66(1), 105-116.

Villoria, N., J. Elliott, C. Muller, J. Shin, L. Zhao, and C. Song (2014). Rapid aggregation of globally gridded crop model outputs to facilitate cross-disciplinary analysis of climate change impacts in agriculture. Available online at: https://mygeohub.org/tools/agmip/.

Voldoire, A., E. Sanchez-Gomez, D. Salas y Mélia, B. Decharme, C. Cassou, S.Sénési, S. Valcke, I. Beau, A. Alias, M. Chevallier, M. Déqué, J. Deshayes, H. Douville, E. Fernandez, G. Madec, E. Maisonnave , M.-P. Moine, S. Planton, D.Saint-Martin, S. Szopa, S. Tyteca, R. Alkama, S. Belamari, A. Braun, L. Coquart, F. Chauvin, (2011), The CNRM-CM5.1 global climate model: description and basic evaluation, Clim. Dyn., accepted, DOI:10.1007/s00382-011-1259-y.

von Lampe, M., D. Willenbockel, H. Ahammad, E. Blanc, Y. Cai, K. Calvin, S. Fujimori, T. Hasegawa, P. Havlik, E. Heyhoe, P. Kyle, H. Lotze-Campen, D. Mason d'Croz, G. C. Nelson, R. D. Sands, C. Schmitz, A. Tabeau, H. Valin, D. van der Mensbrugghe, and H. van Meijl (2014). Why do global long-term scenarios for agriculture differ? An overview of the AgMIP Global Economic Model Intercomparison. Agricultural Economics 45(1), 3-20.

S. Watanabe, T. Hajima, K. Sudo, T. Nagashima, T. Takemura, H. Okajima, T. Nozawa, H. Kawase, M. Abe, T. Yokohata, T. Ise, H. Sato, E. Kato, K. Takata, S. Emori, and M. Kawamiya, (2011), MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments, Geosci. Model Dev., 4, 845-872, 2011, http://www.geosci-model-dev.net/4/845/2011/

You, G. J.-Y. and C. Ringler (2010). Hydro-economic modeling of climate change impacts in Ethiopia. IFPRI Discussion Papers 960, International Food Policy Research Institute (IFPRI).

Yukimoto, S., Adachi, Y., Hosaka, M., Sakami, T, Yoshimura, H. Hirabara, M., Tanaka, T., Shindo, E., Tsujino, H. Deushi, M., Mizuta, R. Yabu, S., Obata, A., Nakano, H., Koshiro, T., Ose, T., Kitoh, A., (2012), A New Global Climate Model of the Meteorological Research Institute: MRI-CGCM3;Model Description and Basic Performance; Journal of the Meteorological Society of Japan, Vol. 90A, No. 0. (2012), pp. 23-64, doi:10.2151/jmsj.2012-a02

Appendix A: The elasticity of transformation between rainfed and irrigable land

The elasticity of transformation between rainfed and irrigable land is calibrated to replicate the irrigated land supply elasticity in Baker (2011). In particular, he estimates this elasticity (Equation A1) for the US using data of harvested irrigated land coverage and irrigated land rents from the USDA National Agricultural Statistics Service (NASS) from 1997 to 2002.

$$\varepsilon_{\text{supply}} = \frac{\%\Delta \text{ irrigated land}}{\%\Delta \text{ irrigated land rent}} \quad \text{(A1)}$$

Then, he computes the supply elasticity for all other EPPA regions, by assuming the percent change in irrigated land rents for the US as a proxy for the rest of the world. Percent changes in harvested irrigated land coverage are taken from data developed by Freydank and Siebert (2008). Table A1 shows the supply elasticities in Baker (2011).

Region	ε_{supply}
USA	0.23
CAN	0.56
MEX	0.24
JPN	-
ANZ	0.33
EUR	0.04
ROE	0.05
RUS	-
ASI	0.16
CHN	0.18
IND	0.78
BRA	0.9
AFR	0.31
MES	0.27
LAM	0.06
REA	0.3
World	0.32

Table A1: The supply elasticity in Baker (2011)

We use the average irrigated land supply elasticity in Baker (2011) to calibrate the elasticity of transformation between rainfed and irrigable land. As shown in Table A2, ICES-IRR computes irrigated land supply elasticity closed to Baker's estimate when the elasticity of transformation is set at the value of -0.5.

ε_{supply}	σ_{CET}
0.08	-0.1
0.23	-0.3
0.41	-0.5
0.74	-0.8
1.01	-1
-5.76	-5

Table A2: The supply elasticity computed by ICES-IRR

Another important feature of the model that should be tested is the land allocation or land conversion from the supply side, since this new formulation allows the land owner to transform, first pasture land to cropland (or vice versa) and then rainfed land into irrigable land (or vice versa) as depicted in **Figure 20**. There are two parameters governing these behaviours, and we run a systematic sensitivity analysis to assess the robustness of the models results.
We first conduct a systematic sensitivity analysis (SSA) to test the robustness of the simulation results to the value of the elasticity of transformation between rainfed and irrigable land. The baseline value of this parameter (0.5) is assumed to vary over the range $\pm 50\%$, following a symmetric triangular distribution. Figure 31 shows the irrigated land demand when land productivity is uniformly reduced by -10%, and 95% confidence intervals for a normal distribution, computed from the SSA results.

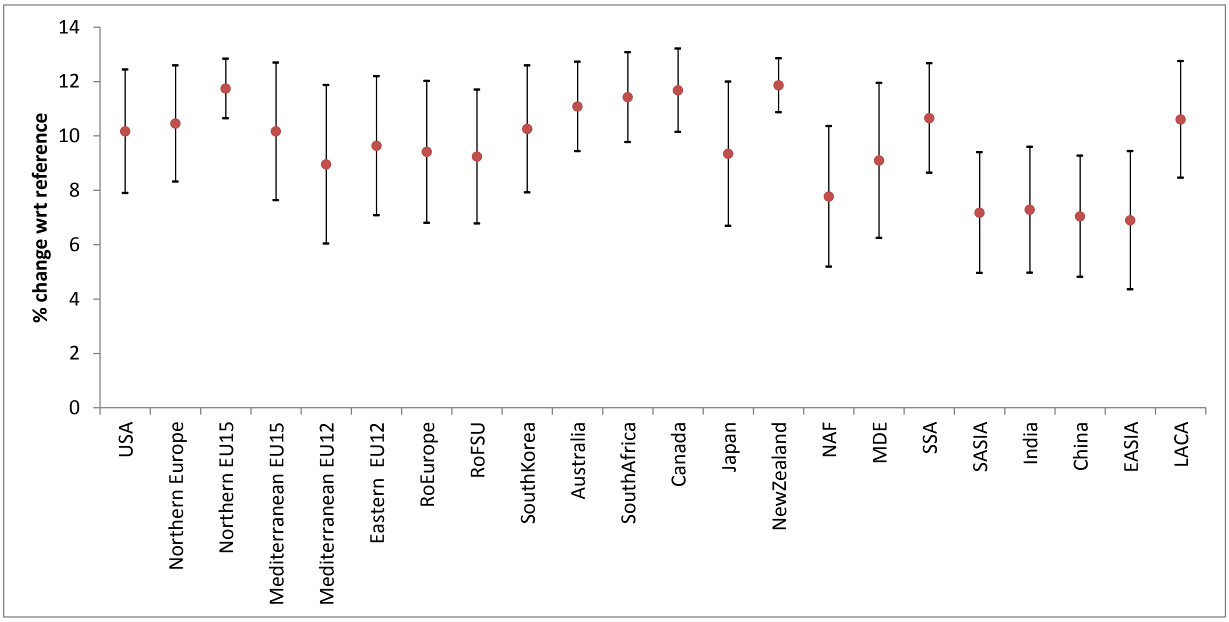


Figure 31: Changes in irrigated land demand in the sensitivity analysis

Appendix B: Information to extend the ICES-IRR database

	Rice	Wheat	CerCrops	VegFruits	Total
USA	0.39	0.07	0.22	0.13	0.19
MEUR	0.38	0.01	0.19	0.11	0.09
NEUR	0.40	0.00	0.03	0.00	0.01
EEUR	0.43	0.01	0.03	0.16	0.02
FSU	0.45	0.03	0.27	0.01	0.06
KOSAU	0.35	0.01	0.03	0.08	0.05
CAJANZ	0.36	0.01	0.02	0.17	0.07
NAF	0.47	0.20	0.47	0.46	0.31
MDE	0.43	0.17	0.27	0.29	0.20
SSA	0.17	0.08	0.01	0.02	0.03
SASIA	0.68	0.78	0.13	0.42	0.66
CHINA	1.00	0.72	0.46	0.37	0.67
EASIA	0.28	0.21	0.30	0.41	0.32
LACA	0.28	0.06	0.07	0.03	0.06

Table 38: Share of irrigated production in total production

	YS_r	$FF\_CS_{"IrrServ",r}$
USA	1.633	0.1
MEUR	1.025	0.063
NEUR	1.281	0.078
EEUR	1.31	0.08
FSU	1.282	0.078
KOSAU	1.229	0.075
CAJANZ	1.164	0.071
NAF	2.052	0.126
MDE	1.019	0.062
SSA	1.207	0.074
SASIA	1.529	0.094
CHINA	1.72	0.105
EASIA	1.104	0.068
LACA	1.119	0.069

Table 39: Ratio of irrigated to rainfed yield and the fixed factor share, by region

Appendix C: Simulation results for selected regions

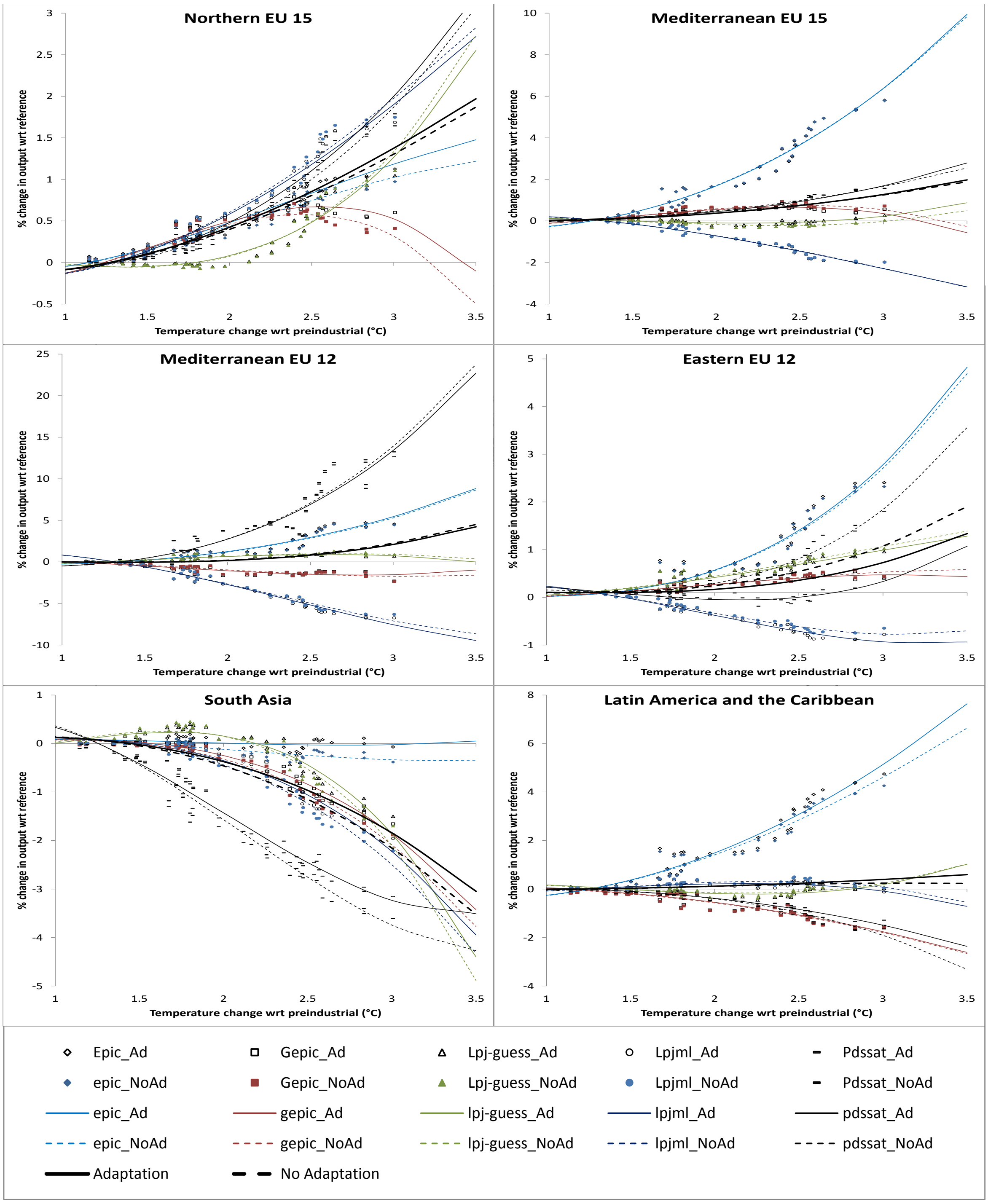


Figure 32: Impacts on wheat production in selected regions for RCP 8.5 (with and without adaptation)

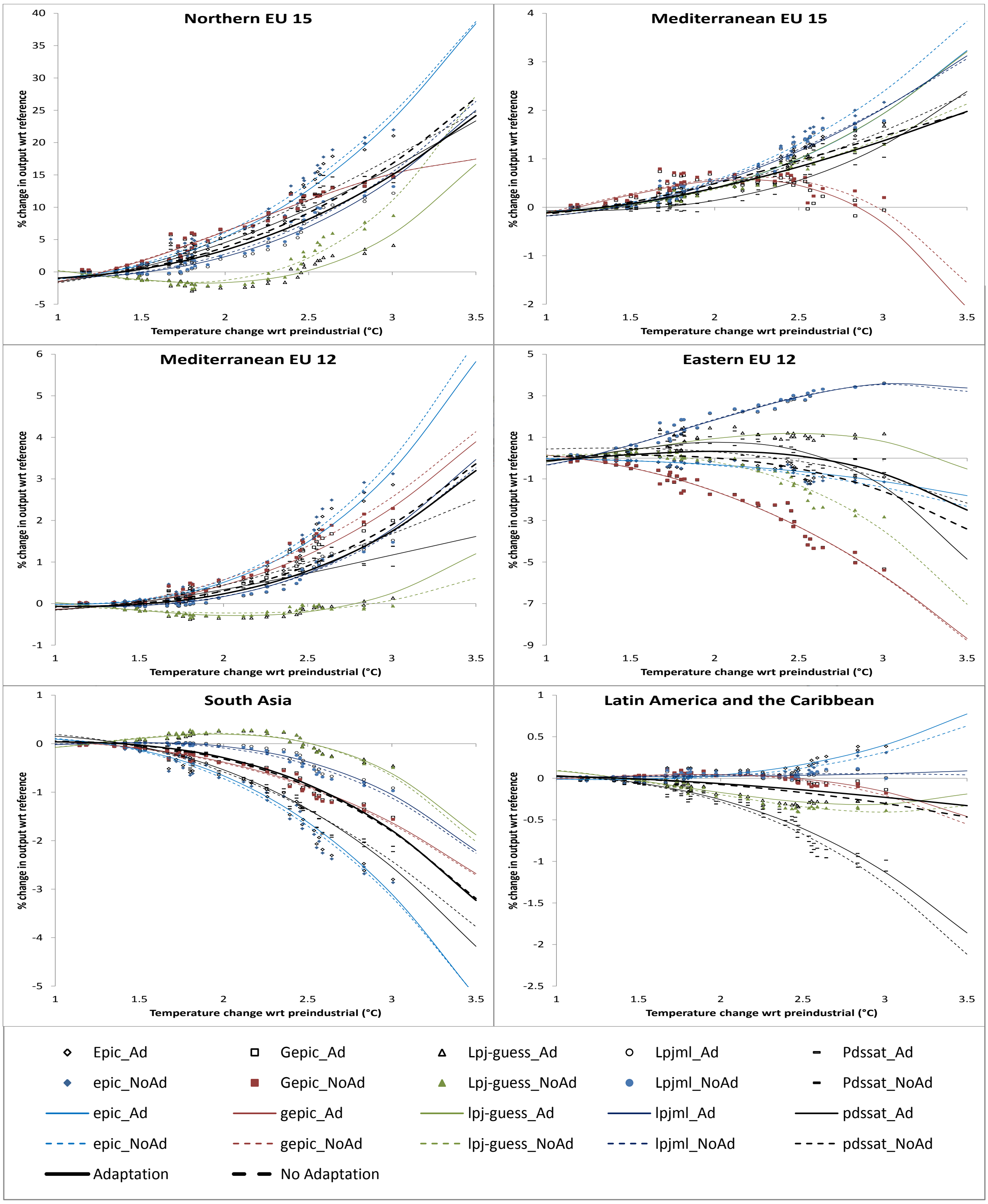


Figure 33: Impacts on rice production in selected regions for RCP 8.5 (with and without adaptation)

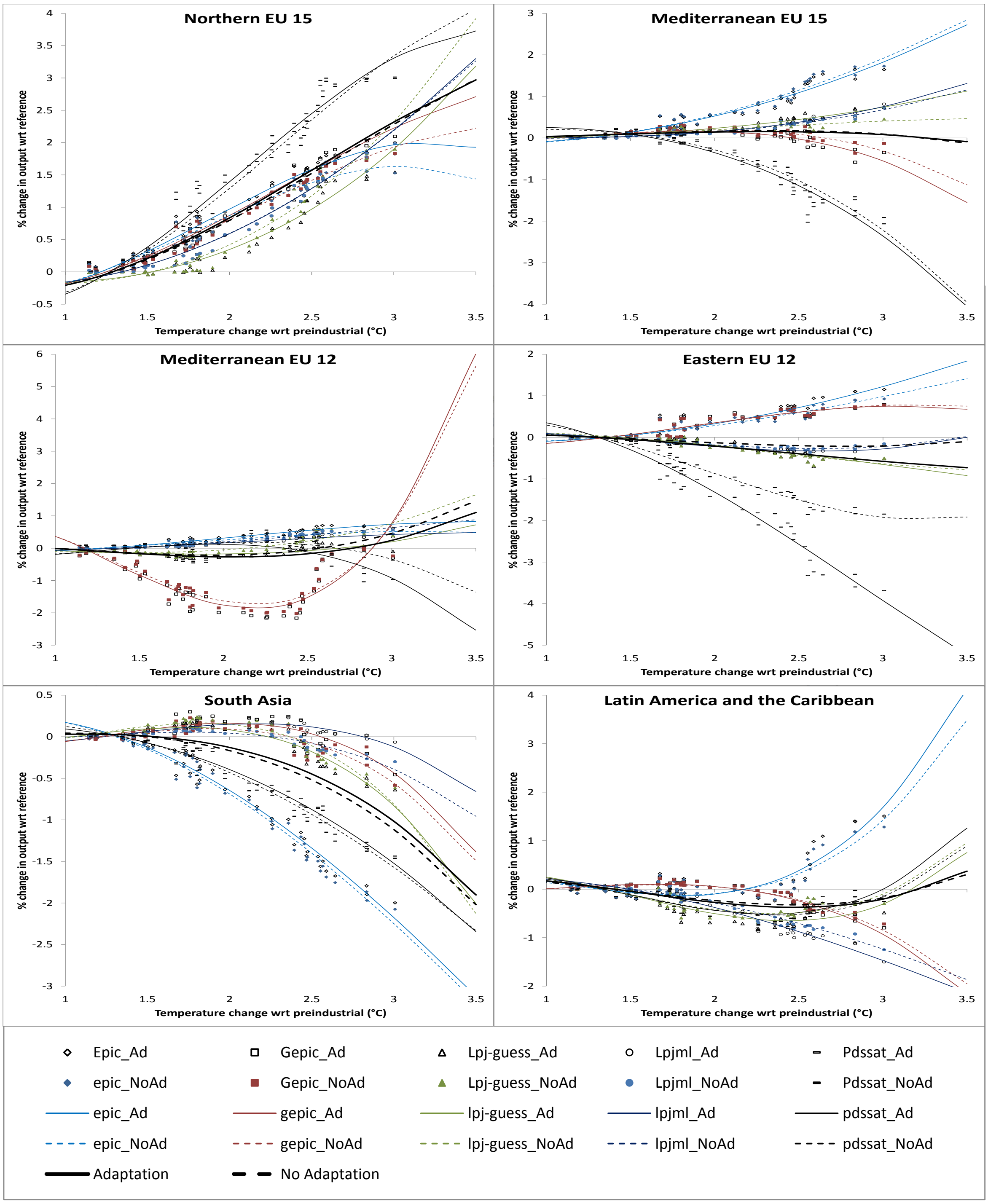


Figure 34: Impacts on vegetables and fruits production in selected regions for RCP 8.5 (with and without adaptation)

ECONADAPT

The Economics of Adaptation

Funded by the European Union

Deliverable 8.2.3: Modelling Planned Adaptation for Coastal Zone Protection in a General Equilibrium Framework[41]

Francesco Bosello (CMCC), Ramiro Parrado (CMCC), Elisa Delpiazzo (CMCC)

Deliverable number	D8.2.3
Work Package Number	WP8
Submission date	July 2016
Type of Activity	RTD
Nature	R = Report
Dissemination level	Public

[41] The authors gratefully acknowledge funding from the European Union under contract number EVK2-2000-22024 to develop the Dynamic Interactive Vulnerability Assessment (DIVA) model. The data was extracted from the model from the Inter-Sectoral Impact Model Intercomparison Project Fast Track funded by the German Federal Ministry of Education and Research (Project 01LS1201A). Further analysis occurred under the European Commission's Seventh Framework Programme's collaborative project RISES-AM-(contract FP7-ENV-2013-twostage-603396).

We also acknowledge funding from the Italian Ministry of Education, University and Research and the Italian Ministry of Environment, Land and Sea under the GEMINA project.

Document information

Title:	Deliverable 8.2.3: Modelling Planned Adaptation for Coastal Zone Protection in a General Equilibrium Framework
Authors:	Francesco Bosello (CMCC), Ramiro Parrado(CMCC), Elisa Delpiazzo (CMCC)
Other Contributors	Sally Brown (University of Southampton), Jochen Hinkel (Global Climate Forum), Daniel Lincke(Global Climate Forum)
Date:	July 2016
Contact details	Ramiro Parrado, ramiro.parrado@feem.it
Work Package Number	WP
Deliverable number	D8.2.3
Filename:	D8.2.3-Planned-Adaptation-Sea-Level-Rise.docx
Document history:	Version 1
Type of Activity	RTD
Nature	R = Report, O = Other
Dissemination / distribution level	PU = Public: PP = Restricted to other programme participants (including the Commission Services); RE = Restricted to a group specified by the consortium (including the Commission Services); CO = Confidential, only for members of the consortium (including the Commission Services)
Citation:	Deliverable 8.2.3 of the ECONADAPT Project.
Copyright:	

The ECONADAPT project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no 603906.

To find out more about the ECONADAPT project, please visit the web-site: www.econadapt.eu

For further information on the ECONADAPT project contact Alistair Hunt at: ecsasph@bath.ac.uk

Table of Contents

1 Introduction

Climate change impact on coastal zones, and sea-level rise (SLR) in particular, are of utmost concern since a large fraction of population and economic activities are already located in these areas (World Bank, 2010). Moreover, future projections suggest that in the 21st century damages will increase significantly both because of socioeconomic development bringing more population and capital at risk; and because of increasing SLR trends linked to global warming processes (IPCC 2015). However, there is a high degree of uncertainty on the magnitude of SLR, and thus damages, and on the adaptation investments needed to lower these impacts.

A particular dimension of SLR impacts is their potential stress on public budgets. This issue was initially introduced, in broader terms, by Heller (2003) indicating climate change as one of the major threats (together with demographic changes and globalization) posed on public budgets in future decades. On the one hand, countries heavily dependent on few climate sensitive productive sectors may face significant revenue reductions. On the other hand, public spending may increase to contrast or prevent for instance intensified incidence of vector borne diseases, stress on infrastructures or population movements. The importance (and sign) of these fiscal impacts will vary across countries, but they are likely to be mostly adverse precisely where vulnerabilities to climate change are greatest (IMF, 2008).

Adaptation in particular, will require increased public expenditure, both on climate related public goods (such as information acquisition and dissemination on likely extreme events) and to protect public and private assets at risk like transportation systems, water and health systems. Eventually, adaptation can reduce or increase the stress on public budgets depending on its effectiveness, the structure of the tax system, the size of adaptation investment, and the funding sources available (Osberghaus and Reif, 2010).

This deliverable aims to assess the costs of SLR impacts and adaptation using a Computable General Equilibrium (CGE) model extended with a sophisticated description of the public sector. The final goal is to account not only for the GDP effects of adaptation, but also for the impacts on public finance. More specifically, we assume that adaptation expenditure is not financed through new taxes but issuing government bonds. Future projections of SLR damages are generated by the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework (Hinkel et al, 2013, 2014; Vafeidis et al. 2008). DIVA is a socio-economically driven geo-bio-physical model which projects the impacts and costs of sea-level rise, and subsequent adaptation for a range of scenarios. Outputs from two climate models (MIROC and NorESM) and the SSP2 socioeconomic scenario were used as drivers for the DIVA model for RCP2.5 and RCP8.5 scenarios generated by Hinkel et al. (2014). Final impacts depend on adaptation measures that in the model take the form of dike building. Optimum levels of protection under a range of different climatic conditions use a demand-for-safety function. This is a function of GDP, per capita income, sea level rise and population density (Hinkel et al. 2014). The costs of coastal protection are a function of sea level rise, extreme water level, per capita income and GDP.[42] The DIVA assessment is of partial equilibrium in nature as it cannot capture explicitly the intersectoral and international economic impacts triggered by se-level rise, nor their rebounds on the sectors and countries initially impacted. This is however possible with CGE models that quantify the impacts on the value of production and ultimately on GDP accounting for all those interactions. It is thus particularly interesting to compare the consistency of the projections of a partial equilibrium assessment such as in the DIVA model, with that of a general equilibrium assessment tool.

[42] A complete description of adaptation in the DIVA model is in Hinkel et al, (2014).

2 Methodology

CGE models consider, by construction, the so called “market-driven adaptation” i.e. the functioning of autonomous mechanisms – primarily, demand and supply reactions to endogenous changes in relative prices - which characterize instantaneous resource allocation across two market equilibria in response to exogenous economic shocks (Bosello and Parrado, 2014). There are few examples of the modelling of planned adaptation to sea level rise using a static CGE model with investments carried out by the public sector (Bosello et al, 2007 and Ciscar et al 2009). In the case of SLR in particular, coastal protection expenditures mainly consist of huge infrastructure expenditures which are primarily financed by public funds. For instance, CEPS and ZEW (2010) establish that more than 95% of investments against SLR in Europe are publicly financed. Nicholls et al. (2010) suggest that much of the costs for adaptation to SLR falls on government finance while only a minority of adaptation could be funded by private investments (i.e. port and harbour upgrade). Against this background, this work implements in a recursive dynamic CGE model, public planned expenditure targeted to coastal protection, inclusive of investment and operation and maintenance costs. It further develops a more realistic description of the public sector behaviour to better capture coastal protection expenditure effects on public finance.

2.1. Overview of the ICES-XPS model

Our analysis is based on the ICES CGE model which has been used already to assess climate change impacts including SLR (Bosello et al, 2012; Bosello and Parrado, 2014; Eboli et al, 2010). In the basic model version, derived from the GTAP model (Hertel et al 1996), the government behaves as a representative household. This has two major implications. Firstly, the public income uses are completely independent from their sources. Secondly, the possibility for the public sector to save is not considered at all. This represents a limitation when public spending on adaptation has to be evaluated. To address this issue we developed an extended model version where the government is a separate actor with its own budget constraint. The ICES-XPS (ICES-eXtended Public Sector)[43] model now includes different transfers between the government and households such as social transfers, and interest payments on debt stock. There are also transfers among governments in the form of international aid. Government transfers, consumption, and investments build government expenditure, government income derives from taxes. Accordingly, at the regional level, investments are both private and public linked into a Cobb-Douglas formulation. The gap between public savings and public investments represent the government’s financial needs (borrowing). This gap is financed by private households’ savings, since both domestic and foreign households supply a homogenous saving commodity. Investment is internationally mobile and regional savings (private plus public) from all regions are pooled in a global bank. Subsequently investment is allocated to equalize expected rates of return to capital in the long-run.

Savings and investments are equalized at the world, but not at the regional level. Therefore, each region could have an imbalance between disposable savings and investment demand. This imbalance is closed by a surplus/deficit in foreign transactions (considered as the sum of trade surpluses/deficits and the net inflows of international transfers). In this context, government borrowing reduces the availability of regional savings with a consequent increase in saving prices which are negatively correlated to the rate of return to capital.

[43] The detailed description of the public sector in the ICES-XPS is in Appendix A.

2.2 Modelling adaptation to sea level rise

Planned Adaptation refers to proactive actions taken to avoid the expected negative impacts of a particular phenomenon. In the case of coastal protection against SLR this means investing in protective infrastructure, such as building or raising dikes to safeguard endangered zones. Once these measures have been put in place there remains only a residual damage that would be much lower than in the case with no planned adaptation. However, adaptation is costly. These costs are of two types: i) investments in protective infrastructure, and ii) the corresponding maintenance costs.

Public planned adaptation expenditures in coastal protection encompass both investments in the construction of protective infrastructure and maintenance costs. This implies firstly to introduce additional public investment in infrastructure ($\Delta GOVINV_{CNST,r}$) for the construction of dikes. Accordingly, public investments become:

$$GOVINV_r = \varepsilon_r \cdot NETINV_r + \Delta GOVINV_{CNST,r}$$

In our set up, we assume that these additional public investments are financed by (national and foreign) household savings. That is, government finances the expansion of adaptation expenditure issuing public sector bonds which crowd out private investments.

Secondly, new infrastructures incur on maintenance costs that are additional public expenditures addressed to construction services ($QG_{CNST,r}$) to cover for the maintenance activities. Care is taken not to alter the initial government recurrent expenditures on the remaining sectors of the economy. Formally, total government expenditures are:

$$PGOV_r \cdot QGOV_r = \sum_i PG_{i,r} \cdot QG_{i,r}$$

In the construction sector (*i* = *CNST*), the demand becomes:

$$PG_{CNST,r} \cdot QG_{CNST,r} = PG_{CNST,r} \cdot QG_{CNST,r} + \Delta QG_{CNST,r}$$

which ends up increasing total government expenditure by the same amount ($\Delta QG_{CNST,r}$).

This way of channelling adaptation expenditure has two immediate consequences: i) total public expenditure expands, and most importantly, ii) by conveying part of household savings from private investment toward public consumption (of construction services) adaptation decreases the resources available to accumulate capital stock.

Ultimately thus, the purpose of the assessment is to verify whether or not the lower growth of capital stock induced by adaptation is more than compensated by the lower climate-change induced losses on capital, land stock and labour productivity; and how all this relates to public budgets dynamics.

3 Sea-level rise and adaptation data

This exercise uses outputs from the DIVA model (Hinkel et al., 2014; Hinkel et al., 2013; Hinkel et al., 2012; Hinkel and Klein, 2009). The main drivers of the model are socio-economic change and sea-level rise. Socio-economic change is represented through population density and GDP. Shared Socioeconomic Pathway (SSP) 2 was used in this study (O'Neill et al., 2014). Sea-level rise from two climate models (NorESM[44] and MIROC-ESM[45]) for two RCPs (2.6, and 8.5) were analysed. To account for uncertainty in land-based ice melt, the 5%, and 95% percentiles ice melting uncertainty offering a 'very likely' range for low and high SLR estimates. These regionalised (patterned) sea-level rise scenarios are taken from Hinkel et al. (2014).[46] The study considered a "No additional adaptation scenario", with constant protection adaptation strategy from a base year of 1995. In 1995, the demand-for-safety function was applied. We also applied a "with adaptation scenario", where the demand for safety for dikes increases as sea-levels and populations change. Further detail is available in Hinkel et al. (2014).

The following information is available for each scenario:

- Annual land loss due to submergence: Land is considered to be unusable, and thus lost, if it is situated below the 1-in-1 year flood water level and not protected by a dike (km^2/year).
- Annual cost of land loss due to submergence (only the land value based on GDP, not the assets - million US$/year).
- Expected annual damages to assets by sea floods (mathematical expectation of damages to assets integrating from the 1-in-1 year flood to the 1-in- 10,000 year flood - million US$/year).
- Expected annual number of people flooded per year (mathematical expectation of damages to people integrating from the 1-in-1 year flood to the 1-in-10,000 year flood - Thousands/year).
- Total assets situated below the 1-in-10,000 year flood level (million US$/year)
- Annual cost of construction of new dikes as well as rising of existing dikes (million US$/year).
- Annual cost of maintaining existing dikes (annual maintenance cost is assumed to be one percent of the dike construction cost of that unit). Dikes that are overtopped by rising sea-level are no longer maintained (million US$/year).

As it is evident from this list, the costs and benefits (damages potentially avoided) of adaptation that the DIVA model refer to direct or partial equilibrium assessments. In other words, the feedback of protecting or not protecting assets exposed to SLR impacts on the overall economic activity, (i.e. on the flow of goods and services potentially achievable by an economic system), is not part of the analysis.

---

[44] Bentsen et al (2013)

[45] Watanabe et al. (2011)

[46] The regional patterns are from the Greenland and Antarctic ice sheets and their peripheral glaciers and ice caps, plus from the steric contribution of sea-level rise. A global mean value is added to the regionalised components from glaciers and ice caps in other parts of the world.

The CGE analysis that is proposed here is meant to capture those aspects. As the cost benefit logic behind DIVA is based on different principles than those governing the CGE model, it is particularly interesting to check if the level of protection prescribed by the former are robust even when transferred in the context of the latter.

As said, costs of SLR and adaptation from DIVA are the input information for the ICES CGE model. SLR impacts are implemented through supply-side land stock, labour productivity and capital stock losses. Specifically: land stock for agricultural uses is reduced consistently with the information of submerged land; labour productivity losses are computed assuming that expected people flooded are not able to work for 2 working weeks per year.[47] To estimate capital losses we use the following procedure: first, we compute the share of total assets in coastal zones from DIVA over the total capital stock in ICES-XPS. Then we adjust the empirically estimated asset to GDP ratio used in DIVA with the own regional asset to GDP ratio calculated within the ICES-XPS database. Finally, we use this information along with the value of land lost to compute expected damages in absolute terms and decrease accordingly the capital stock.[48]

Adaptation costs are included as described in section 2.2. The annual cost of protection infrastructure derives from DIVA which includes information for maintenance costs for both the 'no additional adaptation' and 'with adaptation' scenarios. In ICES-XPS we take into account only the additional costs for maintenance of the new infrastructure. This choice is made assuming that maintenance costs in DIVA's no adaptation scenario are part of our reference scenario. Indeed, these maintenance costs are related to existing infrastructures and are not a consequence of climate change impacts (Hinkel et al., 2014). To estimate adaptation costs that are consistent with the capital losses in the CGE model we follow two steps. First, we compute the cost benefit ratios from the original DIVA data, and then apply those ratios to the adjusted values for the expected damages in terms of the ICES-XPS capital stock.

Figure 35 and **Figure 36** show ranges for land stock, labour productivity and capital stock percent losses for RCP2.6 and RCP8.5, in 2050 with respect to 2007 in the 'no additional adaptation' (No Ad) and 'with adaptation' cases (Ad). These will be the input information for the subsequent CGE analysis. The per cent land losses due to submergence are rather small compared with those of capital stock and of labour productivity. As losses are computed in 2050 it is also worth noting that they do not differ significantly between the two RCPs. In percent over total land the most affected region is North Europe with a land loss ranging between 0.09% and 0.19% in RCP8.5 and 0.07% and 0.24% in RCP2.6. Other regions with noticeable land losses are USA, rest of Former Soviet Union, Oceania, Canada, Middle East, Sub Saharan Africa, South Asia, India, East Asia and Latin America and the Caribbean. The rest of the regions have very small impacts.

[47] This value is rather arbitrary, and derives from assumptions made in Bosello et al (2012) on the period of time that people will not be able to work after being affected by river floods.

[48] By shocking the national capital stocks with DIVA's expected annual national damages, we assume that all countries of the world would experience in every year a flood that exactly does the expected damage. We acknowledge that the probability of this happening in reality is null. Addressing this would, however, require a quite different approach such as a Monte-Carlo analysis which considering the general equilibrium model would imply a time and computing resources consuming effort. For this reason we assume that our results are pessimistic on the high-range of damage estimates.

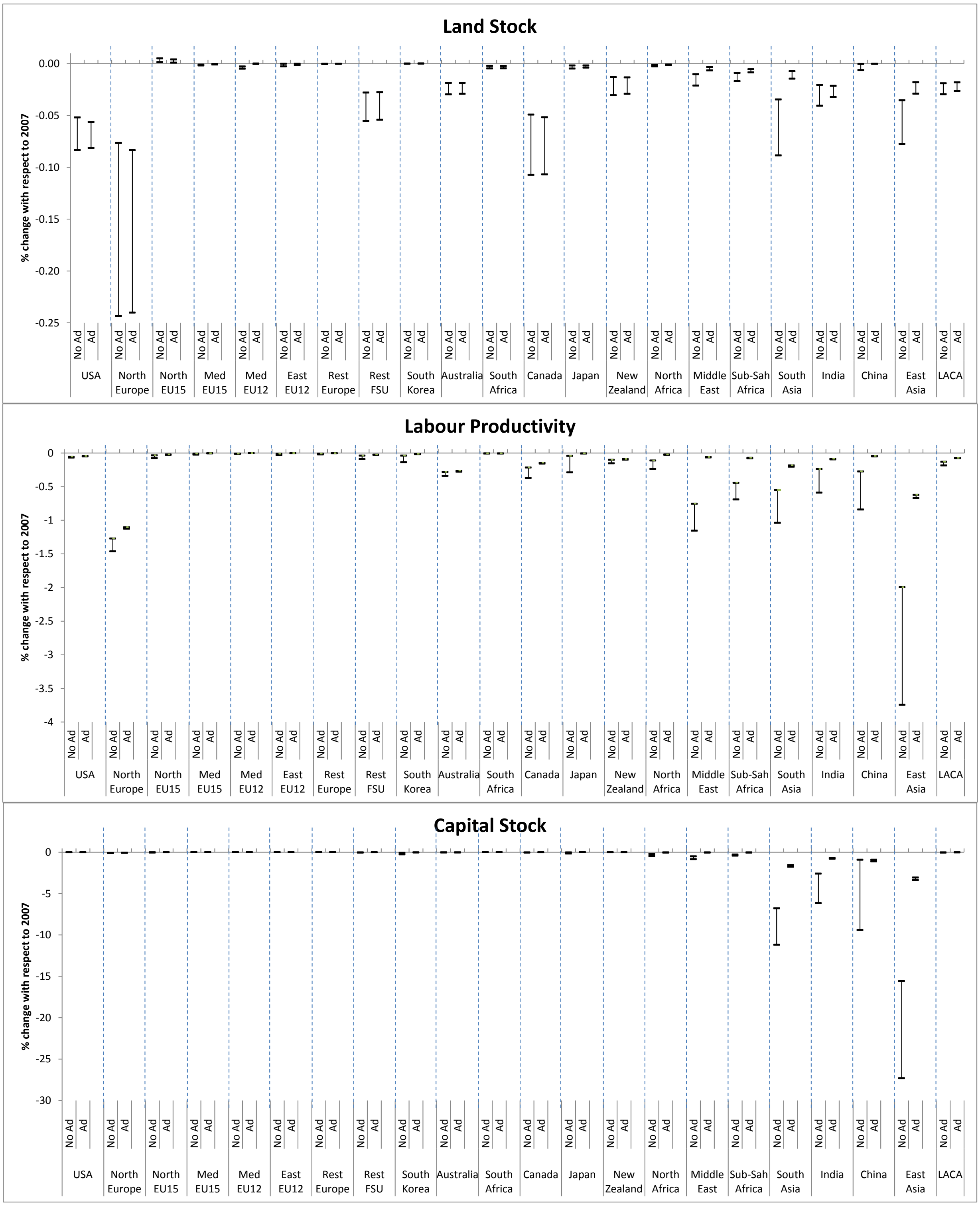


Figure 35: Changes for capital stock, land, and labour productivity for RCP 2.6 in 2050 (with and without adaptation)

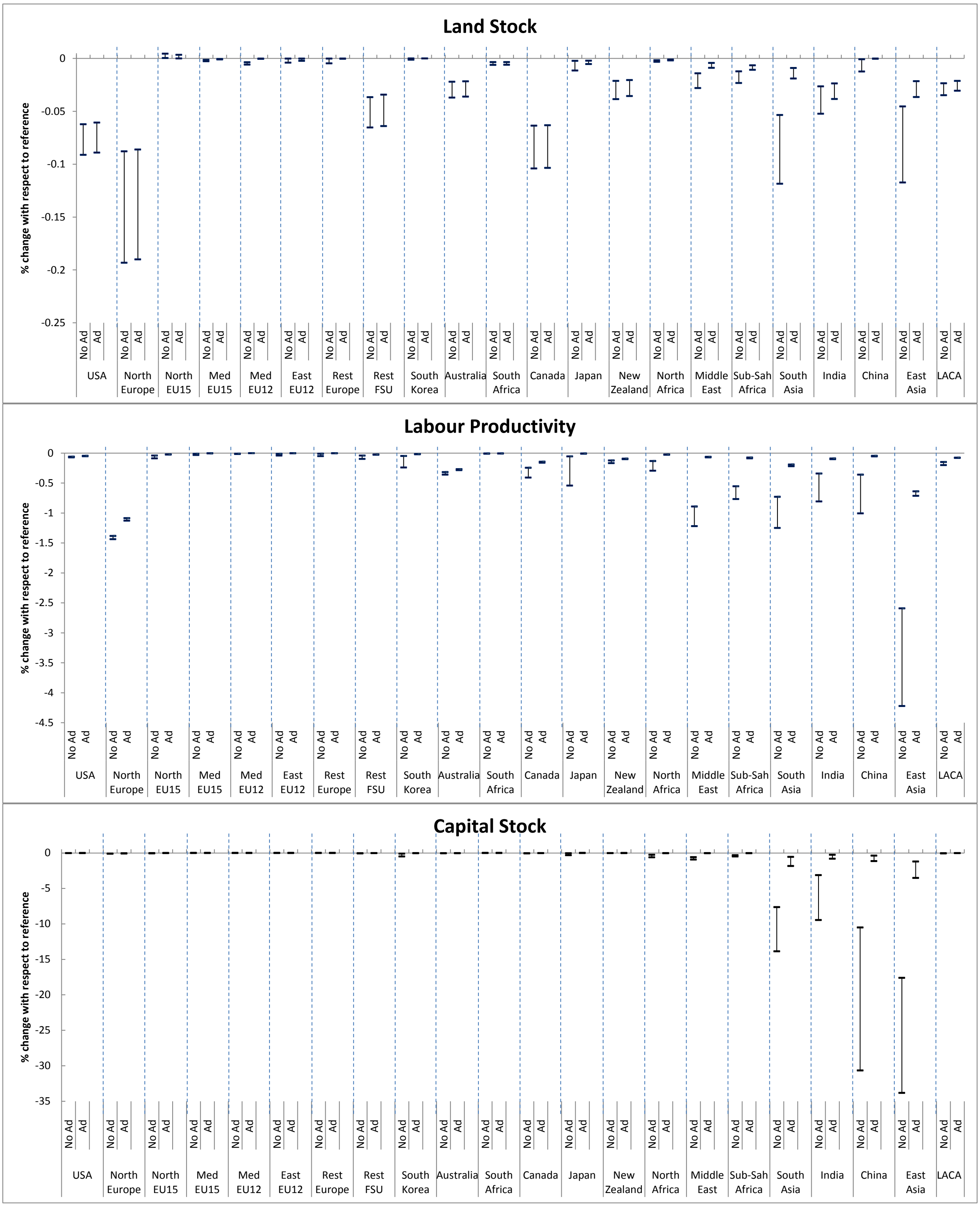


Figure 35: Changes for land stock, labour productivity and capital stock in RCP 8.5 in 2050 (with and without adaptation)

Countries that benefit the most from adaptation are located in developing regions such as South Asia, East Asia, India, Middle East, Sub Saharan Africa, China, Japan, Latin America and the Caribbean. There are other regions that only reduce slightly land loss as in the case of USA, Europe, Rest of Former Soviet Union, Canada and Oceania; while for the rest of the regions the difference is not noticeable due to the small scale of the impact.

Regarding labour productivity the most affected region is East Asia with a reduction ranging from -4.2% to -2.6% in RCP8.5, and from -3.7% and -2% in RCP2.6. Other regions with visible impacts are North Europe, the rest of Asian countries, Africa, Middle East, Canada, Latin America and the Caribbean. It is also worth noting that Asian regions show wider variability in impacts.

The benefits of adaptation are mode evident for East Asia followed by Middle East, South Asia, China, India, Sub Saharan Africa, and the rest of Asia. North Europe lowers its impact but it is the most affected region in this scenario with a loss in labour productivity of nearly -1.1% in both RCPs.

Impacts on assets are significant in Asian countries, especially in East Asia, China South Asia, and India, ranging between -3% and -33%, while in other countries are close to zero. However, adaptation reduces impacts on assets almost to zero.

Considering the combination of the three shocks, Asian regions suffer the highest impacts, while European regions are marginally affected with impacts mainly due to land loss. The shocks on land and labour productivity are more widespread across countries than impacts on capital stock which are more concentrated in Asian countries.

4 Scenarios

The general equilibrium analysis is developed comparing three scenarios.

Reference "no impact" scenario: this is SSP2 "Middle of the Road" scenario (O'Neill et al., 2014) for GDP growth projections from the OECD based on population projections from IIASA[49] and do not include any impact from SLR.

No (additional) adaptation scenario: it includes SLR impacts, as reported in section 3. This represents a counter factual scenario with adaptation frozen at 1995 protection levels.

(With) adaptation scenario: Public intervention to protect coastal zones against SLR as prescribed by the DIVA model, thus including some residual damages, is imposed according to the description of section 2.2.

---

[49] The benchmark scenario is described in Deliverable 8.1: Report on the ICES and the GEM-E3 model benchmark scenario for the subsequent analysis.

5 Simulation results

Figure 36 compares impacts on regional GDP for RCP2.6 and RCP8.5 in 2050 with and without adaptation. The ‘no additional adaptation’ scenarios (No Ad) features a generalized GDP loss in all regions for both RCPs.[50] The magnitude of losses is strictly dependent on the size of impacts on capital, land and labour productivity. The most affected countries are East Asia that could lose from 3% to 5% of GDP in 2050, China (up to 2%), North Europe and South Asia (both by more than 1%). In the rest of Asian countries, Middle East, North and South Africa and Canada the GDP decreases less than 1%, in European regions less than 0.5%.

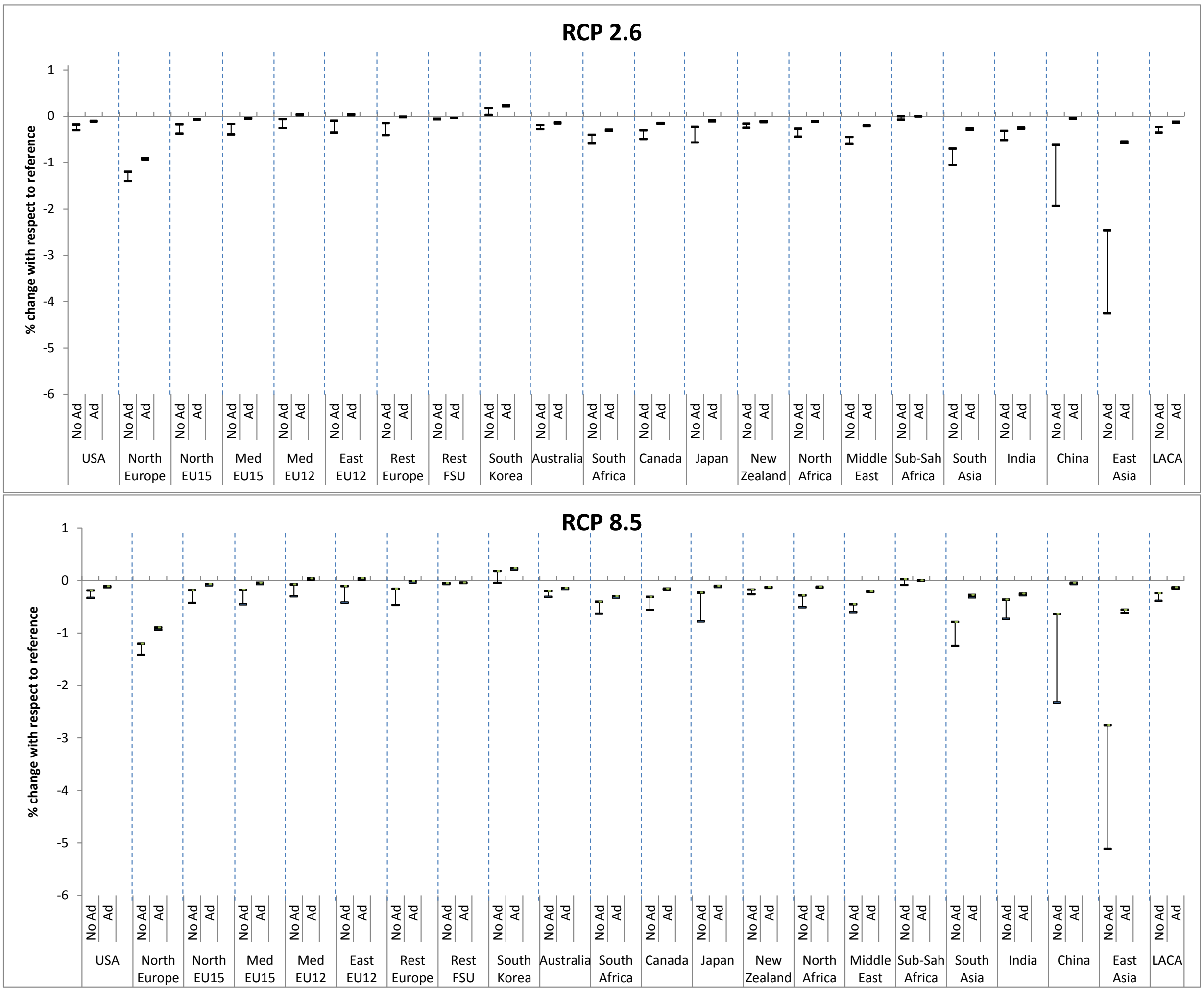


Figure 36: Impacts on real GDP by region and RCP in 2050 (with and without Adaptation)

[50] Only South Korea shows a slight increase in GDP for some simulations due to a positive effect on energy intensive sectors’ production and exports that in the base year accounts for nearly 60% of total exports.

Figure 36 clearly highlights the ability of adaptation to reduce GDP losses from sea-level rise, which is more pronounced in those regions like Asian, Sub Saharan, Middle East and North Africa countries, where sea-level rise has more pronounced impacts.

This positive result of adaptation is the compounded effect of two mechanisms directly and indirectly related with the impacts of SLR. The first one regards the avoided direct impacts (loss of labour productivity, land and capital). In this case, the avoided capital losses are the main drivers of the benefits, due to their key role in determining growth in a recursive dynamic model like ICES-XPS. The second mechanism is the public deficit effect shown in **Figure 38** and **Figure 39** that has an indirect effect on GDP growth.[51] Without adaptation, all regions increase their public deficits or reduce their surpluses respect to reference scenario. These increases can be substantive in absolute terms: e.g. more than $ 200 billion in China, $ 80 billion in East Asia, $ 25 billion in Latin America and the Caribbean and $ 17 billion in India. Public deficit worsening is mainly driven by the reduction in tax revenues, strictly dependent on the tax system structure, and by the interaction between input taxes affected by the negative effects on land capital and labour, and output taxes affected by the decline in GDP. A higher deficit deteriorates public finance therefore the government borrows from household savings, which eventually reduces also the available resources for private investments. Since lower impacts of SLR translate in lower deficits, then the government borrows less from households which would allow for an increased capital accumulation in the long-run. Furthermore, lower deficits imply lower debt accumulation, and consequently a lower debt service. This also allows more resources devoted to growth.
Eventually, according to the ICES-XPS analysis, the protection investments prescribed by DIVA in a partial equilibrium set up are robust also in general equilibrium, i.e. accounting for the full economic interactions.

To conclude, **Figure 38** highlights some typical patterns in the evolution of deficit with and without adaptation in four EU regions and two Asian regions. Initially, public deficits are higher when adaptation investments are being put in place, to become lower only in the long run. This is a direct consequence of the long-run nature of sea-level rise impacts that are more damaging for GDP and also deteriorate the ability to raise tax revenues in the longer term.

All in all, at least in the case of sea-level rise impact, support to adaptation in deficit spending is not necessarily bad for GDP growth, and might trigger positive effects on public finance sustainability. This highlights a potentially interesting policy insight: adaptation expenditure can enable virtuous processes even though initially financed with debt.

It is also important to stress that the present analysis compares costs and benefits of coastal protection on economic flows. It thus considers only marginally and indirectly SLR impacts on stock losses. It is well known that comparing for instance the cost of coastal protection against the value of the land that would be lost otherwise, rather than with the contribution to GDP that that land originates in one year (which is what the current study does), the cost benefit ratios can be totally different. In principle, in a first-best world, the value of land should be exactly equal to the cumulated stream of revenues that land can produce over its lifetime. In this case, a stock perspective would immediately justify a much higher protection.

[51] Effects on public debt, which are straightforwardly linked to public deficit, are reported in **Figure 40**, appendix B.

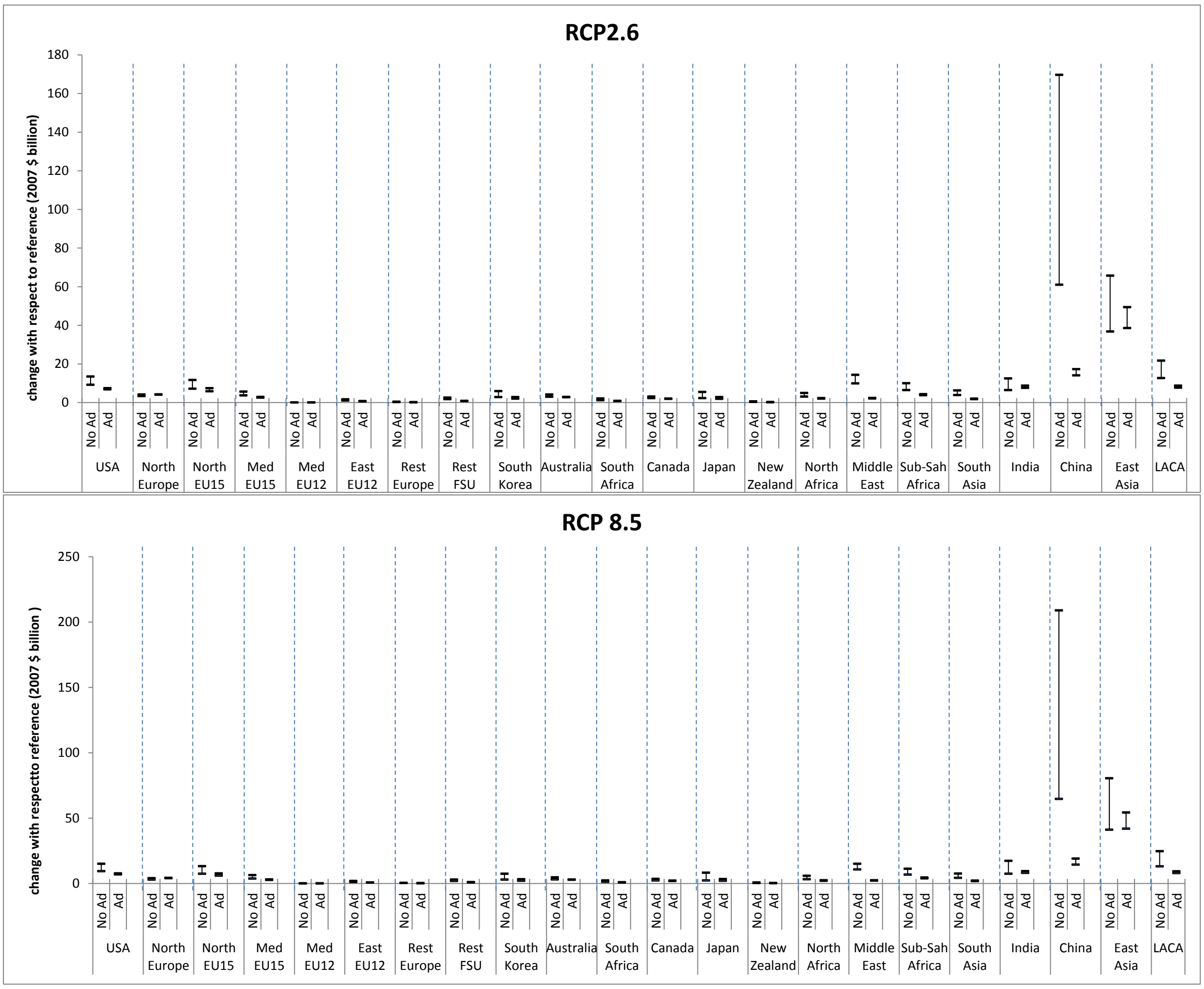


Figure 37: Impacts on public deficit by region and RCP in 2050 (with and without Adaptation)

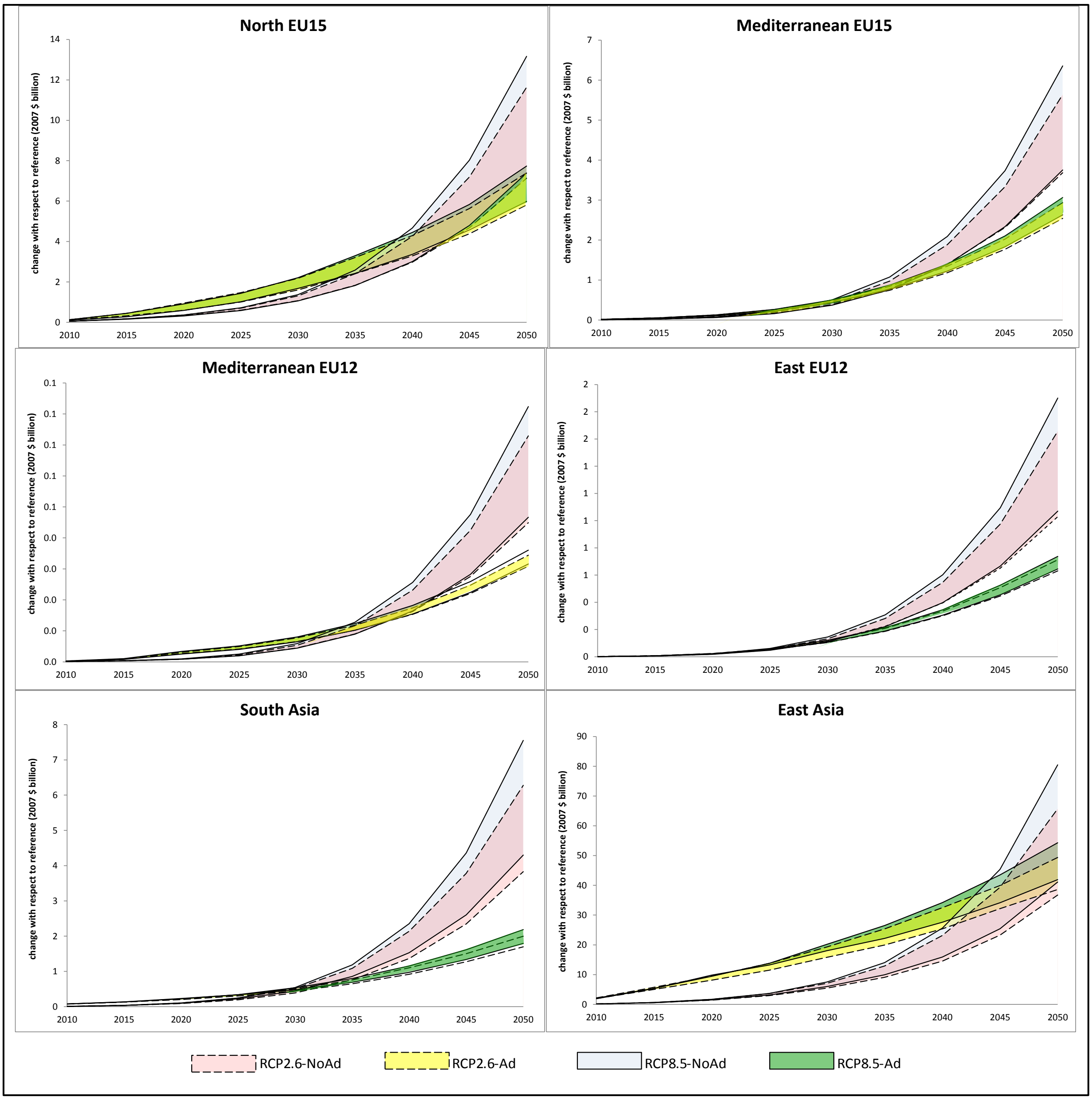


Figure 38: Impacts on public deficit by RCP for selected regions in 2050 (with and without additional adaptation)

6 Conclusions

This deliverable analyses the economic implications of publicly planned adaptation to protect coastal zones against SLR. Input to the analysis are land, capital and labour productivity losses as well as coastal protection costs elaborated from the DIVA model runs for two RCPs (2.6 and 8.5) and two GCMs (NorESM and MIROC-ESM). The economy-wide assessment is conducted with ICES-XPS, a multi-sector and multi-region CGE model enhanced with a detailed description of the public sector. Planned adaptation against SLR takes the form of public investments and expenditure for operation and maintenance addressing the building sector. This expenditure is funded issuing government bonds.

In a scenario where there is no additional adaptation, almost all world regions suffer a GDP loss with the exception of South Korea. The most damaged countries are in Asia, while EU regions would expect moderate GDP losses lower than 1% in 2050.

When coastal protection takes place, the highest GDP gains compared to the case of no protection are observed mostly in developing countries where SLR impacts are markedly high and adaptation expenditures particularly effective. In the remaining regions GDP gains are also experienced, but are lower. The beneficial effect of adaptation on GDP is the result of two mechanisms. The first one regards the avoided direct impacts (loss of labour productivity, land and capital). The second one is the public deficit effect. When adaptation to SLR reduces GDP losses, it also triggers a tax interaction effect which produces higher tax revenues. Therefore the government borrows less from households savings and has to pay a lower debt service, both of which allows for an increased capital accumulation in the long run.

As a general conclusion, support to adaptation in deficit spending might be not necessarily bad for GDP growth, and might also trigger positive effects on public finance sustainability. This highlights a potentially interesting policy outcome. Adaptation expenditure could enable virtuous processes even though initially financed with debt. This can be good news for countries where increasing tax pressure is particularly problematic. This raises the issue of the different results that could be obtained through, for instance, earmarked taxation for adaptation that can potentially trigger different dynamics on debt accumulation and thus on the consumption-investment balance and growth. This will be a topic for future analysis.

7 References

Bentsen, M., I. Bethke, J. B. Debernard, T. Iversen, A. Kirkevåg, Ø. Seland, H. Drange, C. Roelandt, I. A. Seierstad, C. Hoose, and J. E. Kristjansson (2013). The Norwegian Earth System Model, NorESM1-M. Part 1: Description and basic evaluation of the physical climate, Geosci. Model Dev., 6, 687-720, doi:10.5194/gmd-6-687-2013

Bosello F., Nicholls R.J., Richards J., Roson R. and Tol R., (2012), "Economic Impacts of Climate Change in Europe: Sea-Level Rise", *Climatic Change*, 112: 63-81.

Bosello F., Roson R., Tol R.S.J. (2007). Economy wide estimates of the implication of climate change: sea- level rise. Environmental Resource Economics, 37: 549- 571.

Bosello F., Eboli, F., Pierfederici, R. (2012). Assessing the Economic Impacts of Climate Change. An Updated CGE Point of View, Working Papers 2012.02, Fondazione Eni Enrico Mattei.

Bosello, F. and R. Parrado (2014). Climate change impacts and market driven adaptation: The costs of inaction including market rigidities. Working Papers 2014.64, Fondazione Eni Enrico Mattei.

Ciscar, J.C., Goodess, C., Christensen, O., Iglesias, A., Garrote, L., Moreno, M. Quiroga, S., Feyen, L., Dankers, R., Nicholls, R., Richards, J., Bosello, F., Roson, R. Amelung, B., Moreno, A., Watkiss, P., Hunt, A., Pye, S., Horrocks, I., Szabó, L., van Regermorter, D. and Soria, A. (2009), Climate change impacts in Europe Final report of the PESETA research project, Luxembourg, Publications Office of the European Union.

Chateau J., Dellink R., Lanzi E. (2014). An Overview of the OECD ENV-Linkages Model: Version 3. OECD Environment Working Papers, No. 65, OECD Publishing. http://dx.doi.org/10.1787/5jz2qck2b2vd-en

Delpiazzo E., Parrado R., Standardi G. (forthcoming). Extending the public sector in ICES with an explicit government institution. FEEM Note di Lavoro.

CEPS and ZEW (2010). The fiscal implication of climate change adaptation. Final report of the ADAM project. Centre for European Policy Studies (CEPS) and Centre for European Economic Research (ZEW).

Eboli F., Parrado R. and Roson R. (2010). Climate-change feedback on economic growth: Explorations with a dynamic general equilibrium model. Environment and Development Economics, 15: 515-533.

Heller P. (2003). Who Will Pay? Coping with Aging Societies, Climate Change, and Other Long-Term Fiscal Challenges. Washington D.C.: International Monetary Fund.

Hinkel J., Lincke D., Vafeidis A.T., Perrette M., Nicholls R.J., Tol R.S.J., Marzeion B., Fettweis X., Ionescu C., Levermann A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. PNAS, 111 (9): 3292-3297.

Hinkel J., van Vuuren D.P., Nicholls R.J., Klein R.J.T. (2013). The effects of adaptation and mitigation on coastal flood impacts during the 21st century. An application of the DIVA and IMAGE models. Climatic Change, 117: 783-794.

Hinkel J., Brown S., Exner L., Nicholls R.J., Vafeidis A.T., Kebede A.S. (2012). Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA. Regional Environmental Change, 12: 207-224.

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

IMF (2016). World Economic Outlook database, available on line at: https://www.imf.org/external/pubs/ft/weo/2015/02/weodata/index.aspx

IMF (2008). The Fiscal Implication of Climate Change. Fiscal Affairs Department International Monetary Fund

International Institute for Applied System Analysis (2016). Shared Socioeconomic Pathways Database. Available on line at: https://secure.iiasa.ac.at/web-apps/ene/SspDb

Lemelin A. and Decaluwé B. (2007). Issues in Recursive Dynamic CGE Modelling: Investemnt by Destination, Savings and Public Debt. A survey. Université du Québec, INRS-Urbanisation, Culture et Société CIRPÉE, Université Laval. Available online at: https://www.pep-net.org/sites/pep-net.org/files/typo3doc/pdf/RevLitt_MEGC_EN.pdf

McDonald S. and Sonmez Y. (2004). Augmenting the GTAP Database with Data on Inter-Regional Transactions. Sheffield Economic Research Paper Series, SERP Number: 2004009, pp. 26. Department of Economics, University of Sheffield: Sheffield. Available online at: http://eprints.whiterose.ac.uk/9895/1/SERP2004009.pdf

Nicholls R., Brown S., Hanson S., and Hinkle J. (2010). Economics of Coastal Zones Adaptation to Climate Change. Discussion Paper no.10. The World Bank: Washington.

Osberghaus D., Reif C. (2010). Total Costs and Budgetary Effects of Adaptation to Climate Change: An Assessment for the European Union. ZEW Discussion Paper no. 10-046. Mannheim: Center for European Economic Research.

Parrado R. and De Cian E. (2014). Technology spillovers embodied in international trade: Intertemporal, regional and sectoral effects in a global CGE framework. Energy Economics, 41: 76-89

Robinson S. (2006). Macro Models and Multipliers: Leontief, Stone, Keynes, and CGE Models. In de Janvry A. and Kanbur R. (eds.), Poverty, Inequality and Development: Essays in Honor of Erik Thorbecke. New York: Springer Science.

Watanabe, S., T. Hajima, K. Sudo, T. Nagashima, T. Takemura, H. Okajima, T. Nozawa, H. Kawase, M. Abe, T. Yokohata, T. Ise, H. Sato, E. Kato, K. Takata, S. Emori, and M. Kawamiya, (2011), MIROC-ESM 2010: model description and basic results of CMIP5-20c3m experiments, Geosci. Model Dev., 4, 845-872, 2011, http://www.geosci-model-dev.net/4/845/2011/

Vafeidis, A. T., R. J. Nicholls, L. McFadden, R. S. J. Tol, J. Hinkel, T. Spencer, P. S. Grashoff, G. Boot, and R. J. T. Klein (2008). A new global coastal database for impact and vulnerability analysis to sea-level rise, Journal of Coastal Research 24.4, pp. 917–924. doi: 10.2112/06-0725.1.

World Bank (2010). The Economics of Adaptation to Climate Change (EACC): Synthesis Report. The World Bank Group, Washington, DC.

Appendix A:

The ICES-eXtended Public Sector (ICES-XPS) model

For this assessment, we use an extended version of a recursive dynamic model (Delpiazzo *et al*., 2016). The model uses a Walrasian perfect competition paradigm to simulate market adjustment processes. Industries are modelled through a representative price-taker firm that minimizes production costs. Output prices are given by average production costs. The production functions are specified via a series of nested Constant Elasticity of Substitution (CES) functions. Domestic and foreign inputs are imperfect substitutes, according to the Armington assumption.

A private representative consumer in each region receives income (YH_r), defined as the service value of national primary factors (natural resources, land, labour, capital). Capital and labour are perfectly mobile domestically, but immobile internationally. Land and natural resources, on the other hand, are industry-specific.

Equation (1) describes private income respect to sources. It is composed of four main elements: (i) factor use remuneration (divided into labour and capital income, $\mathrm{YHL_r}, \mathrm{YHK_r}$ respectively); (ii) social transfers from the government ($\mathrm{YHTR_r}$); (iii) the net of other transfers between private households and government ($\mathrm{YHOGI_r}, \mathrm{YHOGE_r}$) which is functional to the balancing of the base year; (iv) income from interest on public debt ($\mathrm{YHI_r}$).

$$YH_r = YHL_r + YHK_r + YHTR_r - YHOGI_r + YHOGE_r + YHI_r \qquad (1)$$

Where:

$$YHTR_r = \alpha_{TR,r} \cdot YG_r \qquad (2)$$

$$YHOGI_r = \alpha_{OGI,r} \cdot YH_r \qquad (3)$$

$$YHOGE_r = \alpha_{OGE,r} \cdot YG_r \qquad (4)$$

$$YHI_r = INTD_r + INTI_r \qquad (5)$$

Transfers are fixed shares of income of the agent paying out the transfer. For instance, social transfers from government to the private household (equation 2) are a fixed share ($\alpha_{TR,r}$) of the government income. Similarly, other expenditures (equations 3 and 4) are respectively fixed shares of government and household income (according to shares $\alpha_{OGE,r}$ and $\alpha_{OGI,r}$). Interest income to households (equation 5) is the sum of interest paid from the domestic government and interest from abroad.

This income is used to finance aggregate household consumption ($PRIV\_EXP_r$) and household savings ($PRIV\_SAV_r$). The expenditure ($\beta_{PEXP,r}$) and saving ($1 - \beta_{PEXP,r}$) shares are fixed, which means that the top-level utility function has a Cobb-Douglas specification. Equation 6 defines the private income equation respect to uses; equations 7 and 8 isolate the Cobb-Douglas structure between consumption and savings.

$$YH_r = PRIV\_EXP_r + PRIV\_SAV_r \quad (6)$$

$$PRIV\_EXP_r = \beta_{PEXP,r} \cdot YH_r \quad (7)$$

$$PRIV\_SAV_r = (1 - \beta_{PEXP,r}) \cdot YH_r \quad (8)$$

Private consumption is split in a series of alternative composite Armington aggregates. The functional specification used at this level is the Constant Difference in Elasticities (CDE) form: a non-homothetic function, which is used to account for possible differences in income elasticities for the various consumption goods. Equation 9 represents the identity between regional private expenditure and its decomposition into prices and quantities, while equation 10 states that total regional private consumption is nothing else than the sum of private consumption by goods.

$$PRIV\_EXP_r = PPRIV_r \cdot QPRIV_r \quad (9)$$

$$PPRIV_r \cdot QPRIV_r = \sum_i PP_{i,r} \cdot QP_{i,r} \quad (10)$$

The government is a separate agent, that receives income from four main sources: (i) tax revenues ($TTAX_r$); (ii) the net transfers with private households ($YHOGI_r - YHTR_r - YHOGE_r$); (iii) net interest payments to resident and non- resident households (YGI_r); (iv) net foreign transfers among governments ($AIDI_r - AIDO_r$) Government income is used for consumption (GOV_EXP_r) and savings (SAV_GOV_r). Equations 11 and 12 represent the government income respect to sources and uses.

$$YG_r = TTAX_r - YHTR_r + YHOGI_r - YHOGE_r - YGI_r + AIDI_r - AIDO_r \quad (11)$$

$$YG_r = GOV\_EXP_r + SAV\_GOV_r \quad (12)$$

Where:

$$YGI_r = INTD_r + INTO_r \quad (13)$$

$$AIDO_r = \alpha_{AIDO,r} YG_r \cdot aidout_r \quad (14)$$

$$AIDI_r = \overline{AIDI_r} \cdot aidin_r \quad (15)$$

Equations 13 to 15 show the definition of new variables. YGI_r is the total amount of interest paid from a government (so it is the sum of payment to residents ($INTD_r$) and non-residents ($INTO_r$). Outflows of grants ($AIDO_r$) are a fixed share of government income, multiplied by a scaling parameter ($aidout_r$) which reflects the change in the global amount of grants to be allocated. Inflows of grants ($AIDI_r$), are simply rescaled considering the initial level.

Since there is no bilateral matrix to track international transfers (i.e. grants), we use the approach described in McDonald and Sonmez (2004), where an artificial accounting agent (named “Globe”) collects all outflows and distribute them to the countries. This leads to a clearing condition (equation 16) in the global market of aid of this kind:

$$\sum_r \overline{AIDI_r} \cdot aidin_r = \sum_r \overline{AIDO_r} \cdot aidout_r \quad (16)$$

Government income is used to consume and save according to equation 12. Regional real government expenditures are a fixed share of real regional GDP (equation 18), while nominal expenditures are the sum of the single commodity consumption (equation 19).

$$GOV\_EXP_r = PGOV_r \cdot QGOV_r \quad (17)$$

$$QGOV_r = \beta_{GEXP,r} \cdot QGDP_r \quad (18)$$

$$PGOV_r \cdot QGOV_{r_r} = \sum_i PG_{i,r} \cdot QG_{i,r} \quad (19)$$

Total regional investments are modelled through a Cobb-Douglas function of private and public investments. Regional investment net of depreciation ($NETINV_r$) is split into public (GOV_INV_r) and private investments ($PRIV\_INV_r$) according to fixed shares (equation 20).

$$NETINV_r = GOV\_INV_r + PRIV\_INV_r \quad (20)$$

Where:

$$GOV\_INV_r = \varepsilon_r \cdot NETINV_r + \Delta GOVINV_{CNST,r} \quad (21)$$

$$PRIV\_INV_r = (1 - \varepsilon_r) \cdot NETINV_r \quad (22)$$

and ($\Delta GOVINV_{CNST,r}$), are additional adaptation infrastructure investments.

The gap between public savings and public investments is the amount of borrowing the government requires. This gap is financed by private households. Both domestic and foreign households supply a homogenous saving commodity. Therefore, equation (23) is satisfied in each time period of the simulation:

$$GOV\_INV_r = SAV\_GOV_r + GBOR_r \quad (23)$$

Note that a positive value of the variable $GBOR_r$ means a deficit, thus the government is borrowing, while a negative sign means a surplus so that the government is a lending resources.

Investment is internationally mobile. Regional savings (private plus public) from all regions are pooled by a Global Bank, and subsequently investment is allocated to achieve equality of expected rates of return to capital in the long term. Savings and investments are aligned at the world, but not at the regional level. Therefore, each region could have an imbalance between disposable savings and investment demand, which is closed by a surplus/deficit in foreign transactions (considered as the sum of trade surpluses/deficits and the net inflows of international transfers).

The ICES-XPS model is a recursive dynamic model, thus each year is linked to the previous one via capital accumulation. The structure of the debt accumulation for the government is close to the capital accumulation. There is a stock from the previous simulation year ($GDEBT_{t-1,r}$) which is increased by government's borrowing in the current simulation year ($GBOR_{t,r}$). Denoting the current simulation year as *t* and the previous year as *t-1*, we have the following accumulation rule:

$$GDEBT_{t,r} = GDEBT_{t-1,r} + GBOR_{t,r} \quad (24)$$

We split the accumulation rule to consider interest payments for domestic and foreign debt according to a fixed share $fdshr_r$, defined as the share of foreign debt on total debt in region *r* in the base year.

$$GDDEBT_{t,r} = GDDEBT_{t-1,r} + (1 - fdshr_r) \cdot GBOR_{t,r} \quad (25)$$

$$GFDEBT_{t,r} = GFDEBT_{t-1,r} + fdshr_r \cdot GBOR_{t,r} \quad (26)$$

Interest payments on government's domestic and foreign debt stocks ($INTD_{t,r}, INTF_{t,r}$) are defined as an exogenous interest rate (ir_r) multiplied by the related previous year debt stock (equations 27 and 28). This means that interest payments are a consequence of the level of indebtedness (Lemelin and Decaluwé, 2007)

$$INTD_{t,r} = ir_r \cdot GDDEBT_{t-1,r} \quad (27)$$

$$INTF_{t,r} = ir_r \cdot GFDEBT_{t-1,r} \quad (28)$$

Similarly to the case of international grants, there is a clearing condition in the world market for interest payments (equation 29). This condition ensures that the total amount of interests governments pay to non- residents equals the total amount of interest payments from abroad. This does not mean that there is a balance in outflows and inflows of foreign interest payments but each country could face a positive or negative net value.

$$\sum_r INTI_{r,t} = \sum_r INTF_{r,t} \quad (29)$$

Moreover, each country receives an amount of interests from abroad that depends on the mean value of the interest collected in the world market (from equation 30), and on a scaling parameter ($psavshr_{r,t-1}$) which represents the country contribution to world private investment in the previous year.

$$psavshr_{r,t-1} = \frac{SAV\_PRIV_{r,t-1}}{\sum_r SAV\_PRIV_{r,t-1}} \quad (30)$$

This share reflects the contribution of private households in each country to finance total world debt. Since public and private savings are homogenous goods, private households lend a fraction of their savings to governments. As a consequence, the public agent pays interests to the household. If households save more, they could devote a higher fraction of their savings to finance public debt. This means that at time *t+1* they obtain higher interest payments. Therefore, foreign interest inflows become:

$$INTI_{r,t} = INTAVI_r \cdot psavshr_{r,t-1} \quad (31)$$

Government closure rule choice for ICES-XPS model

When the public agent is introduced in a CGE model, it is important to choose how to close the sector. In other words, deciding the causality among income, expenditures and savings (Robinson, 2003). There are essentially two alternatives: (i) endogenous government savings and the other components exogenous or (ii) exogenous government savings. Since, the aim of this study is to assess the budgetary effects of impacts and adaptation expenditures we follow the first approach. Therefore, taxes follow exogenous tax rates, expenditures (both recurrent and investments) are fixed exogenously and, as a consequence, the model calculates final savings (or public borrowing) as the gap between revenues and expenditures.

However, there are no projections for government expenditures up to 2050. Some estimates are in IMF's World Economic Outlook (IMF, 2016) up to 2020 but there is no clear and unique correspondence between its aggregate "general government total expenditures" and the ICES-XPS variables. Therefore, we project the trends of these variables in the socioeconomic baseline (SSP2) applying two approaches for public expenditures and investments. Firstly, real recurrent expenditures are a fixed share of real GDP following Chateau *et al*. (2014). Secondly, real government investments are a fixed share of total regional investments. Therefore, public and private investments can be represented as a Cobb-Douglas function respect to total (depreciated) regional investments.

Considering fixed government expenditures implies assuming the government has a minimum level of expenditures to maintain for other scenarios when impacts or adaptation occur. Moreover, this choice allows having a clearer link between inputs and final outcomes. In fact, in this framework SLR impacts act on the supply side of the economy, as they are modelled as changes in stocks and productivity. As a consequence, tax revenues change in correspondence. When additional adaptation investments are considered the final effect on public budget depends solely on the additional expenditures and the effects on revenues due to residual impacts.

Appendix B:

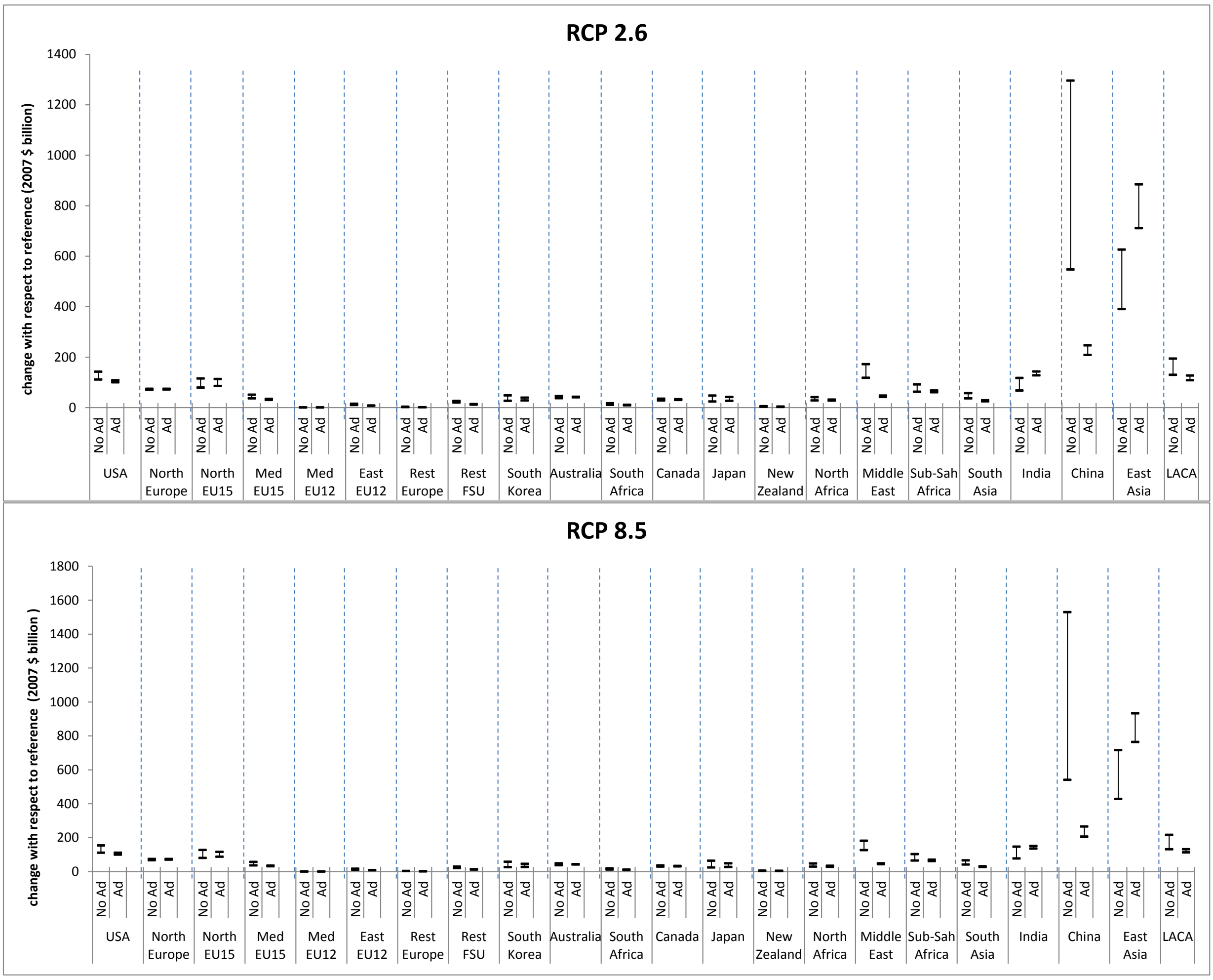


Figure 39: Impacts on public debt stock by region and RCP in 2050 (with and without Adaptation)