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"ESSAYS ON ECONOMIC MODELLING OF CLIMATE CHANGE IMPACTS AND ENVIRONMENTAL POLICIES"

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Contents

List of Tables

List of Figures

Preface

Climate change and environmental sustainability are an increasing challenge of our times. Over the last century, the global average surface temperature has increased by about 0.8 °C; the Greenland and Antarctic ice sheets have been losing mass; glaciers have been retreating worldwide; and the global mean sea level has risen by around 0.19 m. Natural causes alone cannot explain these changes. Indeed, one of the main drivers of climate change is the increase in greenhouse gas (GHG) emissions due to human activity. The continued accumulation of these heat-trapping gases in the atmosphere raises the probability of future global warming and of changes in regional climate. This in turn, directly affects economic activities, such as agriculture, fisheries, tourism, recreation, energy, health, and transportation.

Since the beginning of the '90s, both policy-makers and scientists have been focusing on the economic impact of global warming and the cost-effectiveness of proposed environmental policies. Initially, the attention was on emission reduction policies. More recently, the scientific debate has started to consider also adaptation strategies to deal with current and expected climate impacts.

Although climate change has become increasingly recognized as a pressing issue, quantifying its economic effects is demanding. In fact, climate change has many interlinked dimensions (science, economics, society, politics, etc.). There are both local and global effects, short- and long-term consequences, and time-lags between climate change and its impacts. Moreover, these effects are inherently unpredictable as a result of nonlinear, complex, and discontinuous responses. Consequently, defining optimal mitigation policies, and strategies to adapt the economic system to climate changes, is extremely challenging too.

The complexity and the multi-dimensionality of climate change require a holistic/interdisciplinary investigative approach. At the same time, the complexity needs to be reduced to manageable levels. This has fostered the development of integrated assessment (IA) models, which are an established tool to study cause-effect linkages between the human and the natural system, combining knowledge from different scientific fields.

There are many different types of IA models. But, when integrated assessment tackles the economic dimension, two different modelling approaches are usually used: bottom-up and top-down. The former focuses on specific production sectors and considers a high level of technological details, taking the macroeconomic drivers as exogenous. Top-down models, on the other hand, have a comprehensive representation of climate change and human response. Hence, they can assess the economy-wide features, and higher-order effects, of environmental policies. The top-down approach includes, among others, applied or computable general equilibrium models (AGE/CGE) and dynamic growth models.

Dynamic growth models are built on neoclassical or on endogenous economic growth theory. They are used to represent the economic dimension of many hard-linked IA models, which combine climate and economic features in a "unified" system. Hence, they give a full-representation of the phenomenon. The climate module usually feeds a damage function, which provides the effects of climate change on the economy. Dynamic growth models assume that perfectly-informed global or regional social planners maximize an intertemporal discounted utility function, by setting the level of investment in different capital stocks, energy R&D, energy technologies and the level of final energy consumption. Technological change can be either exogenous or endogenous, driven by "Learning by Doing" or "Learning by Researching" processes. Dynamic growth models have a full representation of intertemporal effects. Nevertheless, because of the complexity of solving intertemporal optimization problems, they lose detail in terms of regional and sectoral representation. In fact, they are usually one-country and one-sector models that do not describe endogenous price adjustments and international trade effects.

CGE models, on the other hand, are multi-sector and multi-country models, explicitly representing agents and market interactions, and international trade. The systemic representation of the economy allows capturing macroeconomic feedback or "rebound" effects of environmental policies. They have been commonly applied to represent the economic dimension of soft-linked integrated assessment models. They can describe higher-order effects, due to linkages and feedbacks between different sectors, actors and countries. However, their comprehensiveness comes at a cost: a stylized representation of dynamics and of technological change. Indeed, they are static, or feature simplified dynamics (typically "recursive"), based on the assumption of "adaptive" or "static" expectations (i.e. agents do not use all the scarce and costly information available to anticipate future climate change impacts). Technological change, on the other hand, is exogenous, represented by an autonomous energy efficiency improvement parameter. They have been largely used to analyze mitigation policies and, more recently, the economic effects of climate change and of market-driven adaptation. However, only few models include planned adaptation, through a re-direction of investments, at the regional or global level. By doing so, responses to climate change at the sectoral level are not considered.

Both approaches described above have advantages and disadvantages. Because of the ability of CGE models to provide a more comprehensive representation of economic linkages and feedbacks, this thesis focuses on this second category. However, given their previously described limits, the main goal of this work is to improve this modelling approach by enhancing the representation of intertemporal decisions and by introducing planned adaptation at the agricultural level.

This thesis consists of three essays on issues related to the economic modelling of climate change and environmental policies.

In Chapter 1, we review the state-of-the-art of applied economic models currently used in the climate change debate. We focus on the top-down approach, by considering dynamic growth and computable general equilibrium models. We select some relevant models and compared them in terms of the modelling strategy adopted to assess climate change impacts and adaptation policies. The final purpose of this chapter is to highlight limits of these approaches and to identify potential improvements.

In Chapter 2, we improve upon the myopic representation of expectations offered by standard recursive dynamic CGE models. We develop a new specification of the Intertemporal Computable Equilibrium System (ICES) model to include rational expectations assumption (called ICES_RE). We then analyze how different expectation structures affect the cost-effectiveness of mitigation policy. By using the EU climate policy as a case study, under the assumption that governments' purposes are credible from the beginning of our simulation period, we verify if, with rational agents, an anticipation effect occurs, and how this affects main economic variables prior to the policy implementation.

In Chapter 3, we develop a new modelling approach to include irrigation as a planned adaptation strategy, within the ICES model (called ICES-IRR). The new specification distinguishes between irrigable and rainfed land. Moreover, ICES-IRR takes into account the additional capital, operational and maintenance costs that farmers face when they decide to substitute rainfed land with irrigable land. The new version of the ICES model has been used to analyze whether farmers decide to convert rainfed land into irrigated land as a consequence of climate change impacts.

Chapter 1

Top-down economic modelling of climate change impacts and adaptation: A literature review

Anna Dellarole[*]

Abstract

Climate change is a multi-facetted and complex phenomenon. An interdisciplinary approach is required to understand and to quantify its economic effects. Since climate change is already happening, and some impacts are inevitable throughout this century and beyond, aggressive mitigation policies are not any longer sufficient. In fact, they can only slow down the process of climate change without stopping it. In this context, adaptation policies become mandatory to reduce the vulnerability of countries or of specific areas. However, because of the complexity of the phenomenon, few models are able to analyze the effects of adaptive strategies. The aim of this paper is to review the literature on modelling climate change impacts and adaptation policies, by focusing on the top-down approach. We select some relevant models and compare the different strategies applied to deal with climate change and adaptation. The final purpose of this paper is to highlight limits of this approach and to identify potential improvements.

JEL classification: Q51, C60, C68

Keywords: Climate Change; Adaptation; Integrated Impact Assessment Models; Top-down models.

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1.1 Introduction

Since 1900, the global average surface temperature has increased by about 0.8 °C. Over the period 1992 to 2011, the Greenland and Antarctic ice sheets have been losing mass and glaciers have been retreating worldwide. This has been accompanied by sea-level rise. In fact, over the period 1901 to 2010, global mean sea level has risen by around 0.19 m (IPCC, 2014b). Natural causes alone cannot explain these changes. One of the main drivers of climate change is the increase in greenhouse gas (GHG) emissions due to human activity, with CO_2 emissions being the most relevant one. The combustion of fossil fuels is the predominant source of this increase. Indeed, since the Industrial Revolution, human activities have raised atmospheric CO_2 concentrations by about 40% and about half of this increase has occurred in the last 40 years (IPCC, 2014b). The continued accumulation of these heat-trapping gases in the atmosphere raises the probability of future global warming and of changes in regional climate. This in turn, directly affects economic activities, such as agriculture, fisheries, tourism, recreation, energy, health, transportation, etc.

The prime objective of any environmental policy, and the current hot topic in international climate negotiation, is GHG emissions reduction and the shift from a high- to a low-carbon economy, to avoid irreversible and potentially catastrophic events. However, even if aggressive mitigation policies were introduced, climate change is already happening and due to climate inertia some impacts are inevitable throughout this century and beyond. Hence, in order to reduce the vulnerability of countries, adaptation[1] policies should be mandatory. The complementarity of mitigation and adaptation is clearly underlined in the EC Green Paper on adaptation, which states that: "with climate change already happening, societies worldwide face the parallel challenge of having to adapt to its impacts as a certain degree of climate change is inevitable throughout this century and beyond, even if global mitigation efforts over the next decades prove successful. While adaptation action has therefore become an unavoidable and indispensable complement to mitigation action, it is not an alternative to reducing GHG emissions. It has its limits. Once certain temperature thresholds are exceeded, certain climate impacts (e.g. major displacement of populations) are expected to become severe and irreversible" (EC 2007, p.1).

Although climate change has become increasingly recognized as a pressing issue, quantifying its economic effects is demanding. Consequently, defining strategies to adapt the economic system to climate changes is extremely challenging too. In fact, climate change has many interlinked dimensions (science, economics, society, politics, etc.). There are both local and global effects, short- and long-term consequences, and time-lags between climate change and its impacts. Moreover, these effects are inherently unpredictable as a result of nonlinear, complex, and discontinuous responses. Therefore the estimation of the economic costs of climate impacts is a difficult task.

The complexity and the multi-dimensionality of this phenomenon require a holistic/interdisciplinary investigative approach, especially when the economic impacts of climate change and the effects of environmental

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[1] According to the IPCC, "adaptation is the adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli, and their effects or impacts. This term refers to changes in processes, practices or structures to moderate or offset potential damages or to take advantages of opportunities associated with changes in climate" (IPCC, 2001).

policies have to be quantified. At the same time, the complexity needs to be reduced to manageable levels. This has fostered the development of integrated assessment (IA) models, which can be defined as “a process aimed at combining, interpreting and communicating knowledge from diverse scientific fields in order to tackle an environmental problem comprehensively by stressing its cause-effect links in their entirety” (Rotmans and Dowlatabadi, 1998). There are many different types of IA models. But, when integrated assessment tackles the economic dimension, two different modelling approaches are usually used: *bottom-up* and *top-down*. Bottom-up models focus on specific production sectors (usually the energy sector) and consider a high level of technological details. Top-down models, on the other hand, have a comprehensive representation of climate change and human response. Hence, only the latter can assess the economy-wide features, and higher-order effects, of environmental policies.

The present survey aims to review the state-of-the-art of applied top-down economic models currently used in the climate change debate. We aim to compare them in terms of the modelling strategy adopted to assess climate change impacts and adaptation policies. By highlighting their limits, we will also identify potential for improvements.

The remainder of the paper is organized as follows. Section 1.2 provides an overall classification of models used to assess the impact of climate change and adaptation policy. Section 1.3 outlines how climate change impacts are treated by top-down models while Section 1.4 describes the modelling strategies used to analyze different forms of adaptation. Section 1.5 reviews the main results and Section 1.6 concludes by offering new directions for future research.

1.2 Models classification

The multi-facetted nature of climate change requires an interdisciplinary investigative approach that is able to represent the interaction between complex systems. In this context, integrated assessment models play a key role. They are able to describe linkages between socio-economic factors and climate and environmental systems. Therefore they are widely used to inform policy-makers on the economic impacts of future climate change and on the cost-effectiveness of environmental policies.

Many modelling approaches exist within the class of IA models. Different ways of classifying them have been proposed. For instance, it is possible to divide process-(or environmental-) oriented models, characterized by considerable physical details, from economic-oriented ones, that focused on both environmental and economic factors (Patt et al., 2010).

Weyant et al. (1996) classify economic-oriented models into policy optimization and policy evaluation models.

Policy optimization models establish the optimal least-cost path for future emission reduction. They can be used for both cost-benefit and cost-effectiveness analyses. In the first case, policy-makers maximize a social welfare function. Indeed, the optimal policy is obtained when there is the equality between marginal costs (the opportunity costs of what the country has to sacrifice) and marginal benefits of mitigation (the avoided climate change damage in monetary terms, due to an additional unit of emission reductions). In cost-effectiveness analysis, the optimization is instead subject to an environmental constraint, which is usually expressed in terms of CO_2 equivalent concentration. The complexity of solving intertemporal optimization problems leads to an over-simplified representation of climate and economic relationships and limits the number of production sectors and geographic regions that can be treated (Mastrandrea, 2010). For example, the DICE model (Nordhaus, 1992; Nordhaus and Boyer, 2000), probably the most used and known IA model for the study of climate change policies, considers only one world region, one aggregate economic sector and one damage function. *Policy evaluation models* instead simulate economic impacts of exogenously specified policies or scenarios. Because they avoid intertemporal optimization, they can have a high level of details on environmental, economic or social aspects.

Another typology pertains the way economic components interact with the climate and environmental modules. According to this criterion, economic-oriented IA models are grouped as either hard-linked or soft-linked models (Bosello, 2014).

Hard-linked IA models combine climate and economic aspects in a "unified" system, represented by a consistent set of differential equations. As shown in Figure 1.1, they are able to represent the cause and effect chain of climate change. They take into account the effect of economic activities on emissions and the impacts of these emissions on atmospheric concentration of greenhouse gases. Then, they consider the consequent changes in temperature and precipitation, which lead to ecosystem and economic damages, which in turn have repercussions on climate (de Bruin, Dellink and Tol, 2009). Therefore the "loop" between climate module, impact module and economic module is closed.

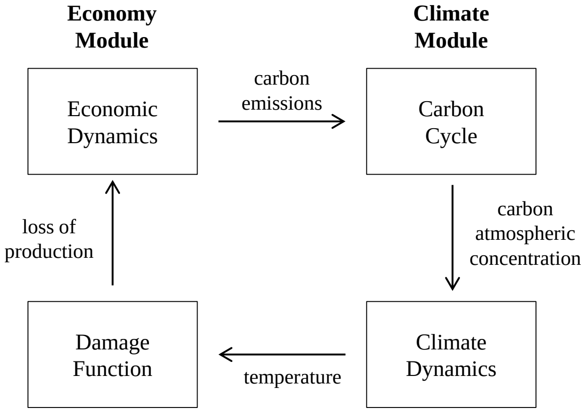

Figure 1.1: Interactions between economic and climate systems
[Source: Edwards et al. (2005)]

The obvious strength of hard-linked climate-economic models is that they integrate different systems in a fully consistent modelling framework. They are particularly suitable for long-term policy optimization analysis. They have been largely used to study optimal abatement paths, the economic costs of mitigation and adaptation policies, and the trade-off between different environmental policies. They have also analyzed which incentives would increase participation in international environmental agreements. Moreover, they have been used to consider investments in renewable energy, green R&D and adaptation R&D. The DICE and RICE model (Nordhaus, 1992; Nordhaus and Boyer, 2000; Nordhaus and Yang, 1996), for example, belong to this category. However, there are some limitations to this approach. Firstly, its interdisciplinary nature obviously has an impact on the level of details. Indeed, the representations of atmospheric phenomena and climate change damage are highly simplified, by using reduced form functions. In addition, the economic system is strongly aggregated in terms of regions and production sectors. Secondly, the complexity of these models may affect their transparency. Finally, although they are well-designed for long-term policy analysis, they are less suitable for short-term studies.

In *soft-linked models*, climatic, environmental and economic modules are run separately. They are connected exogenously in a causal chain through a sequential output/input exchange process. In principle, this process should be iterated until all the model results converge. In practice, very few soft-linked exercises conduct such convergence tests. Figure 1.2 shows how climate change and its physical and economic impacts may be considered in a multi-step methodology. Firstly, future socio-economic scenarios (i.e. economic growth and population dynamics) are chosen in order to obtain projections of GHG emissions and the atmospheric CO_2 concentration. Then, climate models are used (i.e. global circulation models or high resolution/regional climate models) to convert CO_2 concentration into expected changes in temperature, precipitation and sea-level rise. Then, physical impacts are quantified by using environmental bottom-up models or taking data from available impact studies. These physical impacts are finally processed by economic models. Often these are computable general equilibrium model (CGE) where endowments, productivity or behavioral parameters are shocked (e.g. losses in land or capital endowments due to sea-level rise; changes in land productivity due to precipitation variation; changes in energy demand for heating due to temperature changes).

The major advantage of soft-linked approach is that it can give a more detailed description of linkages and feedbacks within each module. Indeed, more complex climatic phenomena and environmental effects can be considered. Moreover, the economic system can be highly disaggregated, taking into account many regions, production sectors and available technologies. However, the advantage of having a more detailed description of each block is counterbalanced by the possibility of inconsistencies and non-converging solutions. Indeed often soft-linked exercises do not consider how endogenous adjustments in the economic system can affect climatic phenomena. Accordingly, they are better suited for impact simulation or policy evaluation rather than policy optimization analysis. Many soft-linked models, such as the AIM (Morita et al., 1994; 2003) and the IMAGE model (Alcamo et al., 1998), have been largely used to develop the IPCC SRES scenarios (IPCC, 2000).

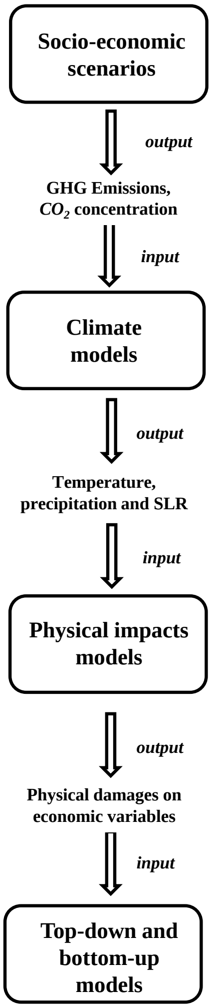

Figure 1.2: Multi-step approach to simulate the economic impacts of climate change

Another possible classification is between *deterministic* and *probabilistic* models. Most of them are deterministic in the sense that they include only one value, i.e. the "best-guess" or expected value, for each parameter. In this class, uncertainty in climate and social circumstances can be taken into account only by running sensitivity analysis. On the contrary, probabilistic models, such as the PAGE model (Hope et al., 1993; Hope, 2006; 2009), include the assumption of a probability distribution for some parameters (Mastrandrea, 2010).

Considering instead the way the economic system is represented, IA models can be classified as bottom-up or top-down (Bosello, 2014).[2]

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[2] Other classifications have been found in the literature. Although they are not identical, they are not even completely alternative

Bottom-up engineering models perform partial equilibrium analysis. They focus only on one sector, usually the energy sector, taking the macroeconomic drivers as exogenous. For instance, bottom-up energy models describe in great detail technologies from primary energy demand to final energy use systems, considering conversion, transport and distribution processes (Böhringer and Rutherford, 2008). They are usually included in the class of optimization models, since they minimize costs by choosing between different energy technologies, subject to some technical and policy constraints. The end-use demand for energy services is usually exogenous, either obtained from macroeconomic models or specified according to demand curves. They can simulate the interaction/competition between different energy technologies, both on the demand side (e.g. clean coal technology, fuel substitution, renewable energy) and on the supply side (e.g. the substitution possibilities between different energy inputs). Therefore they have been largely used to quantify the economic costs of mitigation policies and the level of investments required to achieve specific emission reduction targets. The weakness of bottom-up models is that they do not consider higher-order effects, such as price responses, trade and competition effects, or structural changes of the economiy-wide system (Hourcade et al., 2006). For this reason, bottom-up models are less suitable to assess climate change impacts than top-down models. POLES (JCR EC, 2010) and MiniCAM (Clarke et al., 2007) models belong to this category.

The *top-down approach* is based on macroeconomic theory and econometric analysis of historical data, which are used to model final demand for goods and primary factors, and supply from different sectors (e.g. energy sector, agriculture, industry and services). They offer a more comprehensive representation of climate change and human response. In addition, they can be integrated with bottom-up models, increasing the accuracy of input data.

In the economic assessment of climate change impacts, three types of top-down models can be identified: applied or computable general equilibrium models (AGE/CGE), dynamic growth models and macroeconometric models.

General equilibrium models

They are multi-sector and multi-country models, explicitly representing agents and market interactions and international trade.[3] Although there is not a universally accepted definition, they are "simulations that combine the abstract general equilibrium structure formalized by Arrow and Debreu with realistic economic data to solve numerically for the levels of supply, demand and price that support equilibrium across a specified set of markets" (Wing 2004, p.3). Different types of model are included in this class. However, the Walrasian

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to the previous ones. For example, Stanton et al. (2008) classify economic-oriented models into five categories: (i) welfare optimization models; (ii) general equilibrium models; (iii) partial equilibrium models; (iv) simulation models; and (v) cost minimization models. Ortiz and Markandya (2009), on the other hand, classify them into three classes: (i) fully integrated impact assessment models; (ii) non-computable general equilibrium (CGE) models; and (iii) CGE-type models.

[3] Since the early 1960s, they have become a standard tool in empirical economics analysis. In the last decades, there has been a rapid increase in the use of CGE models and a strong expansion of the number of addressed issues. They are used to analyze an enormous variety of questions ranging from the effects of exogenous shocks (e.g. changes in production technologies, in land and labor endowments, etc.) to the impacts of specific policy (e.g. fiscal policy, international trade policy, regional policy, environmental and energy policy) on aggregate welfare, income distribution and structural changes within a country and between countries. They are largely used for policy evaluation by national and international organizations, such as the European Union Commission, the World Bank, and the International Monetary Fund, etc.

equilibrium can be considered the starting point for all of them. Equilibrium is guaranteed by three conditions, i.e. market clearing conditions, zero profit conditions and income balance conditions, which are simultaneously solved for a set of prices and for the allocation of goods and factors (Wing, 2004). Due to these explicit specifications of agents' optimization behavior and market clearing prices, they can also be defined as "micro-consistent representation of price-dependent market interactions" (Böhringer et al. 2003, p.1).

CGE models have been largely used to analyze different aspects of mitigation policies, e.g. the cost-effectiveness of national mitigation policies and international agreement on emissions reduction, the policy instrument choice, technological innovation, carbon leakages (Dellink et al., 2010; Peterson et al., 2011; Böhringer et al., 2012; Goulder et al., 1999; Parry and Williams, 1999; Böhringer et al., 1997; Bernard and Vielle, 2009; Burniaux and Martins, 2012; Otto et al., 2007). Since the end of the '90s, they have also been used to analyze the cost of climate change impacts. Indeed, they have been commonly applied to represent the economic dimension of soft-linked integrated assessment models. For example, the EPPA CGE model is used in the MIT IGSM framework (Prinn et al., 1999) and the WORLDSCAN CGE model in the IMAGE IA framework.

The main strength of CGE models is their ability to describe key economic relationships and interlinkages, such as market interactions by price adjustments and through changes in terms of trade. Moreover, the systemic representation of the economy allows capturing macroeconomic feedback or "rebound" effects of environmental policies. However, they are affected by some structural limitations and uncertainties. Firstly, their comprehensiveness comes at a cost: a stylized representation of dynamics and of technological change. Indeed, they are static, or feature simplified dynamics (typically "recursive"), based on the assumption of "adaptive" or "static" expectations (i.e. agents do not use all the scarce and costly information available to anticipate future climate change impacts or policies). Technological change, on the other hand, is exogenous, represented by an autonomous energy efficiency improvement parameter. Secondly, agents' choices are rather simplified, by using smooth functional forms and by reducing the number of parameters and data for calibration. Finally, they are often criticized because they are calibrated from a benchmark equilibrium data set, which is arbitrarily chosen. Hence, the calibrated parameters may be unreliable. Moreover, because of this calibration procedure, they better capture short-term rather than long-term effects.

Dynamic growth models

They are built on neoclassical economic growth theory (Solow, 1957; Swan, 1956; Ramsey, 1928; Cass, 1965; Koopmans, 1966) or on endogenous growth theory (Romer, 1986; 1990; Grossman and Helpman, 1994; Aghion and Howitt, 1998). They are used to represent the economic dimension of many hard-linked IA models, such as DICE/RICE (Nordhaus, 1992; Nordhaus and Boyer, 2000; Nordhaus and Yang, 1996), WITCH (Bosetti et al., 2007), ENTICE (Popp, 2004), MIND (Edenhofer et al., 2005), MERGE (Manne et al., 1995; Manne and Richels, 2004), DEMETER (Gerlagh, 2007). They assume that perfectly informed global or regional social planners maximize an intertemporal discounted utility function, by setting the level of investment in different capital stocks, energy R&D, energy technologies, and the level of final energy consumption. Technological change can be either exogenous or endogenous, driven by "Learning by Doing" or "Learning by Researching" processes. The interesting, and new, aspects of the most recent growth models used in IA are the introduction of several types of capital and the detailed representation of the energy sector, combining bottom-up and top-down features.

Dynamic growth models in the hard-linked IA approach have been used to study a wide range of environmental issues. Indeed, they have been largely applied to quantify the so-called social cost of carbon (SCC), i.e. the monetary value of damages associated with an increase of one ton of carbon emissions in a given year (van Vuuren et al., 2011). Moreover, they have been applied to analyze the optimal abatement path, energy and carbon efficiency policies. Some of them propose game-theoretical solutions. Therefore they are able to simulate cooperative and non-cooperative outcomes, and strategic behaviors across countries or groups. Indeed, they have been used to analyze both, incentives to participate in international climate agreements and the stability of these coalitions (Bosello et al., 2003; Bréchet et al., 2011; Bosetti et al., 2013). In their more recent development, they have been applied to quantify the cost-efficiency of adaptation policies and the strategic complementarity between mitigation and adaptation policies (de Bruin, Dellink and Tol, 2009; Bosello et al., 2009; Agrawala et al., 2011; Bosello et al., 2013).

Although they have been largely used to assess the impacts of climate change and environmental policies, they have some limitations. Because of the complexity of solving intertemporal optimization problems, they lose detail in terms of regional and sectoral representation. In fact, they are usually one-country and one-sector models that do not describe endogenous price adjustments and international trade effects.

Macroeconometric models

Unlike dynamic growth and CGE models, macroeconometric models are mainly based on observed data. They employ methods of statistical inference that use cross-section and/or time-series data to estimate their parameters. In particular, they consist of a system of dynamic equations to represent demand and supply functions. They are estimated by using past observations and these relationships are assumed to also prevail in the future.

Most macroeconometric models are based on neo-Keynesian theory. Indeed, they are suitable to analyze departures from perfect competition that account for market imperfections, sticky price and bargaining processes. Moreover, since they are not constructed on one-year's database, they can represent (better than CGE models) non-equilibrium dynamic processes and transitional paths.

The main examples of macroeconometric models used for climate change analysis are the MDM-E3, E3ME and E3MG (Cambridge Econometrics, 2012),[4] which have been applied to study the structural effects of mitigation policies (Barker and Scrieciu, 2010; Barker et al., 2015; Ekins et al., 2012; Pollitt et al., 2012).

The main drawback of this approach concerns data. Econometric models require time-series of input-output matrices, which are difficult to construct because of missing observations, unavailable data or short

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[4] See http://www.camecon.com/Home.aspx.

samples. Moreover, since parameters are estimated by using past observations, they can give misleading long-run effects. Finally, because they are based on macroeconomic empirical observations, they are not able to analyze the effects of a given policy on agents' behavior at the micro level (the so-called "Lucas critique").

1.3 Economic modelling of climate change impacts

Integrated assessment approaches develop different strategies to model the economy-wide implications of climate change.

Hard-linked climate-economic models use reduced-form damage functions to link the climate with the economic module. These damage functions translate the output of the climate model (e.g. changes in temperature or sea level rise) into economic impacts (e.g. GDP loss). Several approaches are used to model this relationship. In particular, damage functions are either specified for particular sectors (e.g. in the PAGE model) or for the whole economy (e.g. the DICE model). The damage function is generally treated as a nonlinear function in temperature. In the PAGE2002 model, for example (Hope, 2009), region-specific economic and non-economic damages are taken into account. Equation 1.1 represents damages in monetary terms ($WI_{t,d,r}$), expressed as share of total output, when adaptation policies are not considered. They are a power function of regional impacts of global warning ($I_{t,d,r}$), which in turn depend upon temperature increase ($RT_{t,r}$) in excess of an adjusted tolerable level (Equation 1.2). The adjusted tolerable level, i.e. the function $g(.)$ in Equation 1.2, depends on some tolerable rate of change ($TR_{d,r}$) and on the tolerable plateau ($TP_{d,r}$).

$$WI_{t,d,r} = \left(\frac{I_{t,d,r}}{2.5}\right)^{POW} W_{d,r} GDP_{t,r} \tag{1.1}$$

$$I_{t,d,r} = max\left[0, RT_{t,r} - g\left(TR_{d,r}, TP_{d,r}\right)\right] \tag{1.2}$$

where the weights $W_{d,r}$ express the percentage of GDP lost for benchmark warming of 2.5 °C in each impact sector d ($d = 1$ and $d = 0$ for economic and non-economic damage sectors, respectively), in region r. The impact function exponent (POW) is the same in all regions and its value ranges from 1 to 3. Moreover, impacts are computed for a reference region and then scaled to specific countries with a system of weighting factors. The tolerable plateau and the tolerable rate in the focus region, the European Union, are defined as uncertain parameters ($TP_{d,0}$ and $TR_{d,0}$, respectively). Their values in all other regions are assumed to be proportional to the values of the EU, through to uncertain regional multipliers (TM_r):

$$TR_{d,r} = TR_{d,0} TM_r \tag{1.3}$$

$$TP_{d,r} = TP_{d,0} TM_r \tag{1.4}$$

In the DICE model instead (Nordhaus, 1992; Nordhaus and Boyer, 2000), aggregate net damages (D_t), expressed as a fraction of total output, are a quadratic function of global mean temperature change (Equation

1.6).[5]

$$\Omega_t = \frac{1}{1+D_t} \tag{1.5}$$

$$D_t = \theta_1 T_t + \theta_2 T_t^2 \tag{1.6}$$

In Equation 1.5, Ω_t is the climate change damage factor that transforms gross output into output net of damages; T_t is the global atmospheric temperature increase over 1900 level; θ_1 and θ_2 are parameters of the damage function, calibrated in order to get a given amount of GDP loss from a set of different impact categories, (i.e. agriculture, coastal areas, human health, other vulnerable markets, non-market amenities and human settlements and ecosystem), in correspondence of a doubling CO_2 concentration or a specific temperature increase.

In the MERGE model (Manne et al., 1995; Manne and Richels, 2004), similarly to PAGE, damages are divided into two categories: market and non-market damages (e.g. human health, species losses and impacts on environmental quality). Like Nordhaus' approach, economic damages rise quadratically with temperature change, but peculiar to the MERGE model is the treatment of the non-market dimension. Indeed, it is used the willingness-to-pay (WTP) approach, i.e. how much consumers would be likely to pay to avoid ecological damages. Equation 1.7 shows how WTP for non-market goods depends on temperature change and per-capita income:

$$WTP_{t,r} = \frac{\theta_3 T_{t,r}^{\theta_4}}{1+100\exp\left[-0.23\frac{GDP_{t,r}}{POP_{t,r}}\right]} \tag{1.7}$$

This relationship is assumed to be S-shaped, which implies that lower-income regions are unwilling to pay much to avoid non-market impacts. The WTP is calibrated so as to give up 2% of GDP in high-income countries to avoid a 2.5 °C temperature rise (1% in low-income countries).

The FUND model (Tol, 2002a; 2002b) includes sector- and region-specific impact functions. Eight key-impact sectors are considered (agriculture, ecosystems, human health, forestry, water resources, energy consumption, extreme weather, and sea level rise), each of them characterized by one or more damage functions (e.g. the human health includes functions for diarrhea, vector-borne diseases, and cardiovascular and respiratory mortality), which in turn are specified by different functional forms. In some sectors damages in monetary units, or in percentage loss of GDP, depend only on temperature, while in others CO_2 concentration is also taken into account (e.g. agriculture and forestry). The functional forms are calibrated by using results from many different empirical works, but the precise linkages are far from transparent (Fisher-Vanden et al., 2011).

Since the end of the '90s, CGE models have also been increasingly used to assess the economic impacts of climate change. Unlike hard-linked climate-economic models, they have neither a climate nor a reduced-form damage module. Physical impacts of climate change are taken from the literature or simulated with bottom-up models. This information is then used to exogenously shock some relevant variables of the economic model. For instance, sea level rise impacts are usually simulated by reducing land and/or capital endowments. The

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[5] Originally, the quadratic form of the damage function was chosen largely for convenience. However, Weitzman (2009; 2012; 2013) has pointed out that these underestimate small-likelihood, high-impact possibilities (the so-called "fat-tail").

impact of changes in temperature and precipitation on agricultural sectors is modelled as land productivity loss, or total factor productivity loss, etc. Then, taking the market substitution mechanism into account, CGE models are able to describe not only the direct, but also indirect impacts of climate change. Indeed, they are widely used to simulate the costs and benefits of climate change and of market-driven autonomous (or passive) adaptation (i.e. agents' reaction to changes in relative prices). Several studies have focused on the effects of climate change on one impact category. Most of them have analyzed the impacts on agriculture and water scarcity (Parry et al., 2004; Iglesias et al., 2011; Fisher et al., 2007; Calzadilla et al., 2010; Liu et al., 2014) or on sea level rise (Deke et al., 2001; Darwin and Tol, 2001; Bosello, Roson and Tol, 2007; Bosello, Nicholls, Richards, Roson and Tol, 2012). Few studies have assessed the impacts on tourism (Berrittella et al., 2006), health (Bosello et al., 2006), energy demand (Bosello, De Cian and Roson, 2007) or ecosystems (Bosello et al., 2011). Some analyses have focused on the interactions of multiple impacts, by analyzing the joint effect of climate change on agriculture, energy demand, human health, tourism flows, sea level rise, floods, fishing and forestry (Eboli et al., 2010; Bosello, Eboli and Pierfederici, 2012; Ciscar et al., 2011; Aaheim et al., 2012; Roson and Van der Mensbrugghe, 2012).

1.4 Economic modelling of adaptation

The modelling literature on adaptation, even though growing rapidly, still remains far less developed than that on mitigation. There are many possible explanations for this; for example, the difficulty to aggregate costs and benefits of adaptation beyond the local level or the complexity to find a well-accepted definition of adaptation.

Even so, some modelling efforts include adaptation in top-down assessments. The first example is the PAGE model (Hope et al., 1993; Hope, 2006; 2009). Here, adaptation expenditure can either increase the tolerable temperature change (i.e. the plateau and the slope of the tolerable global temperature change profile, see Equation 1.8 and 1.9, respectively), or reduce the negative effects of climate change when temperature exceeds tolerability.

$$ATP_{t,d,r} = TP_{d,r} + PLAT_{t,d,r} \tag{1.8}$$

$$ATR_{t,d,r} = TR_{d,r} + SLOPE_{t,d,r} \tag{1.9}$$

The adjusted tolerable level ($ATL_{t,d,r}$), which is the function $g(.)$ in Equation 1.2, is defined as:

$$ATL_{t,d,r} = min\left[ATP_{t,d,r}, ATL_{t-1,d,r} + (ATR_{t,d,r} - ATR_{t-1,d,r})\right] \tag{1.10}$$

As said, adaptation is included in the damage function, by reducing the negative impact of climate change. Thus, it is possible to rewrite Equation 1.1 as:

$$WI_{t,d,r} = \left(\tfrac{I_{t,d,r}}{2.5}\right)^{POW} W_{d,r}\ GDP_{t,r}\left(1 - \frac{IMP_{t,d,r}}{100}\right) \tag{1.11}$$

where $IMP_{t,d,r}$ represents the adaptation policy in terms of percentage reduction of climate change damages.

Adaptation costs ($AC_{t,d,r}$) are also considered. They depend on the change in the slope and plateau of the function representing tolerable temperature increase over time, and on the percentage reduction in weighted impacts that occurs as a result of temperature increase above the tolerable level:

$$AC_{t,d,r} = CP_{d,r}PLAT_{t,d,r} + CS_{d,r}SLOPE_{t,d,r} + CI_{d,r}IMP_{t,d,r} \tag{1.12}$$

where $CP_{d,r}$ is the cost of plateau adaptation (\$M/°C); $CS_{d,r}$ is the cost of slope adaptation (\$M/°C); $CI_{d,r}$ is the cost of impact adaptation (\$M/%). Even though it is the first IA model to include adaptation, this variable is exogenously set by the modeller. Therefore only cost-effectiveness analyses can be done.

A further example of a top-down treatment of adaptation is offered by the FUND model (Tol, 2007). It explicitly models endogenous adaptation against sea level rise, where the level of coastal protection is defined through a cost-benefit criterion (Fankhauser, 1995).

Other developments are provided by de Bruin, Dellink and Agrawala (2009), who introduce reactive adaptation in the AD-DICE/AD-RICE model. They define net damages (Equation 1.13) as a function of protection costs (AC_t) and residual damages, which in turn depend on gross damage and protection ($ADAP_t$). Protection costs are convex in protection levels, that is decreasing marginal returns to adaptation are assumed (Equation 1.14).

$$ND_t = \left(\theta_1 T_t + \theta_2 T_t^2\right)(1 - ADAP_t) + AC_t \quad 0 < ADAP_t < 1 \tag{1.13}$$

$$AC_t = \gamma_1 ADAP_t^{\gamma_2} \quad \gamma_1 > 0; \gamma_2 > 1 \tag{1.14}$$

According to this modelling framework, adaptation is treated as a flow variable, i.e. its costs and benefits accrue within the same period. Indeed, adaptation expenditures are readjusted period-by-period in response to current damage.[6] Bosello et al. (2009), Bosello et al. (2013) and Agrawala et al. (2011) propose a further enrichment, modelling both anticipatory and reactive actions.

In particular, by using the AD-DICE/AD-RICE model, Agrawala et al. (2011) combine reactive/flow (FAD_t) with anticipatory/stock adaptation (SAD_t), in a CES nested function:

$$ADAP_t = \beta_1 \left[\beta_2 FAD_t^{\rho} + (1 - \beta_2) SAD_t^{\rho}\right]^{\frac{\beta_3}{\rho}} \tag{1.15}$$

In Equation 1.15, the adaptation capital stock is created with investments in adaptation (IA_t):

$$SAD_{t+1} = (1 - \delta) SAD_t + IA_t \quad \delta = 5\% \tag{1.16}$$

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[6] The same approach has been used by Hof et al. (2009) to model adaptation and residual damage functions in the FAIR model (den Elzen and van Vuuren, 2007; Hof et al., 2008). They have studied the effectiveness of international financing of adaptation costs, by using the revenue from emission trading.

Adaptation costs are given by both, adaptation flow and investments in adaptation, and the net damage function can be rewritten as:

$$ND_t \quad = \quad \frac{\theta_1 T_t + \theta_2 T_t^2}{1 + ADAP_t} + AC_t \tag{1.17}$$

By using the AD-WITCH[7] model, Bosello et al. (2009) consider three types of adaptation: (i) proactive or anticipatory adaptation, which takes the form of defensive capital stock ($SAD_{r,t}$), and it is used when future damage materializes; (ii) reactive adaptation, which is undertaken simultaneously with climate change damage ($FAD_{r,t}$); and (iii) investing in R&D (or "knowledge adaptation"), which is treated as a special form of anticipatory adaptation, and thus considered as a stock variable ($HAD_{r,t}$). These three adaptation strategies are aggregated by using a nested constant elasticity of substitution function (see Figure 1.3); at the top level, defensive stock and composite reactive adaptation ($RAD_{r,t}$) is aggregated (Equation 1.18), while at the bottom level, composite reactive adaptation is determined by R&D investments and reactive adaptation expenditures (Equation 1.19).

$$ADAP_{r,t} \quad = \quad \beta_1 \left[\beta_2 RAD_{r,t}^{\rho} + (1 - \beta_2)\, SAD_{r,t}^{\rho}\right]^{\frac{\beta_3}{\rho}} \tag{1.18}$$

$$RAD_{r,t} \quad = \quad \theta_1 \left[\theta_2 FAD_{r,t}^{\rho} + (1 - \theta_2)\, HAD_{r,t}^{\rho}\right]^{\frac{\theta 3}{\rho}} \tag{1.19}$$

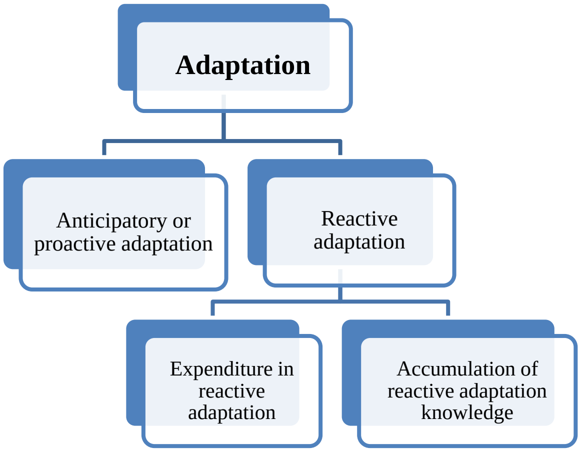

Figure 1.3: The adaptation tree in the AD-WITCH model
[Source: Bosello et al. (2009)]

In Bosello et al. (2013) adaptation is determined instead by aggregating total adaptive capacity building ($ACB_{r,t}$) and adaptation actions ($ACT_{r,t}$), by using a CES function:

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[7] It is the adaptation extension of the WITCH model, which in turn is an energy-economy-climate model that can be solved under two alternative game-theoretic setting: a non-cooperative scenario in which each region maximizes its own welfare, taking other regions' decisions as given; and a cooperative scenario in which a social planner maximizes the world welfare (Bosetti et al., 2007).

$$ADAP_{r,t} \quad = \quad \theta_1 \left[\theta_2 ACT^{\rho}_{r,t} + (1-\theta_2)\, ACB^{\rho}_{r,t}\right]^{\frac{1}{\rho}} \tag{1.20}$$

At the second level of the nested structure, adaptation actions are given by a stock variable for anticipatory adaptation and a flow variable for reactive adaptation (it is equivalent to Equation 1.15 in Agrawala et al.'s version):

$$ACT_{r,t} \quad = \quad \beta_1 \left[\beta_2 FAD^{\rho}_{r,t} + (1-\beta_2)\, SAD^{\rho}_{r,t}\right]^{\frac{1}{\rho}} \tag{1.21}$$

At the second level, as well, adaptive capacity building (i.e. the ability of the system to adjust to climate change) is given by specific ($SAC_{r,t}$) and generic ($GAC_{r,t}$) capacity building, which are stock and flow variables, respectively:

$$ACB_{r,t} \quad = \quad \gamma_1 \left[\gamma_2 SAC^{\rho}_{r,t} + (1-\gamma_2)\, GAC^{\rho}_{r,t}\right]^{\frac{1}{\rho}} \tag{1.22}$$

The generic component is related to economic development of a region and it is modelled as a function of regional total factor productivity. The idea behind this relationship is that the country's ability to adapt depends on its level of development. Specific adaptive capacity instead depends on R&D investments or investments in regional climate change impacts. Figure 1.4 shows the adaptation tree.

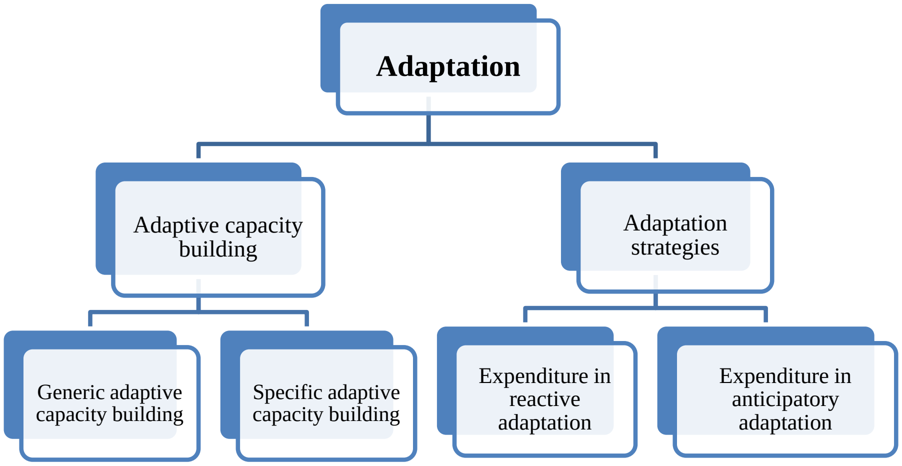

Figure 1.4: The adaptation tree in the AD-WITCH model
[Source: Bosello et al. (2013)]

Millner and Dietz (2015) study the relationship between adaptation and growth in developing countries. By doing so, they develop a model, built on the standard neoclassical growth model (e.g. Nordhaus, 1992; Nordhaus and Boyer, 2000). They consider two types of capital stock: productive capital (KV_t) and adaptive capital (KA_t). The former is aggregated with labor to produce total output, and it is vulnerable to climate change. The latter instead, is unproductive, but can reduce the impacts of climate change. Indeed, the climate change damage factor (Ω_t) depends on aggregate net damages and on adaptive capital:

$$\Omega_t \quad = \quad \frac{1+g(KA_t)}{1+g(KA_t)+\theta_1 T_t+\theta_2 T_t^2} \tag{1.23}$$

$$g(KA_t) \quad = \quad \beta_1 KA_t^{\beta_2} \quad \beta_1 > 0; \beta_2 \in [0,1] \tag{1.24}$$

Finally, there are some examples of the introduction of planned adaptation in CGE models. It is usually modelled as a re-direction of regional resources toward protection activities, which in turn reduce climate impacts. One example is Deke et al. (2001), who use a recursive-dynamic CGE model to quantify the economy-wide effects of the investments necessary to defend coastal areas from sea level rise. Coastal protection (e.g. building or raising dikes, elevating beaches, etc.) reduces regional investment. This essentially decreases capital accumulation, and therefore future GDP and consumption. So, adaptive expenditures are modelled as a capital loss, ignoring the induced investment demand for coastal protection (e.g the demand for dike building and seawalls from the construction sector).

A slightly different strategy to model adaptation investments is proposed by Darwin and Tol (2001). By using a static CGE model, they also analyze the impacts of sea level rise and coastal protection. Although defensive investments reduce capital accumulation, in Darwin and Tol (2001) this reduction occurs within the same period in which coastal protection occurs.

In both studies, adaptation is treated as an investment in unproductive capital. Therefore, ignoring its multiplicative effects on the demand side of the economy, they overestimate the costs of climate change. Moreover, adaptive investments crowd out other forms of investment (and thus reduce capital services) rather than consumption.

Bosello, Roson and Tol (2007) and Bosello, Nicholls, Richards, Roson and Tol (2012) also assess the macroeconomic effects of sea level rise and coastal protection. However, they take into account the multiplicative effects of adaptation on the demand side of the economy. In particular, they exogenously fix regional investments, by adding the additional expenditure for coastal protection and by allowing for endogenous changes in the share of national income devoted to savings. Therefore adaptation investments displace consumption rather than other investments.

1.5 Results

1.5.1 Climate change impacts

The literature on the economic impact of climate change is wide. Since the first study of the global welfare impacts of climate change done by Fankhauser (1994), many others have followed. Their results are well-summarized by the IPCC reports (IPCC, 2001; IPCC, 2007; IPCC, 2014a), the Stern Review (Stern, 2007) and by Tol (2009, 2014).

Both hard-linked and soft-linked IA models study the economic cost of climate change impacts, based on scenarios of economic and demography changes, future emissions, temperature increase and other climatic factors, such as precipitation and sea level rise. They then translate climate impacts into economic consequences. In general, there are two indicators usually used to express the economic costs of climate change: changes in GDP and the social cost of carbon.

By considering the overall impact of climate change on global GDP, studies agree that the loss remains relatively moderate for changes in temperature below 2 °C (a few percentage points of GDP). For example, Bosello, Eboli and Pierfederici (2012) have estimated a global GDP reduction of approximately 0.5% if there is a 1.92 °C temperature increase by 2050. Although estimates are based on extrapolation from few cases studies, as temperatures rise further, the economic impact of climate change, aggregated over countries and over sectors, increases quickly, and the estimated results are widely ranged. Tol (2013) has shown a 1.2% GDP loss by 2100 if temperature increase reaches 3.5 °C. Higher costs have been estimated by Roson and Van Der Mensbrugghe (2012). Accounting only for labor productivity impacts, they have found a 4.6% GDP loss for approximately a 5.5 °C temperature increase (4.87 °C above 2000 levels) by 2100.[8] Nordhaus (2013) instead has found a GDP reduction of 2% if there is a 2.9 °C temperature increase by 2100.

Considering just the aggregated impact of climate change however conveys a partial and potentially misleading picture. Studies that analyze the impacts on regional GDP have shown that low-income countries are subjected to much higher than average economic losses. For example, in Roson and Van Der Mensbrugghe (2012) the most vulnerable region in 2100 is East Asia with a GDP loss of 12.6%, followed by the Middle East and North Africa (-10.3%). In Bosello, Eboli and Pierfederici (2012), South Asia, South-East Asia, North Africa and Sub-Saharan Africa would be the most seriously impacted regions, with GDP loss ranging from -1.5% to -3.1% in 2050. Tol (2013) also found strong negative impacts in some Latin American countries (e.g. Brazil, Peru, Ecuador, and Mexico) and in Russia. There are several reasons to explain the higher economic costs of climate change for developing countries. Firstly, low-income countries tend to be in low-mid latitudes, which are characterized by higher temperature increases. Secondly, these economies are highly reliant on climate-dependent sectors, such as agriculture. Finally, they are less able to adapt because of the lack of institutions and financial resources (Tol, 2009).

Several studies have analyzed the contribution of different impact categories to the overall economic cost of climate change. Bosello, Eboli and Pierfederici (2012) has shown that the global GDP loss is mostly driven by the effects on agriculture, on tourism flow and on sea level rise, rather than by the effects on energy demand, flooding, forestry or health. By focusing only on the impacts of climate change in Europe, Ciscar et al. (2011) found instead that the welfare loss is mostly due to the impacts on agriculture, coastal systems and river floods. By increasing the detail of the investigation, the picture is even more diversified. For example, in the British Isles the impact on coastal systems has the strongest effect on welfare, while in Southern and Northern Europe the impact on agriculture predominates (Figure 1.5).

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[8] Although seven types of impacts (agriculture productivity, sea level rise, water availability, tourism, energy demand, human health and labor productivity) are taken into account, the overall economic cost of climate change is reported only when changes in labor productivity are considered alone. However, accounting for human health effects and direct lower productivity in hot and humid conditions, changes in labor productivity causes 76% of the overall climate change damage in 2100. Therefore they are the most significant component in determining GDP losses.

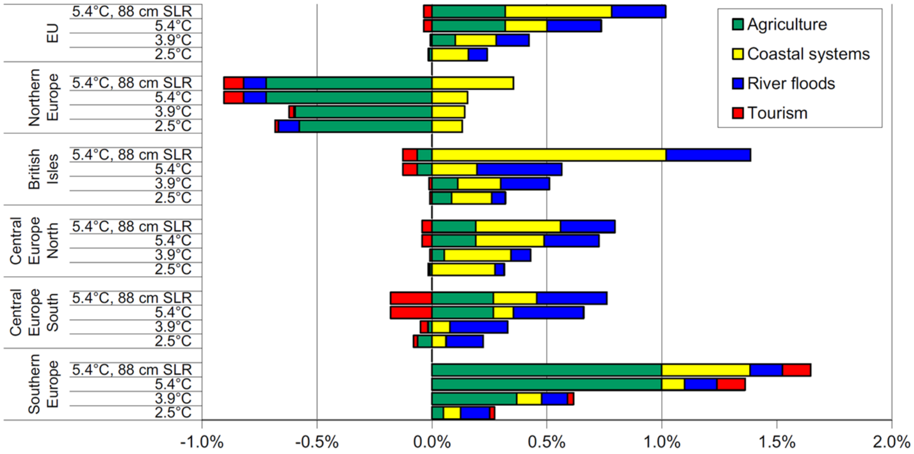

Figure 1.5: Sectoral decomposition of regional welfare loss (Δ%)
[Source: Ciscar et al. (2011)]

Another way generally used to represent the economic cost of climate change, is the social cost of carbon. It monetizes the expected welfare loss of an additional ton of carbon emitted in a given year. It is a measure of the marginal damage from carbon emissions, and thus of the marginal benefit of abatement. When the climate policy is optimal, and without market distortions, the SCC is equal to the Pigouvian tax/price of carbon.

Many highly differentiated estimates of the SCC can be found in the literature (Tol, 2009; 2011; IPCC, 2014a). In his systematic review of 311 published studies, Tol (2011) has found a mean marginal cost of carbon of \$177 per metric tonne of carbon. However, this result is skewed by some very large values; the estimated marginal cost of carbon at the 95th and the 99th percentile is \$669/tC and \$1602/tC, respectively, while at the 33th percentile is only \$35/tC.

The main driver of this huge range is the rate at which future benefits and costs are discounted, primarily due to the pure rate of time preferences (Anthoff and Tol, 2013). The spread in estimates also depends on how regional effects of climate change are aggregated. Some studies use equity weights (i.e. they give more weight to impacts in poor regions rather than in rich regions), while others do not (Anthoff et al., 2009; Fankhauser et al., 1997; Nordhaus, 2011). Diversity in SCC estimates can also depend on assumptions about future population and economic growth, future emissions, future climate change, future vulnerability and on the incorporation of uncertainty (Ackerman and Stanton, 2012; Kopp et al., 2012).

1.5.2 Adaptation

The applied literature on adaptation modelling is less extended. It has focused on some specific topics, by answering the following research questions: how do adaptation and mitigation policies interact? What is their timing profile? What is the optimal mix of adaptation investments? What are the economic costs of climate change and adaptation strategies at the regional level?

The most common answer is that adaptation and mitigation are strategic complements in reducing climate change damages. Therefore both should be considered when designing a climate policy portfolio. By using the PAGE model (PAGE2002 version), Hope (2009) analyzes the costs and benefits of climate change with, and without, adaptive and mitigation actions at the world level. He finds that more than 28% of climate change damage is reduced by adaptation and more than 32% when mitigation actions are also implemented. In line with these results, de Bruin, Dellink and Agrawala (2009), Agrawala et al. (2011), Bosello et al. (2009) and Bosello et al. (2013) also find that both mitigation and adaptation are key elements of environmental policies. However, even if adaptation benefits are higher than its costs, unlike Hope et al. (2009), they do not suggest a such aggressive adaptation policy.

A second important result is that mitigation and adaptation crowd out reciprocally. Although they complement each other in reducing climate change damage, they are also substitutes, since they compete for the same limited resources. Moreover, investing in adaptation reduces the need for investing in mitigation, and vice versa (Agrawala et al., 2011; de Bruin, Dellink and Agrawala, 2009). De Bruin, Dellink and Agrawala (2009) and Bosello et al. (2009) show that the timing of adaptation and mitigation investments is also very important. However, they report different results. De Bruin, Dellink and Agrawala (2009) say that benefits from adaptation are higher than benefits from mitigation in the short-run while the opposite occurs in the long-run. Bosello et al. (2009) instead, find that high mitigation expenditure should be made well in advance with respect to adaptation in order to have benefits in the future. They obtain this result by using the AD-WITCH model, which has a more detailed representation of the energy sector and thus can better represent carbon cycle inertia. Adaptation investments instead become progressively more effective over the long-run, when significant damage occurs.

Another important outcome is related to the composition and the timing of adaptation investments. Bosello et al. (2009), Bosello et al. (2013) and Agrawala et al. (2011) find that investments in adaptation stock should be made in the short-run, because they take time to become effective. On the other hand, investments in reactive adaptation become increasingly necessary afterwards because of the convexity of climate damage. For example, Bosello et al. (2009) show that in the short-run, under a non-cooperative setting, more than 99% of total adaptation expenditure is due to anticipatory adaptation, while in the long-run this percentage is reduced to about 43%. Reactive adaptation, instead, becomes progressively more significant. Along the all-time horizon, investments in R&D remain quite stable (around 0.5% of the total adaptation expenditure).

At the regional level, there are significant differences in terms of adaptation expenditure. In particular, most adaptation strategies are shown to take place in developing countries, which are the most vulnerable regions. Moreover, both Bosello et al. (2009) and Bosello et al. (2013) show that OECD countries devote a relatively large share of the adaptation budget to planned anticipatory adaptation, while in Non-OECD countries reactive adaptation investments are more relevant. This is due to their different sensitivity to climate change. Developed countries are more affected by sea level rise or hydro-geological risks, which require strong investments in anticipatory adaptation. In Non-OECD countries, climate change impacts will increase after the mid-century, and because of their underdevelopment, more rapid and effective action will be necessary. Therefore they will invest more in reactive adaptation.

By combining the AD-WITCH model with a CGE model, Bosello et al. (2009) consider not only policy-driven, but also market-driven adaptation. In particular, they first simulate damage with the ICES model taking only autonomous adaptation into account, and then they re-calibrate the damage function in the AD-WITCH model in order to replicate results from ICES. Once the calibration procedure is concluded, they re-examine policy-driven adaptation, and find that market-driven adaptation can reduce climate change damage, although not eliminate it.

Finally, most of these studies point out how the optimal level of mitigation and adaptation depends directly on some of the assumptions of the model, particularly those related to the level of future damage and to the rate of time preferences. They all suggest that a lower discount rate[9] increases the relative contribution of mitigation in the optimal climate policy. Intuitively, as the discount rate is lowered, the relative value of future damage becomes more relevant. Thus, mitigation, which is more suitable to deal with long-term damage, becomes the preferred policy instrument (Bosello et al., 2009; de Bruin, Dellink and Agrawala, 2009). However, when adaptation is treated as a flow variable, mitigation substitutes adaptation (de Bruin, Dellink and Agrawala, 2009); while instead adaptation stock is also considered, the optimal level of both strategies increases (Agrawala et al., 2011; Bosello et al., 2009; Bosello et al., 2013). Moreover, a lower discount rate favours anticipatory adaptation and investments in adaptive capacity building, to the detriment of reactive adaptation (Agrawala et al., 2011; Bosello et al., 2013).

Another assumption that can affect results is the sensitivity of mitigation and adaptation to damages increase. Higher damages increase both strategies. However, once again, when only reactive adaptation is considered, mitigation efforts become more profitable than adaptation expenditures (de Bruin, Dellink and Agrawala, 2009). If instead, proactive adaptation is included, the opposite occurs, i.e. the optimal level of adaptation increases much more than that of mitigation (Bosello et al., 2009).

As we have pointed out, some studies based on CGE models analyze the effects of explicit or planned adaptation. However, they focus on investments in adaptation to avoid damage from specific climate change impacts (e.g. investments in coastal protection and in irrigation projects, respectively to reduce the impacts of sea level rise and of climate change on agriculture). Therefore a comparison with previous results is difficult.

Almost all the studies on adaptation based on CGE models focus on the effects of anticipatory adaptation to avoid negative impacts of sea level rise. Examples are Deke et al. (2001), Darwin and Tol (2001), Bosello, Roson and Tol (2007) and Bosello, Nicholls, Richards, Roson and Tol (2012). However, they present several dissimilarities, but not only related to the modelling strategy used for adaptation. Therefore comparison of results is complicated. Firstly, they use different strategies to model physical impacts of climate change within the CGE model. Moreover, data for these impacts are taken from different sources. For instance, Bosello, Nicholls, Richards, Roson and Tol (2012) consider only the effects of sea level rise in terms of land loss due to erosion and inundation, while Darwin and Tol (2001) and Bosello, Roson and Tol (2007) take into account also the fixed capital loss, i.e. capital that cannot be economically moved (e.g. buildings, roads, piers, closed

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[9] All the studies choose a 0.1% pure rate of time preference, as proposed by Stern (2007).

to the coastline). The former use data for land loss from the DIVA[10] model. The latter instead use the FUND model to simulate land loss and, because of the lack of data, they assume that capital loss is equal to changes in land endowments.

Secondly, they simulate different adaptation scenarios. Deke et al. (2001) and Bosello, Roson and Tol (2007) are not able to endogenously compute the optimal level of protection. Therefore they run policy simulation rather than policy optimization analysis. Indeed, they compare a full-protection with a non-protection scenario. In particular, in the full-protection scenario, potential damage from sea level rise is totally avoided through anticipatory adaptation investments, assuming that protection costs are much lower than expected damage. On the contrary, in Darwin and Tol (2001) and Bosello, Nicholls, Richards, Roson and Tol (2012), the adaptation scenario is characterized by optimal- rather than full-protection. Darwin and Tol (2001) simulate the optimal level of protection with the FUND model, while Bosello, Nicholls, Richards, Roson and Tol (2012) run DIVA. Moreover, different sources are used to estimate the coastal protection costs (the FUND model in Darwin and Tol (2001) and Bosello, Roson and Tol (2007); the DIVA model in Bosello, Nicholls, Richards, Roson and Tol (2012) and country-specific studies in Deke et al. (2001)).

Finally, other differences, such as the choice of the CGE model, baselines, aggregation level and time horizon, may also affect the results. Moreover, these results are usually reported in different units. For example, they are expressed as percentage variation with respect to the baseline, or in monetary terms, or as a share of GDP. Therefore a comparison of the results is unfortunately impossible. However, some general conclusions can be reached.

By only considering direct costs of sea level rise, the effects of climate change on welfare are misled. In fact, second- and higher-order effects play an important role in quantifying the costs of climate change and adaptation strategies. Because of changes in prices in all markets, allocation and redistribution effects have been observed. For instance, in some countries the negative effects on welfare are much lower than the direct cost of protection, while in others the opposite occurs. Therefore, in order to have a more comprehensive view of the economic costs of climate change and environmental policies, general equilibrium rather than partial equilibrium analysis should be done.

1.6 Discussion and Conclusions

In this paper, we have reviewed the state-of-the-art of applied economic models that are currently applied to assess climate change impacts and to evaluate adaptation policies. We have focused on the top-down approach, by considering dynamic growth and computable general equilibrium models. We have compared them in terms of the modelling strategy adopted to treat climate change impacts and adaptation policy.

Climate change is a complex and multi-facetted phenomenon. Since an interdisciplinary approach is required, hard-linked models are the best option to deal with it. They combine climate and economic features

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[10] The Dynamic and Interactive Vulnerability Assessment model has been developed by the DINAS-COAST consortium, funded by the European Union (Vafeidis et al., 2003).

in a “unified” system. Hence, they give a full-representation of the phenomenon. The climate module usually feeds a damage function, which provides the effects of climate change on the economy. However, previously described damage functions are mostly based on temperature change only, and they are calibrated by considering few impacts functions. Moreover, since there are not empirical evidences, or an economic theory, that tells us how damage function should look like, the existing models are characterized by a significant degree of arbitrary, particularly when the functional forms and the corresponding parameter values are chosen. Therefore, this considerable amount of arbitrary choice would strongly affect IA model results, and consequently, their policy recommendations. In this regard, Pindyck says that “IAM based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading” (Pindyck 2013, p.861). Stern also criticizes IAMs and highlights the necessity of a new generation of models in all three of climate science, impact and economics (Stern, 2013).

Soft-linked models instead do not have an explicit damage function. Exogenous shocks are included in the economic model (e.g. a CGE model) to simulate physical impacts of climate change (e.g. change in primary factors productivity, change in behavioral parameters, etc.). Potentially, they can treat many impacts, and so they can have a more detailed representation of climate change, than hard-linked models. Moreover, once physical impacts are set, the model would simulate the monetary cost of climate change, without the necessity to define an arbitrary damage function. However, they require a large amount of data, which should be produced from experts of different disciplines, by assuming the same socio-economic and climatic scenarios and at the highest resolution, both in geographically and temporally terms. The large amount of required data and the complex interdisciplinary process increase the probability to introduce errors, which expose results to considerable uncertainty.

The economic system can be represented by using either CGE or dynamic growth models. The key strength of CGE models is their ability to address the economy-wide features of climate change, by considering not only direct, but also indirect effects. In particular, they can describe higher-order effects, due to linkages and/or feedbacks between different sectors, actors and countries. Moreover, they can provide the best representation of international trade. Therefore they are able to represent the impacts of climate change on international competitiveness. However, many studies do not take advantage of these potentialities, because the data availability of physical impacts limits their geographical and sectoral resolution. Moreover, even if there would not be constrains related to data availability, their high resolution comes at the cost of their inability to describe intertemporal feedbacks. In fact, the majority of previous works is based on static CGE models, which simulates current or future climate and socio-economic conditions. Some studies have applied recursive dynamic CGE models, characterized by an endogenous capital accumulation. However, these models are based on the assumption of adaptive or static expectations, i.e. when intertemporal decisions have to be taken, agents do not use all the scarce and costly information available. Dynamic growth models instead, are able to consider both backward and forward linkages. Hence, they can fully describe the impact of climate change over time. However, this representation of dynamic features constraints the geographical and sectoral representation of the model. IA models in fact are relatively aggregated (most of them are single-country models or single-production sector model). Both, dynamic growth and CGE models, use sensitivity analysis to deal with uncertainty related to climate variability, by focusing on one parameter at a time. Sensitivity analysis can also be performed by Monte Carlo methods, where multiple unknown parameters are randomized, by assuming a specific probability distribution for each of them. However, this approach requires a large number of model-runs (typically from 100 to 1000 runs), and thus a too long running time. In particular, large-scale CGE model are difficult to run probabilistically.

Many challenges still remain and future research has to be done. Significant progress could be obtained along two lines: firstly, more work has to be made to define damage functional forms and its parameters value. In the calibration procedure of the damage function, more impacts categories should be considered. Moreover, to consider the multi-facets of the climate change phenomenon, more collaboration and integration between different disciplines is required. Experts from different fields should produce data on physical impacts at the highest geographical and sectoral resolution. Futhermore, highly disaggregated economic models should be used. However, improvements have to be done in modelling intertemporal decisions, technical progress and uncertainty.

Secondly, further modelling developments are required to deal with explicit adaptation. Up to now, only few models include planned adaptation, through a re-direction of investments, at the regional or global level. By doing so, responses to climate change at the sectoral level are not considered. In addition, in order to have a better representation of adaptation, more impact categories and more empirical evidences should be used to calibrate adaptation functions. Moreover, uncertainty on key parameters should be considered by using stochastic approaches.

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Chapter 2

Rational versus static expectations in CGE modelling: An analysis of the European mitigation policy

Anna Dellarole[⋆]

Abstract

Most dynamic computable general equilibrium models, used to analyze climate policy impacts, are based on the assumption of "static" expectations. This simplification enables the models to handle huge sectoral and country dimensions. However, intertemporal effects are weakly treated. This paper improves upon the myopic representation of expectations offered by standard recursive dynamic CGE models. It develops a new specification of the Intertemporal Computable Equilibrium System (ICES) model, developed at the Fondazione Eni Enrico Mattei, to include rational expectations assumption. After benchmarking both the standard ICES model and the model with rational expectations to the same economic growth path, we analyze how differently agents behave when European mitigation policies are expected in advance. The simulation results suggest that expectations play a key role in determining the cost-effectiveness of mitigation policies. By anticipating the negative effect of the policy on future capital productivity, rational investors move capital outside Europe, avoiding future economic losses. Because of this reallocation effects across countries, European capital accumulation is negatively affected, increasing macroeconomic costs, compared to the surprising policy scenario. However, these negative effects guarantee emissions reduction prior to the policy implementation.

JEL classification: C68, C63, Q48, Q56

Keywords: Rational expectations; Dynamic Computable General Equilibrium Analysis; Policy anticipation; EU Climate Policy

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2.1 Introduction

The role of expectations is crucially important in determining the outcome of any policy, and the cost-effectiveness of future environmental regulations makes no exception. As a matter of fact, markets respond not only to current policies, but also to predicted future regulations. For instance, expectations of future emissions reduction policies may affect firms' decisions to invest immediately in green technology. Investors may decide to move capital outside of the regulated country to avoid competitiveness losses. Owners of nonrenewable resources may stimulate the demand for such stock before the cost of their extraction is heavily impacted by the new regulation.

The key role of expectations is not a new theme in economics. It was firstly pointed out by Keynes with the so-called "animal spirits"[11] behaviors (1936), but only later complete forecasting rules were developed by the extrapolative (Metzler, 1941; Friedman, 1957) and the rational expectations theories (Muth, 1961; Lucas, 1972; 1973; Sargent and Wallace, 1973). Although there are several formulations of the extrapolative forecasting rule,[12] a least common denominator can be identified: agents base their conditional expectations on present and past realizations of the forecasted variable, by making systematical errors in their predictions. Rational actors instead, use all the scarce and costly information available and, knowing the structure of the economy, they can correctly predict, on average, the future trend of economic variables. Therefore, while backward-looking agents are surprised by the implementation of any policy, rational agents adapt their behaviors in advance expecting future regulations.

Quantitative macro-economic assessments of mitigation policies are mostly based on recursive dynamic computable general equilibrium (CGE) models or on optimal growth models.[13] The former have the advantage of representing explicitly linkages between different components of the economic system, by considering both direct and indirect effects of the evaluated policy (e.g. distributional effects, structural changes in the production structure, trade effects, competitiveness effects, etc.). However, intertemporal effects are weakly treated. Typically, only backward linkages are taken into account and thus intertemporal solution of the

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[11] Keynes stressed the central role of expectations in determining agents' behaviors: "Most, probably, of our decisions to do something positive, the full consequences of which will be drawn out over many days to come, can only be taken as a result of animal spirits-of a spontaneous urge to action rather than inaction, and not as the outcome of a weighted average of quantitative benefits multiplied by quantitative probabilities" (Ch. 12, 1936). However, he did not formulate an explicit expectations formulation rule.

[12] There are different formulations of extrapolative expectations theory. Metzler (1941) suggests that expectations depend on the actual realization of the forecasted variable plus an adjustment factor, which is given by the direction of past changes of that variable. Another formulation is the static/myopic expectation model, which assumes that today expectations are exactly equal to the actual realization of the variable under consideration. The most well-known version of this forecasting theory is the adaptive expectations rule. In particular, most models developed in the 1960s and 1970s incorporate the hypothesis that people form expectations adaptively and so, by using past experiences, they gradually correct forecast errors (Friedman, 1957). For this reason, the adaptive paradigm is also called the error-learning model. In detail, the formulation of expectations is based on a weighted sample mean of past observations, with geometrically decreasing weights going back to the past.

[13] Macroeconometric models can also be used in the economic assessment of mitigation policies (see for example, Barker and Scrieciu, 2010; Barker et al., 2015; Ekins et al., 2012; Pollitt et al., 2012). However, because of data constraints and because of their structural features, they are more suited for national analyses and for short/medium-run studies. For these reasons, they are less used than CGE and dynamic growth models.

model are found as a sequence of static equilibria (e.g. GREEN,[14] MIT-EPPA,[15] WorldScan,[16] GEMINI-E3,[17] DART[18] model, etc.). Hence, while economic actors handle complex static optimization problems in each period, they become myopic and stop to optimize when intertemporal decisions have to be taken. This simplification enables the models to handle huge sectoral and country dimensions; however, it allows agents to make systematical errors in their predictions. Fully-dynamic optimization models instead are based on the rational expectations assumption. They have the advantage of quantifying not only intra-temporal, but also inter-temporal substitution possibilities. However, the presence of both backward and forward linkages makes the models more difficult to solve and constraints the degree of sectoral and regional details. Most of the fully-dynamic models in fact are single-country (e.g., the IGEM[19] model), single-production sector (e.g. the DICE/RICE[20] model) or single-actor intertemporal optimization model (e.g. the MERGE[21] model).

As discussed above, expectations play a key role in determining the policy outcome. Nevertheless, they are not thoroughly represented by CGE models. The main goal of this paper is to improve upon the myopic representation of expectations offered by standard recursive dynamic CGE models.[22] By using the Fair-Taylor algorithm, we simulate rational expectations in ICES[23] (a multi-country, multi-sector, recursive dynamic CGE model), by correcting systematic errors in agents' belief from one iteration to another (Dixon et al., 2005). We then analyze how different expectation structures affect the cost-effectiveness of mitigation policy. By using the EU climate policy as a case study, under the assumption that governments' purposes are credible from the beginning of our simulation period (Adams et al., 2001; Bosetti et al., 2009; Blanford et al., 2009; Bauer et al., 2014), we verify if, with rational agents,[24] an anticipation effect occurs and how this affects main economic variables of interest: environmental effectiveness, sectoral production and country GDP, prior to

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[14] The GeneRal Equilibrium ENvironmental model was developed by the OECD (Burniaux et al., 1992).

[15] The MIT Emissions Predictions and Policy Analysis is a recursive-dynamic multi-regional general equilibrium model of the world economy (Babiker et al., 2001).

[16] WorldScan is a recursively dynamic general equilibrium model for the world economy, developed for the analysis of long-term issues in international economics, such as climate change, economic integration and trade (Bollen et al., 1999).

[17] The General Equilibrium Model of International–National Interactions between Economy, Energy and the Environment was developed jointly by the French Ministry of Equipment and the French Atomic Energy Agency (Bernard and Vielle, 2008).

[18] The Dynamic Applied Regional Trade is a recursive-dynamic, multi-regional trade model (Springer, 1998).

[19] The Intertemporal General Equilibrium Model for the U.S. economy was firstly constructed by Jorgenson and Wilcoxen (1993) and by Ho and Jorgenson (1994).

[20] The Dynamic Integrated Climate and Economy has been developed from a series of energy models by Nordhaus (1992), while the Regional Dynamic Integrated Model of Climate and the Economy was originally developed and presented in Nordhaus and Yang (1996).

[21] It is a model for evaluating regional and global effects of greenhouse gases reduction policies (Manne et al., 1995).

[22] A similar exercise has been done by Babiker et al. (2009), introducing forward-looking behaviors in a recursive dynamic CGE model. In particular, they have combined the standard MIT-EPPA model with the classical Ramsey economic growth model, in which the representative agent maximizes the present value of the utility function. However, the computational demand of intertemporal optimization constraints the degree of sectoral, regional and technology details, and the length of the horizon. Hence, the authors have conclude that "while the forward-looking model has value for some problems, the recursive model produces similar behaviors in the energy sector and provides greater flexibility in the details of the system that can be represented" (Babiker et al. 2009, p.1353).

[23] It is the Intertemporal Computable Equilibrium System developed at the Fondazione Eni Enrico Mattei (www.feem-web.it/ices/).

[24] Since ICES is a deterministic model, rational expectations is equivalent to perfect foresight. However, in a stochastic model, the former implies that forecasts are unbiased and forecast errors are uncorrelated with any information available to economic actors. The latter instead, implies that there is not uncertainty and future events are predicted without errors. Hence, to be more precise, we use the expression of rational expectations referring to "perfect foresight" definition. In fact, in our setting, representative agents know precisely about the future events (i.e. the change in future policy is treated as a deterministic rather than a probabilistic shock).

the policy implementation. Furthermore, we address the issue of timing of the policy, by investigating the different reaction to a gradually-implemented versus a one-shot mitigation policy.

The structure of the paper is as follows. Section 2.2 provides the background regarding anticipation effects of mitigation policies. Section 2.3 gives a brief overview of the standard ICES model and describes its new specification to include forward-looking behaviors. In addition, it presents the baseline scenario and the policy scenarios. Section 2.4 focuses on simulation results and Section 2.5 presents concluding remarks.

2.2 Background

The first Kyoto commitment period[25] ended in 2012, left the world without a global agreement on greenhouse gases (GHG) emissions reduction. While international conferences have followed upon each other trying unsuccessfully to reach such an agreement, individual countries and groups of countries started to introduce unilaterally mitigation policies at regional, national and subnational level. In this context, the European Union has assumed the leadership in international environmental policy. In particular, in 2007 the European leaders committed to the European Energy Policy, known as “20-20-20” strategy (EC, 2007). It is a set of binding regulations, which aims to ensure three targets for 2020: (i) a 20% reduction of the EU greenhouse gas emissions compared to 1990 levels; (ii) a 20% improvement in energy efficiency; and (iii) a 20% share of energy consumption from renewable energy source (RES). In 2014, the EU leaders defined new targets for 2030: domestic greenhouse gas emissions must be reduced by at least 40% compared to 1990 levels, while the other two targets, i.e. the energy efficiency and the share of renewable energy, are set at 27% by 2030 (EC, 2014).

Both European mitigation policies have been announced largely before they came into force to give firms and consumers time to adjust to the new regulation.

If the policy announcement is credible, economic actors react prior to its implementation and two opposite effects can be observed (Smulders et al., 2012): (i) a positive effect when emissions reduction starts prior to the policy implementation since it is less costly to reach gradually the environmental goal (demand side effects); or (ii) a negative effect when owners of fossil fuels resources reduce their prices to stimulate the demand to exhaust their nonrenewable finite stocks prior to the policy implementation (supply side effects). This may determine policy ineffectiveness, by increasing unintentionally global emissions (the so-called “Green Paradox” by Sinn)[26] or total climate costs (the “Strong Green Paradox”).[27] Whether the positive or the negative effects prevail is still an open question.

So far, the green paradox has been analyzed mostly by theoretical papers, especially by focusing on the supply side of fossil fuels markets. Di Maria et al. (2012), by using a la Hotelling model, study the

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[25] The Kyoto Protocol (1997) is the first legally binding international agreement, linked to the United Nations Framework Convention on Climate Change (UNFCCC), which commits its Parties to reduce greenhouse gas emissions by an average of 5% below 1990 levels, during the first commitment period (2008-2012).

[26] “This possibility is called the green paradox, because it shows that good intentions do not always breed good deeds” (Sinn, 2008).

[27] Gerlagh (2011) distinguishes between a weak and a strong green paradox. The former determines an increase in emission prior to the policy implementation, while the latter determines an increase in aggregate welfare costs.

effects of a mitigation policy announcement on both nonrenewable resources extraction and emissions, by considering resources with different carbon content. Less of a nonrenewable resource can be extracted when emissions are constrained. Hence, during the interim period between the policy announcement and the policy implementation, resource owners lower the price and increase extraction of their nonrenewable and finite resources in order to exhaust their stocks. This is the so-called abundance effect. The impact on emissions however depends on the carbon content of the extracted resources (the ordering effect). Only if low-carbon input is relatively scarce or fossil fuels resources are imperfect substitutes, it is optimal to increase both, the extraction of high-carbon content resources and emissions, prior to the policy implementation.

Michielsen (2014) considers a model with three energy types: a dirty exhaustible resource (e.g. oil), and imperfectly substitutable clean (e.g. solar) and abundant dirty backstops (e.g. coal). He finds that the occurrence of the green paradox depends on the substitutability between energy types and the emission-intensities. In particular, the presence of an emission-intensive and abundant dirty backstop reduces the negative effect of announcing carbon taxes. In fact, anticipated carbon taxes determine substitution from coal to oil in the future, which induces oil owners to postpone extraction. However, since today the substitutability between coal and oil is low, the current reduction in oil supply does not cause a significant increase in coal demand.

Both announcement and leakage effects[28] are considered by Eichner and Pethig (2011). By using a two-period, three-country general equilibrium model with forward-looking agents and a nonrenewable resource, the authors find that a unilateral emission reduction always determines carbon leakage. On the contrary, after the announcement of tightening an emissions cap, a green paradox may occur depending on some demand and supply conditions, i.e. intertemporal elasticity of substitution and the price elasticities of fuel demand.

Smulders et al. (2012) study whether the green paradox occurs without assuming the exhaustibility of energy resources. Setting aside scarcity allows them to focus on the announcement effects on consumption-saving decisions, rather than on fossil fuel owners' responses. They find that the green paradox occurs because households, by anticipating future effects of the policy, reduce consumption and increase saving, which in turn stimulate capital stock accumulation. The expansion in capital stock determines an increase in the use of fossil fuels energy, which in turn produces a rise in emissions prior to the policy implementation.

The empirical literature offers fewer quantitative assessments of the announcement effects of mitigation policies. Bosetti et al. (2009), by using a fully-dynamic optimization integrated assessment model, focus on the effects of anticipating future climate policies on optimal investment in energy technology and innovation. They find evidence that developing countries anticipate the effects of future climate policies and start to readjust their investment decisions in advance (10 and 15 years prior to the policy implementation for investment and innovation, respectively). Accordingly, emissions reduction begins prior to policy implementation. Similar results are found in Blanford et al. (2009). They show that developing countries start to decrease their emissions immediately, by anticipating their future participation into climate coalition. The overall economic

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[28] Carbon leakage is the term used to define a situation in which a unilateral mitigation policy negatively affects global emissions. It is conventionally defined as the share of emissions reductions in abating countries that may be offset by an emissions increase in non-abating countries (Paltsev, 2001).

cost of the environmental regulation is reduced too. Bauer et al. (2014) show that both, fossil fuels demand and emissions, decrease in the interim period. If the carbon tax starts at low levels, the reduction begins 5 years before the policy implementation; if instead the tax is initially higher, emissions start to be reduced 15 years before the policy implementation. However, the abundance effect dominates the demand side effects when the announcement is made too early before the tax implementation.

In summary, notwithstanding a quite extended theoretical literature, the existence of a green paradox following the environmental policy announcement has received less attention by quantitative analyses. This leaves space for further applied research, especially considering that the empirical findings seem to be opposite than the theoretical ones.

2.3 The ICES model

Overview of the model

ICES (see Appendix A for more details) is a multi-region, multi-sector, recursive dynamic computable general equilibrium model of the global economy, derived from the static GTAP-E model (Burniaux and Truong, 2002), which in turn is the energy environmental extension of the standard GTAP model (Hertel and Tsigas, 1999).

The main difference of ICES with respect to GTAP-E is the recursive dynamics (GTAP-E is a static model) featuring capital stock accumulation driven by endogenous investment decision. In particular, investments flowing to a country are determined by its real GDP growth and by the deviation of the country expected rate of return to capital from the world rate of return. Recursive dynamics in ICES is a typical operationalization of the extrapolative expectation theory. Agents are myopic or expectations are “static”, i.e. today forecast of next period rate of return coincides with its current realization. This allows for the existence of systematic errors when the future rate of return to capital (i.e. in ICES rate of return at time $t + 1$) does not coincide with the current one (that at time t). Investments then directly affect the evolution of capital stock net of a depreciation rate. Moreover, the model takes into account the possibility that a region can run a foreign debt or a credit position if its saving diverges from its investment. Specifically, the regional debt accumulation depends on the regional trade balance.

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 the 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 utility function.

As in the standard GTAP model, ICES uses the conceptual device of a “global bank” that collects global net savings and allocates them amongst regions according to relative rates of return to capital. In addition, bilateral trade is specified by assuming imperfect substitutability to consider product heterogeneity by virtue of country origin (Armington, 1969). Moreover, a world sector is considered, i.e. international transportation, which produces transportation services due to goods movements from origin to destination region. Particularly, it determines transport cost margins, which are given by the difference between prices reported by the importing country (c.i.f.) and prices reported by the exporting country (f.o.b.).

New specification of ICES to include forward-looking behaviors

To introduce forward looking, non-myopic agents, we implement a new specification for the expected rate of return to capital, which is the main driver of investment.

We do this by using the Fair-Taylor algorithm, which allows us to better approximate rational expectations behavior, by correcting iteratively the systematic forecasting errors (Dixon et al., 2005). In other word, we assume that expectations are determined by the actual realization of next period rate of return, computed from a previous simulation round. The starting one is given by the solution of the standard ICES model. After integrating the system forward, we verify if the rational expectation assumption is satisfied, i.e. the expected is equal to the observed rate of return. If not, an adjustment factor is introduced to correct errors in expectations. This algorithm allows solving the model year-by-year separately, without constraining the degree of sectoral and regional details. In Appendix B, there is a detailed description of the Fair-Taylor algorithm and its properties.

Then, the behavior of the standard ICES model with myopic agents (ICES_SE) is compared with the new specification (ICES_RE) in the presence of a mitigation policy. The difference between the two can also partially capture the effects of a surprise in the policy, which is anticipated by ICES_RE, but not by ICES_SE.

Scenarios

ICES uses the GTAP 8 database, which covers 129 regions and 57 sectors (Narayanan et al., 2012), calibrated in 2007. For the present exercise, 17 production sectors, 14 regions and 5 endowments are considered (Table 2.1).

Regions/countries	**Production sectors**	**Endowments**
United States (USA)	Rice	Labor
Mediterranean Europe (MEUR)	Wheat	Capital
Northern Europe (NEUR)	Other Cereal Crops	Land
Eastern Europe (EEUR)	Vegetable Fruits	Natural Resources: Forestry
Former Soviet Union (FSU)	Animals	Natural Resources: Fishing
Korea-South Africa-Australia (KOSAU)	Forestry	Natural Resources: Fossil Fuels
Canada-Japan-New Zealand (CAJANZ)	Fishing	
North Africa (NAF)	Coal	
Middle East (MDE)	Oil	
Sub Saharan Africa (SSA)	Gas	
Southern Asia (SASIA)	Oil Products	
China (CHINA)	Electricity	
Eastern Asia (EASIA)	Industry	
Latin and Central America (LACA)	Transport	
	Residential	
	Market Services	
	Non Market Services	

Table 2.1: Dimensions of the ICES model

This exercise contrasts a reference against two different policy scenarios.

The baseline is a counter-factual scenario, which goes from 2008 to 2030, characterized by no mitigation efforts. The population trend is taken from International Monetary Fund data (WEO, 2014). Historical GDP trends and economic growth projections are also driven from International Monetary Fund data (WEO, 2014); however, after 2019, these paths are in line with IPCC B2 scenario (IIASA GGI Scenario Database, 2009). Historical CO_2 emissions trends are based on the International Energy Agency data (IEA, 2014) while projections are also driven from the IPCC B2 scenario. Fossil fuel price trends are calibrated on estimates by the US Department of Energy (AEO, 2014).

Figure 2.1 and Figure 2.2 show the results of the baseline construction process, while Table 2.2 shows the harmonization between ICES_SE and ICES_RE, highlighting GDP differences smaller than 0.0005%.[29]

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[29] Appendix C describes how the model with rational expectations diverges from ICES_SE baseline if we use the same closure, instead of assuming the same economic growth.

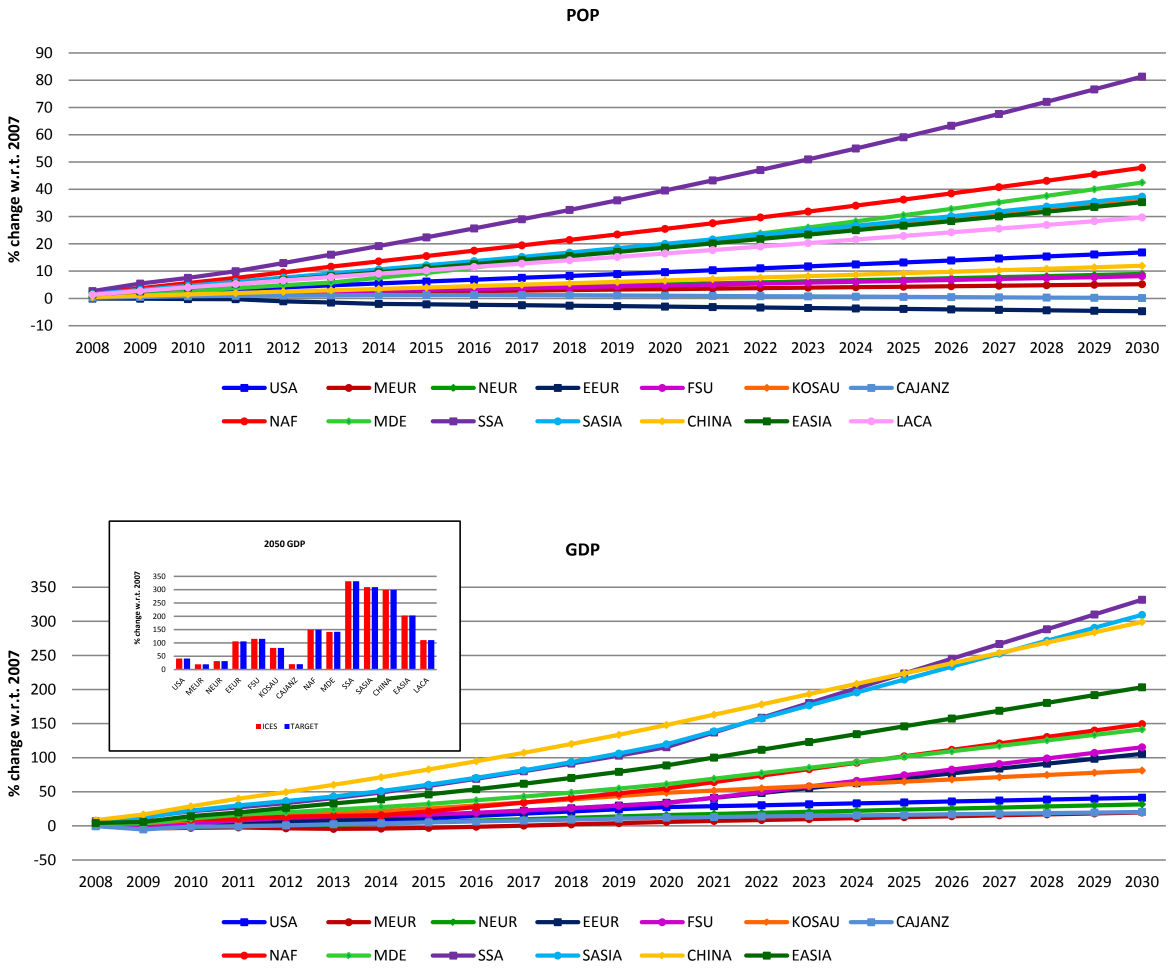

Figure 2.1: Population and GDP trends in the ICES baseline

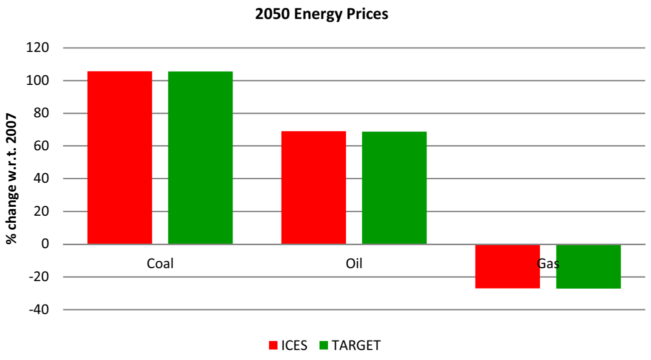

Figure 2.2: 2050 growth rates in energy prices

	2010	2015	2020	2025	2030
USA	0.0001	0.0001	0.0002	-0.0003	-0.0001
MEUR	0.0000	0.0001	0.0001	-0.0001	0.0000
NEUR	0.0001	-0.0001	0.0001	0.0002	0.0000
EEUR	0.0000	0.0001	0.0003	0.0000	-0.0001
FSU	0.0000	0.0002	0.0000	-0.0001	-0.0001
KOSAU	0.0001	0.0000	0.0000	-0.0001	-0.0001
CAJANZ	0.0001	-0.0001	0.0001	-0.0001	-0.0001
NAF	-0.0001	0.0002	0.0000	0.0000	-0.0001
MDE	0.0000	0.0002	0.0001	0.0002	0.0000
SSA	0.0000	-0.0001	0.0001	0.0000	0.0000
SASIA	0.0002	0.0000	0.0000	0.0001	0.0000
CHINA	-0.0001	-0.0001	-0.0001	0.0000	-0.0001
EASIA	0.0001	0.0002	0.0001	-0.0001	0.0001
LACA	0.0001	0.0000	0.0001	-0.0001	-0.0002

Table 2.2: Deviation in GDP between ICES_RE and ICES_SE (Δ%)

Even if the two models determine very similar economic growth paths, dissimilarities in the two baselines cannot be completely canceled as the economic structure cannot be identical across the two models. By taking into account the trend in CO_2 emissions for instance, differences can be observed, but anyway generally lower than the 1% (Figure 2.3).

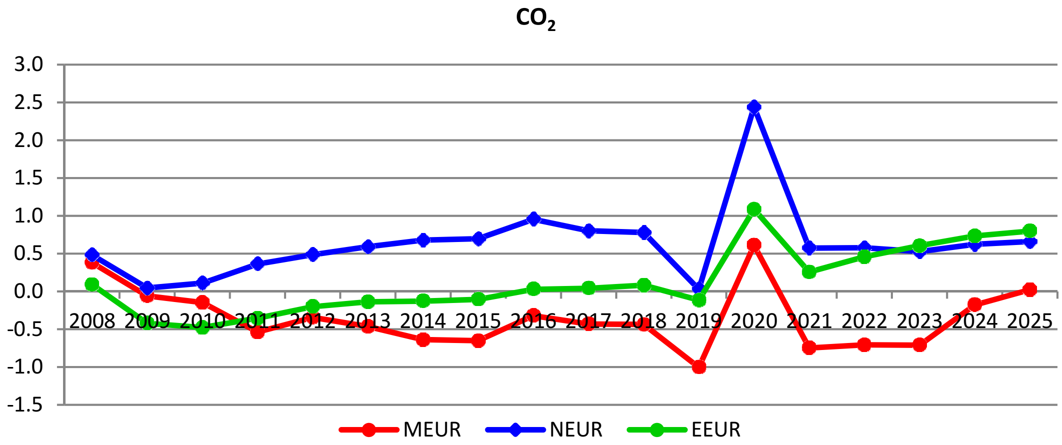

Figure 2.3: Deviation in CO_2 emissions between ICES_RE and ICES_SE (Δ%)

We consider two European mitigation policies: the 20% emissions reduction target for 2020 (2020_target) and a 30% reduction to be achieved in 2025 (2025_target), both with respect to 1990 emissions levels. This second scenario can be considered as a middle passage to achieve the recently announced EU's goals for 2030 (EC, 2014).

Both abatement targets are efficiently achieved through a cap-and-trade system, i.e. emissions in each of the three European regions of ICES are initially capped, and allocated allowances can be traded within Europe. Differently from the actual European mitigation policy, we assume that the cap-and-trade system covers all production sectors and thus only one carbon market is considered. Under this assumption, emissions are efficiently reduced in those countries and sectors where the abatement costs are lower. In particular, trading emission allowances guarantees the equalization of the marginal cost of abatement across the three European regions and thus a uniform emission price.

The initial allocation of permits is determined by assuming that each region has to reduce its emissions by 20% and 30%, with respect to 1990 level, under the two scenarios.

Policy scenarios diverge not only in terms of mitigation efforts, but also in terms of timing. The 2020 target is implemented in one-period (one-shot policy in year 2020), while the 2030 target is implemented both, gradually from 2020 to 2025 (phased-in policy) or introduced in one-period only (year 2025). Table 2.3 summarizes the policy scenarios. Results are reported as percentage deviation with respect to baselines.

Scenario Name	Target	Timing Strategy	Expectation Formation
ICES_SE_OP_2020	20% by 2020	one-shot policy	Static expectations - Unexpected policy
ICES_RE_OP_2020	20% by 2020	one-shot policy	Rational expectations - Expected policy
ICES_SE_OP_2025	30% by 2025	one-shot policy	Static expectations - Unexpected policy
ICES_RE_OP_2025	30% by 2025	one-shot policy	Rational expectations - Expected policy
ICES_SE_MP_2025	30% by 2025	phased-in policy	Static expectations - Unexpected policy
ICES_RE_MP_2025	30% by 2025	phased-in policy	Rational expectations - Expected policy

Table 2.3: Policy scenarios

2.4 Results

Unexpected 20% and 30% targets

These scenarios report the outcomes of the "standard" ICES model version, i.e. its recursive dynamic with "myopic expectations". They are commented here as offering the benchmark against which rational expectations are then tested. The 20% and the 30% emission reduction targets entail for the EU an average GDP cost of 0.38% and 1.09%, compared to baseline levels, respectively in 2020 and 2025.[30] Variation in regional GDP provides an estimate of changes in overall economic activity from the environmental policy. However, it is not necessarily indicative of how emissions reduction targets affect welfare. In this regard, we compute welfare impacts by using changes in aggregate private consumption, i.e. changes in household utility. At the EU level, the 20% target leads to a welfare reduction of less than -0.3%, compared to baseline (around -1.26% for the 30% target).

The model estimates a carbon price of 53 and $122\$_{2007}/tCO_2$, when the 2020 and 2025 emission reduction targets are respectively introduced.[31]

The cost-efficient achievement of both emission reduction targets would require that Eastern Europe puts the strongest efforts into force. This is because of an apparent lower marginal abatement costs due to the lower efficiency in energy-intensive sectors. This also translates into higher macroeconomic (GDP) costs: 0.78% in the 20% emission reduction scenario, and potentially 2.3% in the 30% emission reduction scenario. Turning to the other EU regions, the 20% emission reduction causes a GDP loss of 0.4% in MEUR and 0.32% in NEUR while for the 30% target the GDP reduction is around 1.1% and 0.9%, respectively.

By looking at Non-EU countries, the model seems to suggest negligible macroeconomic benefits. Indeed, non-EU GDP increases just by 0.02% in the 20% emission reduction scenario and by 0.1% in the 30% scenario.

Environmental leakage can be anyway problematic. In particular, non-EU countries increase their emissions by 0.75% in 2020 (and by 1.2% in 2025), which neutralizes 37.41% of European mitigation efforts (36.18% in the 30% scenario).[32] Macroeconomic effects are summarized in Table 2.D1 in Appendix D.

By following the cost increases of fossil fuels inputs, output in all sectors falls. As can be seen in Figure 2.4, larger contraction is experienced by energy sectors, where in 2020 European production decreases by 18.39% for gas, 9.82% for coal, 5.2% for oil products and 3.77% for electricity, compared to 2020 baseline levels.[33] Transportation sector, characterized by high-carbon intensity,[34] follows electricity and fossil fuels sectors in terms of output contraction (around 2.2%). All other sectors are marginally affected by the mitigation policy and their output contraction is smaller than 0.6%, compare to baseline levels.

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[30] These results are in the range of those found in the literature. In EC (2010), the 20% mitigation policy costs 0.32% of GDP, while in Bosello et al. (2013) and Kiuila et al. (2014) higher costs are found (0.57% and 0.7%, respectively). However, in these two papers the carbon market is split between ETS and non-ETS sectors and thus costs should be higher than the first-best policy. To my knowledge, no paper analyzes the effects of a 30% emissions reduction to be achieved in 2025, probably because the EU does not define the emission reduction path to achieve the 40% target in 2030. However, it is possible to compare our results with previously quoted papers, which also analyze the effects of a 30% emission reduction target to be achieved in 2020. In particular, the GDP loss is 0.63% in EC (2010), 1.26% in Bosello et al. (2013) and 1.7% in Kiuila et al. (2014). As for the 20% target, we find lower costs with respect to those studies based on second-best policies.

[31] The carbon price due to the 20% emissions reduction target, found in our analysis ($38€/tCO_2$), is in the range of values observed in the literature. However this range is rather wide. In Böringher et al. (2009), the carbon price is $68€/tCO_2$ by using the DART model, while instead it is $72€/tCO_2$ by using the GEMINI-E3 model. In the same paper, a lower price has been found if the PACE model is applied $36€/tCO_2$. In Bosello et al. (2013) the carbon price is even lower ($30.2€/tCO_2$).

[32] This result is obtained by using the leakage rate definition proposed by Paltsev (2001), i.e. the ratio of additional foreign emissions to the domestic emissions reduction.

[33] See Figure 2.D1 in Appendix D for the policy impacts on specific energy sectors.

[34] In the GTAP 8 database the transportation sector includes not only water, air, road and rail transport and but also transport via pipelines and supporting and auxiliary transport activities. This sector is characterized by high-carbon intensity.

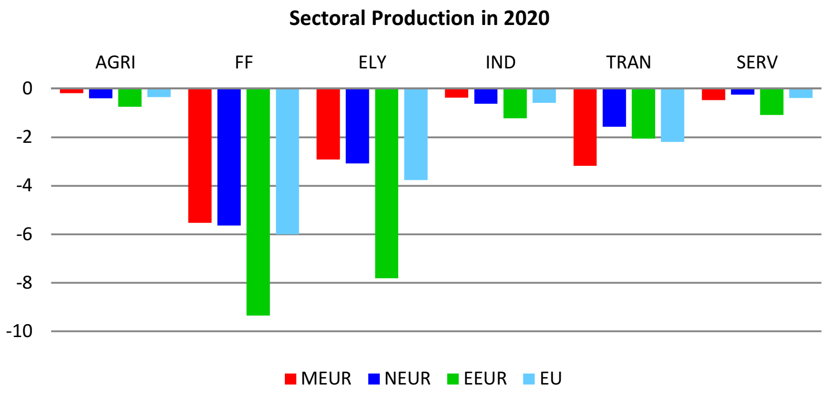

Figure 2.4: 2020 sectoral production in the EU: % change compared to baseline

The 30% target produces stronger output contraction in fossil fuels sectors. While the mitigation efforts increase by 50%, at the EU level the average production reduction in fossil fuels sectors almost doubles.[35] As it is shown in Figure 2.5, production decreases by 14.2% in fossil fuels, by 7% in the electricity sector and by 4.9% in the transportation sector, compared to 2025 baseline levels. Within Europe, the policy impacts on energy sectors depend on regional efforts in terms of emissions reduction. Hence, fossil fuels and electricity sectors are strongly affected by the environmental policy in Eastern Europe, where abatement efforts are higher compared to the other two regions.

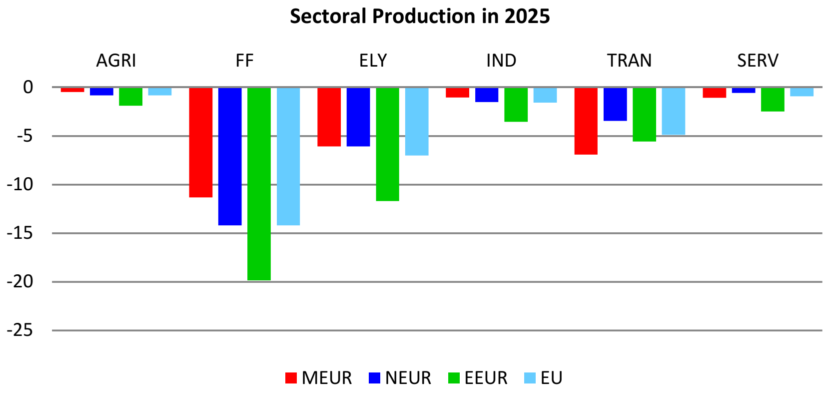

Figure 2.5: 2025 sectoral production in the EU: % change compared to baseline

Turning to effects in the primary factor markets, it can be noted that the reduction in energy use, especially of fossil origin, induces a redistribution of inputs towards other sectors. In particular, capital increases in

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[35] It is computed as the percentage variation between the change in fossil fuels production with the 30% target and with the 20% target (both are expressed in percent with respect to base-year). See Table 2.D2 in Appendix D.

agriculture and services while labor in transportation, electricity and industry sectors (see Figure 2.6 and 2.7).

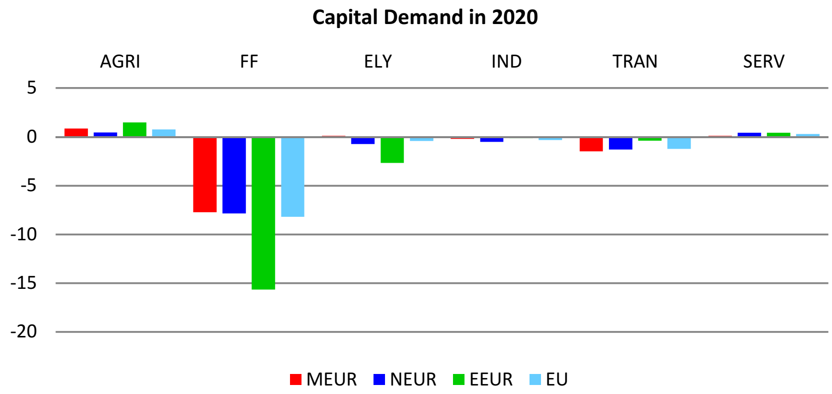

Figure 2.6: Sectoral capital demand in the EU: % change compared to baseline

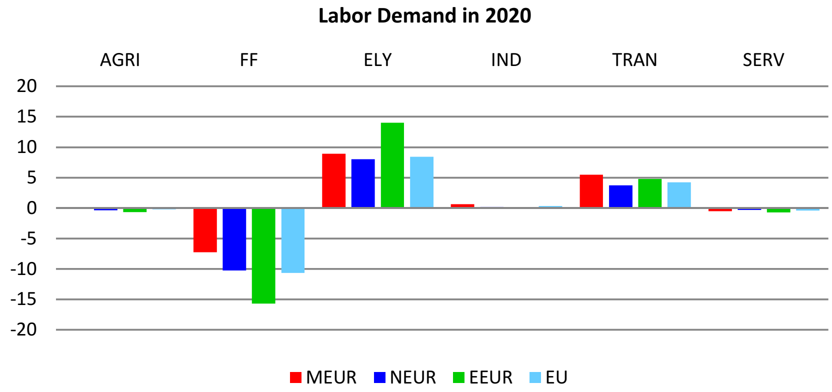

Figure 2.7: Sectoral labor demand in the EU: % change compared to baseline

Because endowments supply is fixed within periods, wages and capital rental rates have to decline in order to clear factor markets (Figure 2.8). At the European level, wage and capital prices decrease respectively by 0.37% and 1.72%, compared to the 2020 baseline level, and by 0.84% and 2.7%, compared to the 2025 baseline levels.

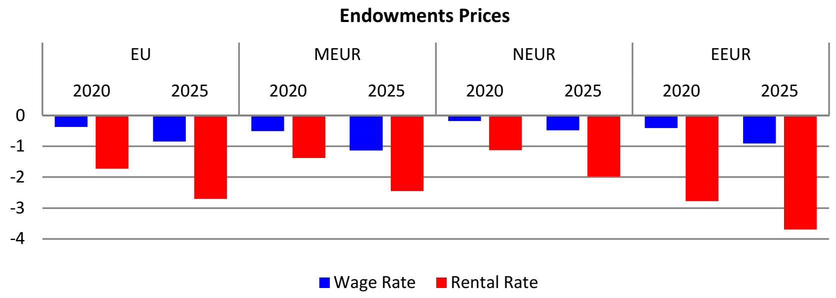

Figure 2.8: Labor and capital prices in the EU: % change compared to baseline

Moreover, because of this decline in the capital rental rate, there is a decrease in the rate of return on fixed capital[36] so that investors respond to the mitigation policy reallocating capital outside Europe.

To sum up, the European mitigation policy has negative impacts on capital price and capital rate of return, creating profitable opportunities outside Europe, observed by investments reallocation.

At the EU level, investments decline on average by 1.19% and by 2.37%, compared to 2020 and 2025 baseline levels, respectively (Figure 2.9). The largest effect on investment demand is in Eastern Europe (-2.9% and -5.3%, compared to 2020 and 2025 baseline levels), where the cost-efficient achievement of both emission reduction targets requires strongest efforts.

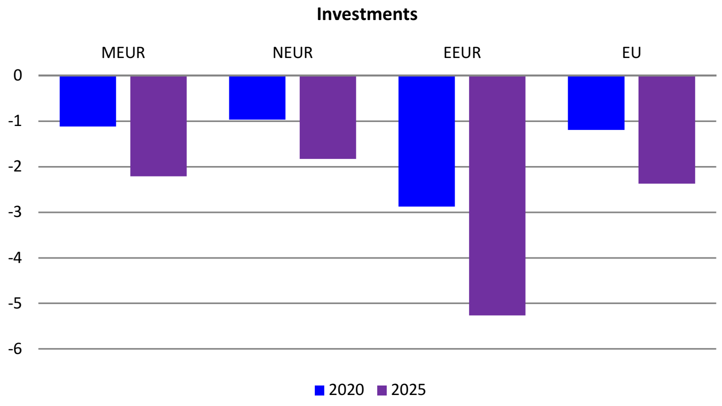

Figure 2.9: Investment in the EU: % change compared to baseline

So far our results are in line with the existing literature. In the next subsections we turn to the model with improved adaptation structure.

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[36] In the ICES model, it is defined as the ratio of the rental for capital services to the purchase price of capital goods, less depreciation rate.

Rational vs myopic expectations: one-shot policy

The key consequence of considering rational agents is to include correct expectations about the effects of the policy before it is effectively implemented. In our case, agents know that the rate of return to capital will fall, and they start to move capital out of Europe in advance (as it is shown in Figure 2.10 the investment drop occurs two periods before the policy implementation). In addition, the anticipation of the policy smooths the capital outflow (-0.96% in 2019) with respect to the case with static expectations (-1.2% in 2020). Indeed, early capital outflows impact negatively the capital accumulation. Therefore, once the policy is implemented, its negative effects on capital returns are smoothed down by the lower capital supply. Since rational agents correctly anticipate this dynamic, in 2019 they reduce investments less than what myopic agents do in 2020.

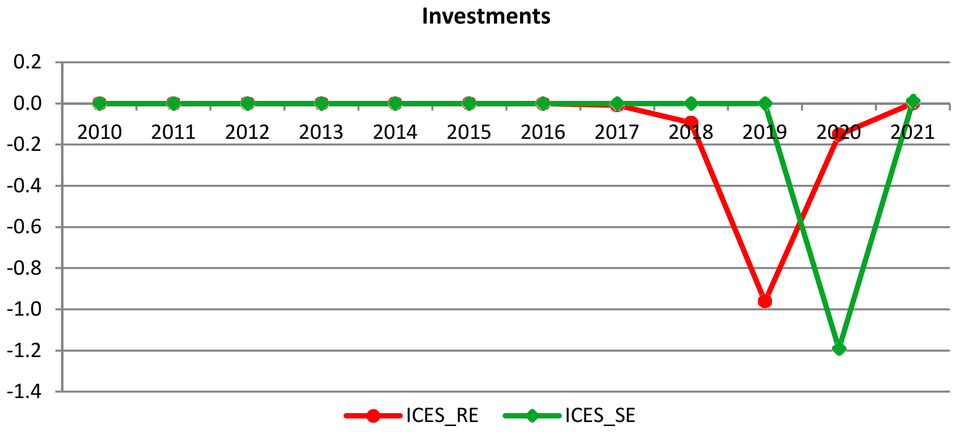

Figure 2.10: Investment in the EU using ICES_SE and ICES_RE: % change compared to baseline

Moreover, rational investors know that the mitigation policy will last only one period, and that the rate of return to capital will go back to its baseline level afterwards. Hence, in 2020 they move capital out of Europe less than myopic agents.

Prior to the policy implementation, capital outflows determine a reduction in the demand for services (-0.3% with respect to 2019 baseline level), which are the main intermediates (in terms of value), used in capital goods production. This negatively affects services production, and consequently decreases the use of primary factors within the sector (-0.12% for both capital and labor demand, compared to 2019 baseline level).[37] Primary factors relocate to the remaining sectors, which in turn increase their output with respect to the myopic behavior case (Figure 2.11).

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[37] See Figure 2.D2 in Appendix D.

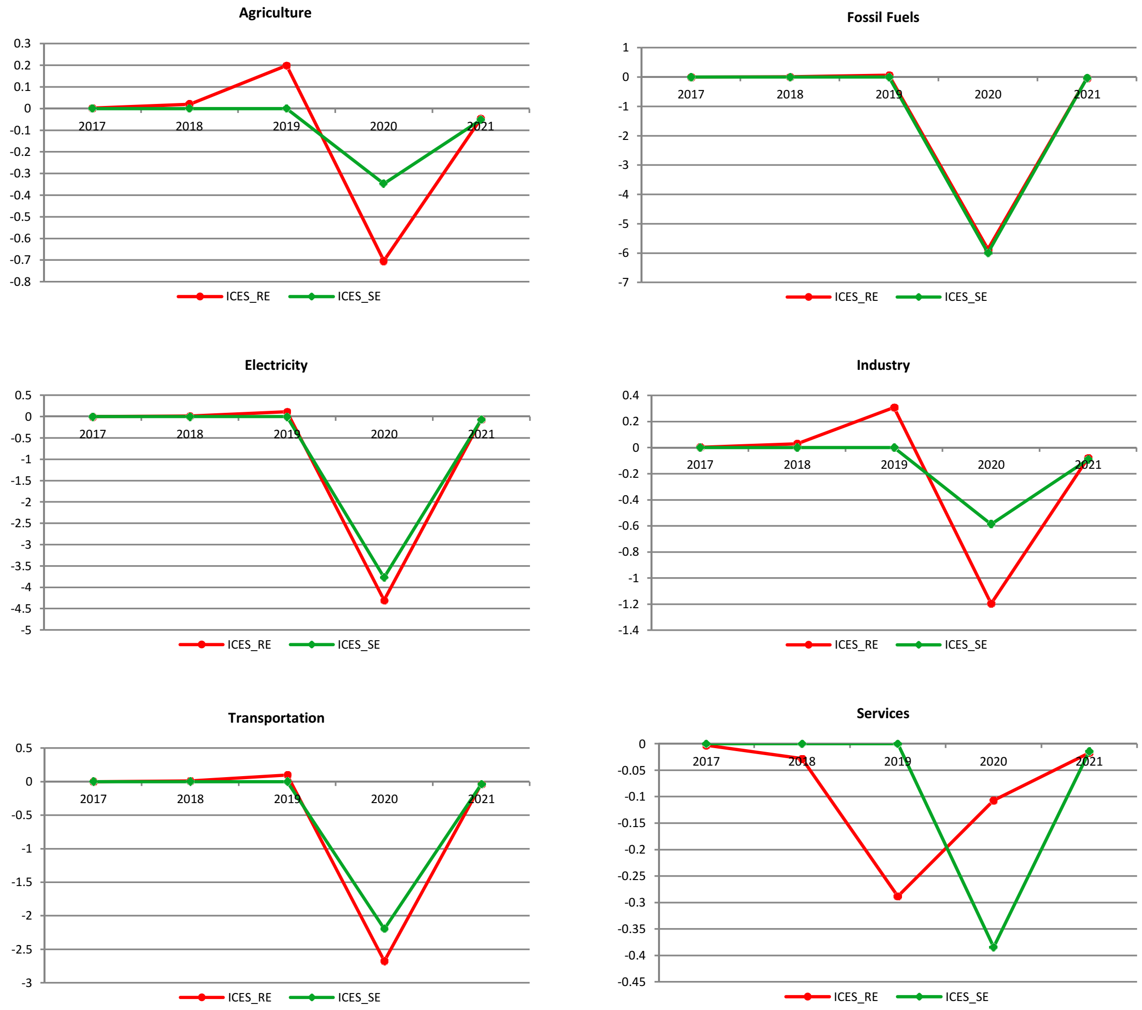

Figure 2.11: Sectoral production in the EU using ICES_SE and ICES_RE: % change compared to baseline

Once the policy is implemented, all sectors are negatively affected. Interestingly, with rational agents, production contraction is not necessarily lower than with myopic agents. In particular, stronger production reductions are observed in those sectors characterized by output expansion prior to the policy.

The milder decrease in services output can be explained looking at the effects of the policy implementation on investments. With rational expectations in 2020 investment demand decreases less than in the unanticipated policy scenario and so does the output in services.

Interestingly, the generalized increase in production (except in the services sector), induced by the anticipation of the policy, does not bring an increase in domestic CO_2 emissions. According to Figure 2.12, the EU emissions start to be reduced, albeit moderately, some years before the implementation of the policy.

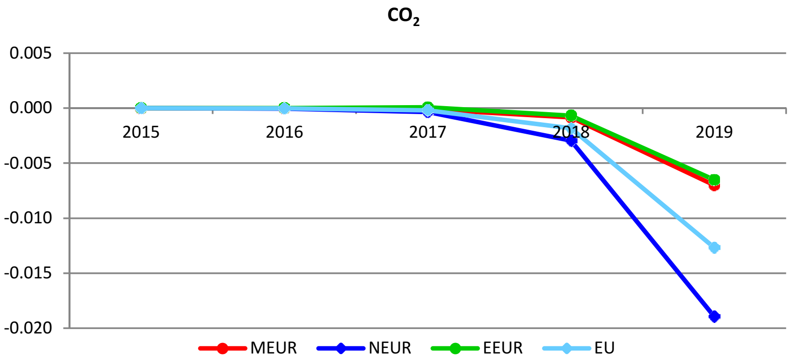

Figure 2.12: CO_2 emissions within the EU using ICES_RE: % change compared to baseline

Because of the reduction of primary factors prices prior to the policy implementation, national good are more competitive on international markets. Indeed, most of the increase in energy production is sold abroad, by affecting foreign rather than domestic emissions. In particular, as can be observed in Figure 2.13, in 2019 emissions increase in the USA, CAJANZ and SASIA. However, in all other regions emissions are reduced by 0.005%. Therefore the policy anticipation generates neither a green paradox nor a global carbon leakage effect.

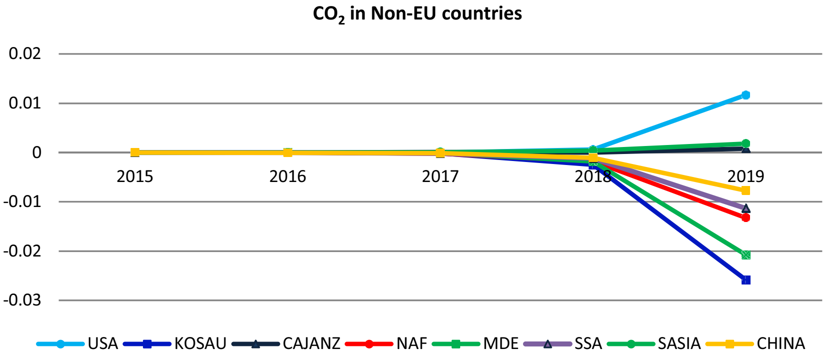

Figure 2.13: CO_2 emissions in Non-EU countries using ICES_RE: % change compared to baseline

The introduction of rational expectation does not affect visibly GDP before 2020. The decreased production of the services sector is almost perfectly compensated by the increased production in the other sectors. In 2020, GDP costs are slightly higher when agents are rational (Figure 2.14) due to the higher reduction in 2020 capital stock. Even though the absolute difference is small, moving from myopic to rational expectations determines anyway a 19.3% increase in GDP loss.

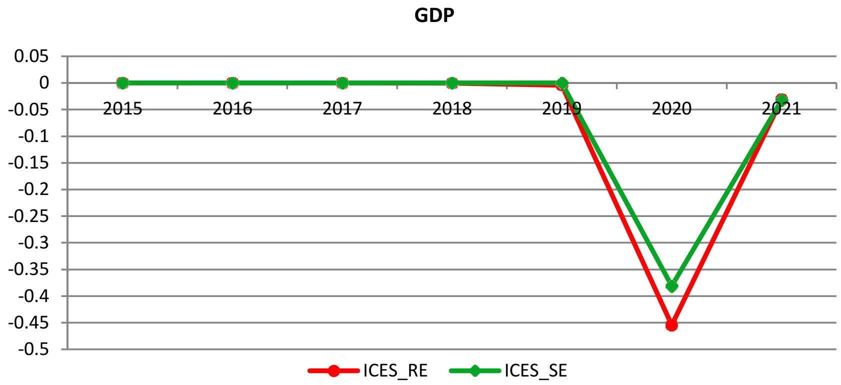

Figure 2.14: GDP in the EU using ICES_SE and ICES_RE: % change compared to baseline

Rational vs myopic expectations: gradually-implemented and one-shot policy

We compare now the effects of a policy implemented one-shot, with one implemented gradually, under both myopic and rational expectations. The policy tested is a 30% emission reduction in 2025, with respect to 1990 levels. This target is a sort of middle of the road target towards the recently announced European mitigation goal of -40% in 2030. This new mitigation goal can thus be achieved either reducing gradually emissions from 2020 to 2025, or with instantaneous implementation in 2025.

In the four scenarios originated (i.e., ICES_SE_OP_2025, ICES_RE_OP_2025, ICES_SE_MP_2025, ICES_RE_MP_2025), the 30% emission reduction target determines an average GDP loss in the range of 0.91-1.13%, compared to 2025 baseline levels (Figure 2.15). Higher macroeconomic costs are observed in Eastern Europe, with respect to the other two regions (see Figure 2.D3 in Appendix D for GDP losses at the regional level).

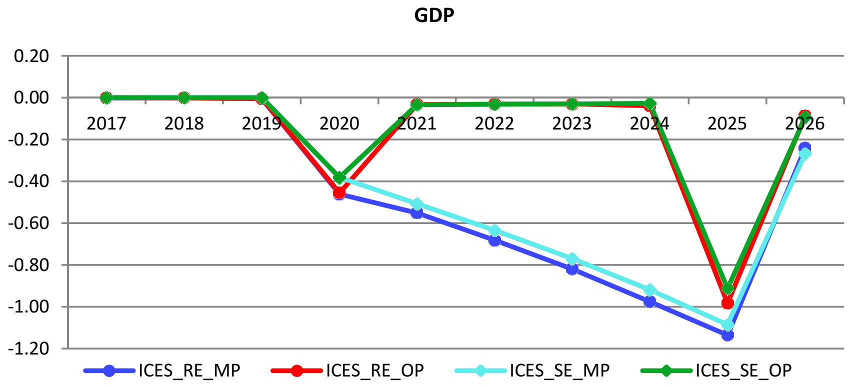

Figure 2.15: The EU GDP under different policy scenarios: % change compared to baseline

The different expectations structure affects GDP along the patterns highlighted already. There are no detectable effects prior the policy implementation (2020 in the gradual case, and 2025 in the instantaneous case) and GDP losses are higher under rational than myopic expectations. In addition, a progressively-implemented emissions reduction target determines stronger GDP contraction, compared to the one-shot policy, under both expectations formation rules.

The effects of different timing strategies and expectations formation rules on investments paths are shown in Figure 2.16. We observe similar patterns to the ones discussed previously. Hence, regardless the timing strategies, rational agents react differently from myopic agents few years before the policy implementation and when it ends. Indeed, rational agents move capital outside Europe before emissions are actually constrained; furthermore, when the policy is expected to end, the capital outflowing is reduced and investments are almost back to their baseline levels (blue and red line in Figure 2.16). On the contrary, under both timing strategies, myopic agents reduce investments only when the policy is implemented (green and light blue line).

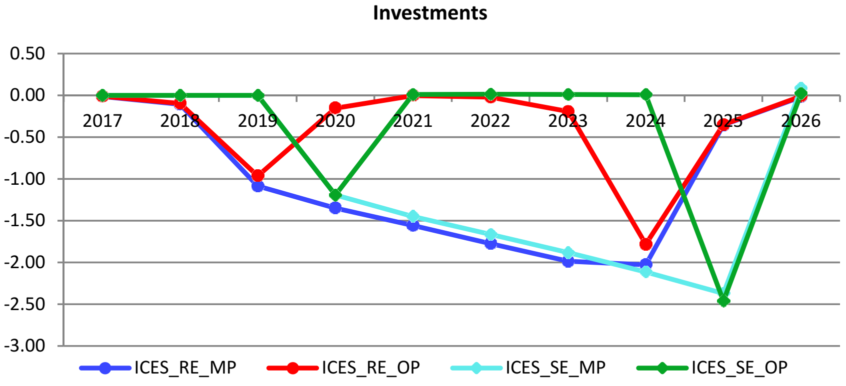

Figure 2.16: European real investments under different policy scenarios: % change compared to baseline

When future environmental regulations are expected, the effects on emissions prior to the policy implementation do not differ from the 20% target results. Hence, anticipation effects are observed. Under the one-shot policy, the EU CO_2 emissions are reduced by 0.013% in 2019 and by 0.068% in 2024, while the gradually-implemented regulation determines an emissions reduction of 0.014% in 2019.[38] Therefore previous results are confirmed, i.e. the policy anticipation does not generate a green paradox.

2.5 Conclusions

Expectations play a key role in determining the cost-effectiveness of future environmental regulations, especially when the policy is announced largely in advance. CGE models are a common tool for mitigation policy evaluation. They are static or quasi-dynamic model but, in both cases, expectations are either not considered at all or too-poorly treated. To fill up the gap, we have developed a new specification of the Intertem-

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[38] See Figure 2.D4 in Appendix D for the effects on CO_2 emissions within Europe, prior to the policy implementation.

poral Computable Equilibrium System model, including rational expectations assumption into a large-scale recursive dynamic model (Dixon et al., 2005).

In this paper, we have studied how different expectation structures affect the cost-effectiveness of mitigation policy. Under the assumption that governments' purposes are credible from the beginning of our simulation period, we have verified if with rational agents an anticipation effect occurs. Furthermore, we have addressed the issue of timing of the policy, by investigating the different reaction to a gradually-implemented versus a one-shot mitigation policy. Specifically, we have used the EU climate policy as a case study. Indeed, we have considered a 20% emissions reduction target for 2020 and a 30% reduction for 2025, as a middle passage to achieve the recently announced EU's goals for 2030. Both abatement targets have been efficiently achieved through a cap-and-trade system. Policy scenarios diverge not only in terms of mitigation efforts, but also in terms of timing. The 2020 target is implemented in one-period (one-shot policy), while the 2030 target is implemented both, gradually-from 2020 to 2025 (phased-in policy) or introduced in one-period only (year 2025).

Governments announce mitigation policies largely in advance to give the economy time to reorganize to the new regulation, in order to reduce future climate costs. This is partially confirmed by our results. Similarly to Adams et al. (2001), the anticipated policy determines smoother adjustment paths in terms of investment decisions, compared to those obtained in the surprising scenario. However, we have found an increase in the overall economic cost of the environmental regulation. Since forward-looking behaviors are considered only when investments decisions have to be taken, international capital movements directly affect the cost-effectiveness of the European mitigation policies. Once the policy is expected in fact, European capital accumulation is negatively affected by capital outflows and this directly impacts regional GDP.

Differently from Bosetti et al. (2009), the potential effects of future mitigation policies do not stimulate investments in new abatement technologies within Europe to reduce future climate costs. Indeed, our results show that, by expecting the future increase in production costs, rational investors move capital outside Europe prior to the policy implementation. Since capital is perfect mobile across sectors, this anticipation effect on investments determines a reduction in today capital productivity. Hence, by taking advantages of lower primary factors costs, domestic firms increase output, postponing adjustments in their production process.

However, by looking at the anticipation effects on emissions paths, paradoxical outcomes are not observed. In fact, differently from Smulders et al. (2012), but similarly to Bosetti et al. (2009) and Blanford et al. (2009), we have found that emissions start to be reduced prior to the policy implementation. In Smulders et al. the effects of the policy announcement is driven by changes in households' behaviors. By anticipating the future increase in fossil fuels price, households smooth consumption and increase saving. This increase positively affects the capital accumulation and the use of fossil fuels, which in turn determines the growth in emissions prior to the policy implementation. In our paper instead, consumption and saving decisions are not forward-looking. In fact, as in standard recursive-dynamic CGE models, we have assumed that a fixed share of income is devoted to saving. Hence, perfect foresight investors move capitals outside Europe and this determines a reduction in capital productivity and thus in primary factors costs, prior to the policy implementation. European energy production becomes more competitive on international markets, by affecting foreign rather than domestic emissions.

By addressing the issue of timing of the policy, our results indicate that the different expectations structure does not determine a different reaction to a gradually-implemented versus a one-shot mitigation policy.

Finally, even though differences in absolute terms are small, moving from static to rational expectations determines significant different outcomes. Hence, greater policy impacts would result in amplified differences between the two algorithms.

We can think of at least two directions along which our analysis could be extended. Firstly, we have pointed out the key role of expectations in determining the policy outcome. It would be interesting to investigate whether our results hold also when other economic actors (especially the household) take intertemporal decisions based on rational expectations. Secondly, in order to analyze paradoxical outcomes, expectations about future extraction costs should be considered when non-renewable resources supply is set.

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Appendix A: Production and consumption in the ICES model

In the ICES model, the production side of the economy is characterized by one representative firm for each production sector. Firms demand primary factors and intermediates so as to minimize costs, by taking input prices as given. Since separable and constant returns-to-scale technologies are employed, in each sector total output price is given by average production costs. The firm optimization decision problem can be graphically represented by a "production tree" (Figure 2.A1).

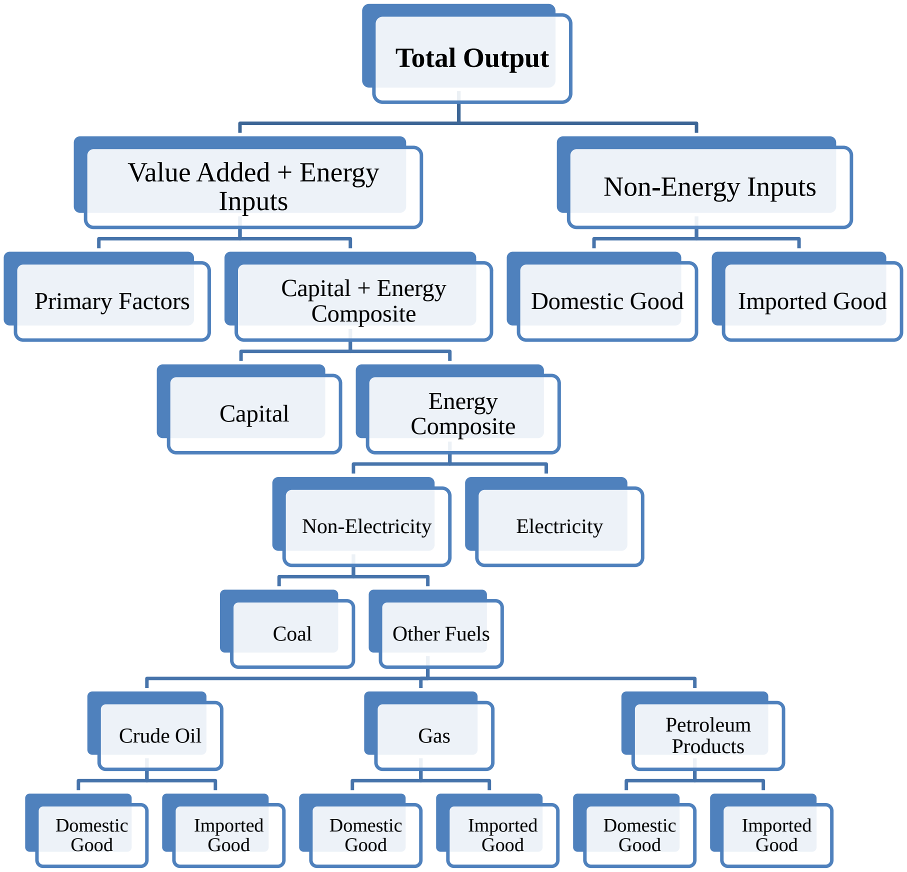

Figure 2.A1: The ICES nested production structure

At the top level, firms combine composite value-added and intermediate inputs, by assuming perfect complementarity. In order to introduce more flexibility in terms of elasticity of substitution, energy inputs are isolated from intermediates and incorporated into the value-added nest, determining a capital-energy composite. Moreover, energy is a composite good, produced with a CES function that aggregates electricity and non-electricity energy inputs, which in turn are given by coal and other fossil fuels inputs (crude oil, gas and petroleum products). As shown in Table 2.A1, capital and fossil fuels sectors are characterized by fixed proportion of energy inputs.

		Energy Substitution Elasticities			
		Capital/ Energy	Electricity/ Non-Electricity	Coal/ Other Fuels	Crude Oil/Gas/ Petroleum Products
Sectors	Fossil Fuels and Capital Goods	0	0	0	0
	Other Sectors	0.5	1	0.5	1

Table 2.A1: Energy substitution elasticities

By considering instead the demand side of the economy, in each region there is a regional household, who receives income from primary factors (labor, capital, land and natural resources). While labor and capital are perfect mobile endowments across sectors, but internationally immobile, natural resources and land are sluggish endowments and their sectoral supply is generated from a Constant Elasticity of Transformation (CET) revenue function (Powell and Gruen, 1968). The representative household allocates its income across aggregate private consumption, public consumption and saving so as to maximize per capita aggregate utility, according to a Cobb-Douglas utility function (Figure 2.A2). Although there is an unambiguous indicator of welfare offered by the regional utility, this formulation of regional household is subject to a strong limit, that is the impossibility to link government expenditures with tax revenues. It could happen in fact that, if taxes are cut, real regional income rises, followed by an increase in both private and government consumption. This limitation is strictly related to the lack of data and in particular to the fact that the GTAP database has incomplete coverage of regional tax instruments.

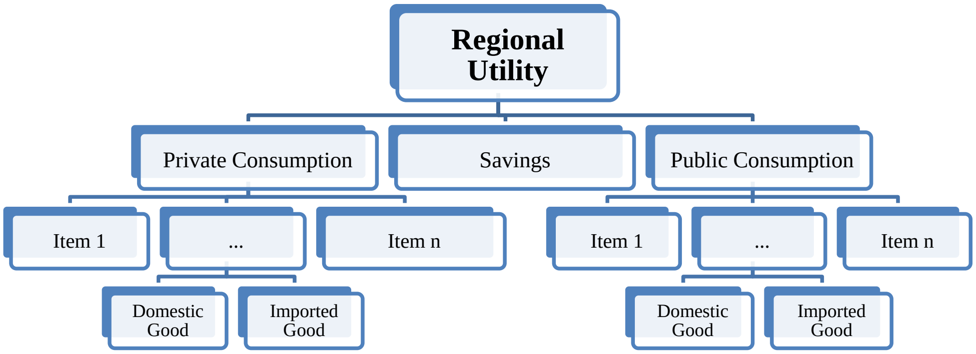

Figure 2.A2: Regional household tree in ICES

Appendix B: The modelling approach used to include forward-looking behaviors

The Fair-Taylor algorithm in ICES

In order to consider the effects of different assumptions on expectations, we decide to use the same structure of the standard ICES model in which expectations are related only to investment decisions. The starting point is the investment demand, which is an increasing function of real GDP ($GDP_{r,t}$) and the deviation of the country expected rate of return to capital $E_{r,t}(r_{r,t+1})$ from the world rate of return rw_t:

$$INV_{r,t} \quad = \quad \alpha_r GDP_{r,t} exp\left[\varrho_r\left(E_{r,t}(r_{r,t+1}) - rw_t\right)\right] \tag{2.B1}$$

where ϱ_r is a flexibility parameter, which controls the speed of capital movements with respect to expectations. Small values for ϱ_r implies that region r has lower capacity to attract capital and thus, it reduces the tendency of investment flows to respond to changes in the rate of return. The highest this parameter, the more sensitive investments are with respect to expectations.

Since in the standard ICES_SE endogenous investments are driven by "static" expectations, the expected rate of return is equal to the actual rate of return on capital:

$$E_{r,t}(r_{r,t+1}) \quad = \quad r_{r,t} \tag{2.B2}$$

Moving from myopic to rational behaviors, we substitute Equation 2.B1 with Equation 2.B3, i.e. expectations of next period rate of return exactly coincide with the actual rate of return of next period:

$$E_{r,t}(r_{r,t+1}) \quad = \quad r_{r,t+1} \tag{2.B3}$$

However, there is a link between the solution for period t and the solution of next period $t+1$. The introduction of the time dimension strongly increases the size of the model. In order to avoid constraints on the degree of sectoral and regional detail, we approximate rational expectations, without solving simultaneously all periods.

Therefore we use the Fair-Taylor Algorithm to simulate rational expectations, by linking today decision with future solution, obtained from previous iterations (Dixon et al., 2005).

First of all, we need an initial solution for the expected rate of return. As a starting point, we use results obtained with the standard ICES model. Hence, by assuming that agents are myopic during the first iteration, the following equation is satisfied:

$$E^1_{r,t}(r_{r,t+1}) \quad = \quad r^1_{r,t} \tag{2.B4}$$

where the superscript indicates the iteration number. At the end of this iteration, the optimal value of the rate of return is known for all periods. At this point it is possible to run a second iteration by introducing rational expectations assumption. In particular, for all periods with the exception of the last one (T), the expected rate of return is equal to the actual rate of return of next period, computed in the first iteration:

$$E^2_{r,t}(r_{r,t+1}) \quad = \quad r^1_{r,t+1} \quad \forall\, t < T \tag{2.B5}$$

Because we do not have a solution for the current rate of return for period $T+1$, we have to assume that in T expectations are exactly equal to expectations from previous period at the same iteration:

$$E^2_{r,T}(r_{r,T+1}) \quad = \quad E^2_{r,T-1}(r_{r,T}) \tag{2.B6}$$

From the third iteration and forward, we assume that expectations in one iteration are equal to expectations from previous iteration if they were fulfilled; otherwise an adjustment factor is introduced to correct errors in expectations. As in the Fair-Taylor algorithm, the updating rule for expectations is:

$$E^n_{r,t}(r_{r,t+1}) \quad = \quad E^{n-1}_{r,t}(r_{r,t+1}) + \alpha \left(r^{n-1}_{r,t+1} - E^{n-1}_{r,t}(r_{r,t+1}) \right) \quad \forall\, t < T \tag{2.B7}$$

where the value of the parameter α has to be in the range of $0 - 1$ to avoid cycling in simulation.

At each iteration, we impose that expectations in period T are equal to expectations in period $T-1$ from the same iteration:

$$E^n_{r,T}(r_{r,T+1}) \quad = \quad E^n_{r,T-1}(r_{r,T}) \tag{2.B8}$$

Convergence is achieved at iteration number N when the convergence criterion has been satisfied, that is:

$$E^N_{r,t}(r_{r,t+1}) - r^N_{r,t+1} \quad \leq \quad \varepsilon \quad \forall\, t < T \tag{2.B9}$$

where ε is a number that is sufficiently small.

Properties of the algorithm

Starting from the convergence criterion (Equation 2.B9), some clarifications have to be done in order to set the value of ε. In ICES, all variables are expressed in terms of percentage changes with respect to their base-year level. Thus, in the convergence criterion, instead of considering the difference between the expected and the current rate of return, we consider the difference between their growth rates, with respect to the base-year, that is:

$$rore^N_{r,t} - rorc^N_{r,t+1} \quad < \quad \epsilon \tag{2.B10}$$

where $rore^N_{r,t}(rorc^N_{r,t+1})$ is the percentage change of the expected rate of return (of the current rate of return) between period t (period $t+1$) and its base-year value, at iteration N.

At the end of any iteration, we have a matrix of differences and its dimension is given by the number of regions (r) and the number of periods minus one ($T-1$). The algorithm stops if the maximum of these differences is smaller than ϵ:

$$max \mid rore^N_{r,t} - rorc^N_{r,t+1} \mid \quad < \quad \epsilon \tag{2.B11}$$

We set $\epsilon = 0.005$, which is equivalent to assume that the gap between the expected and the current rate of return is smaller than 0.0009 percentage points.

The number of iterations to achieve convergence depends on the value of the adjustment parameter α in the updating rule for expectations (Equation 2.B7). In particular, by considering a time horizon from 2010 to 2020, we run several simulations considering different values for α. We find that the faster convergence is obtained when it is equal to 0.8 (Table 2.B1). In this exercise the algorithm stops at iteration 10.

2010_2020	**Iter 1**	**Iter 2**	**Iter 3**	**Iter 4**	**Iter 5**	**Iter 6**	**Iter 7**	**Iter 8**	**Iter 9**	**Iter 10**
Max_Diff. (α = 0.2)	6.129	4.778	3.144	2.018	1.254	0.805	0.540	0.386	0.277	0.205
Max_Diff. (α = 0.5)	6.129	4.778	1.000	0.353	0.247	0.135	0.064	0.029	0.014	0.010
Max_Diff. (α = 0.8)	6.129	4.778	1.716	0.437	0.220	0.087	0.026	0.016	0.008	0.003
Max_Diff. (α = 1)	6.129	4.778	3.322	0.971	0.490	0.276	0.088	0.060	0.020	0.013

Table 2.B1: Convergence check for different values of the parameter α

Figure 2.B1 shows the deviation of the expected rate of return in each iteration from its value at the tenth iteration, which represents the solution of the model with rational expectations. The error in using static expectations as a proxy of forward-looking behaviors (yellow line) follows different paths across countries. In particular, for some regions, such as Eastern Europe, Mediterranean Europe, Middle East, the gap tends to decrease over time while for others, such as China, Latin and Central America, it increases. In general, we can conclude that static expectations cannot be a good approximation of rational expectations. From the forth iteration and so on, lines overlap the horizontal axis, which means that the error with respect to the rational expectations iteration is close to zero. For some regions, such as Northern and Mediterranean Europe, the error is already close to the x-axis at the iteration 3.

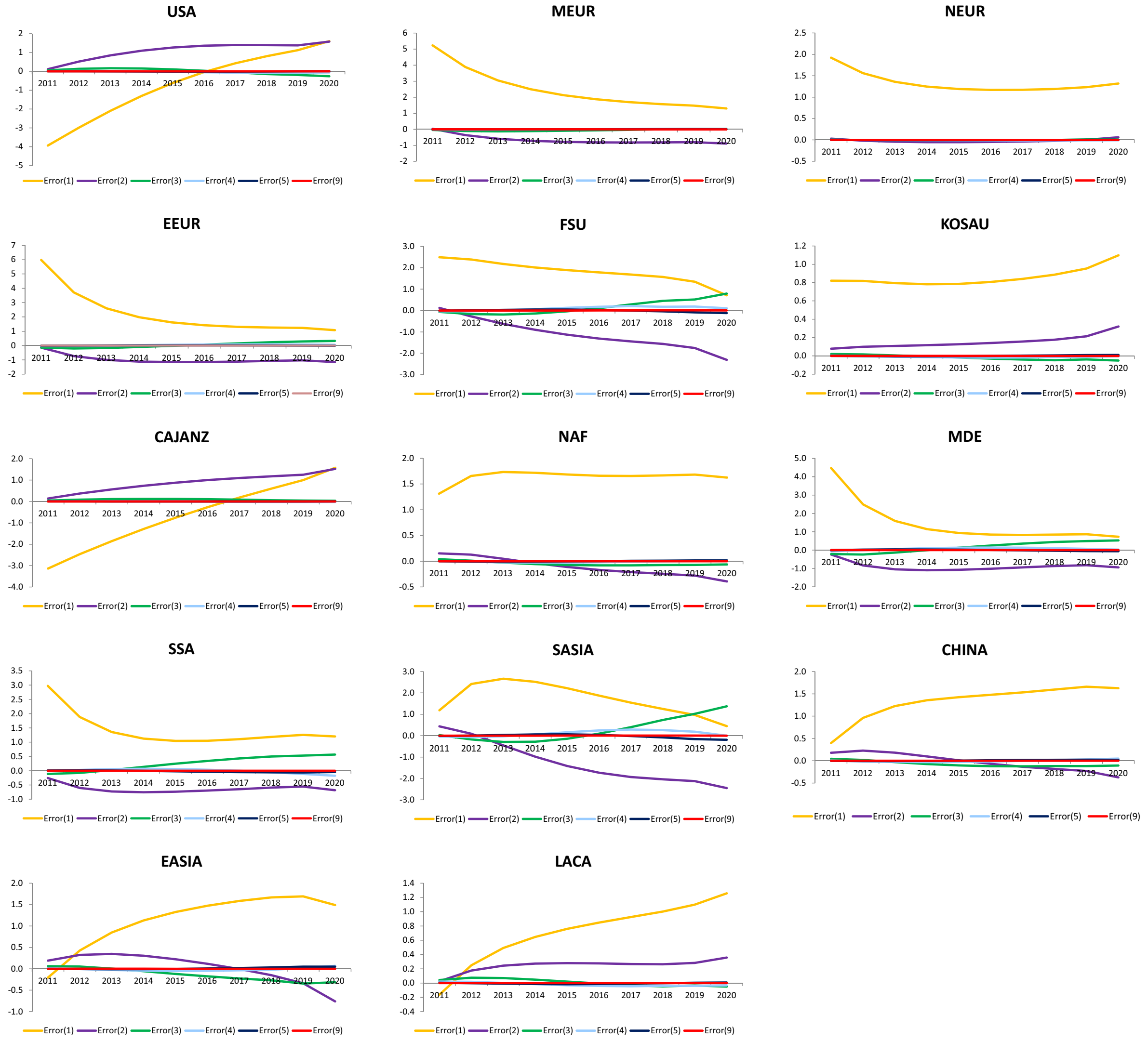

Figure 2.B1: Error in the expected rate of return, compared to the rational expectations iteration (percentage points)

In the last iterations, when the algorithm tends to converge, errors are slightly stronger in the long-run, compared to early periods. This implies that the number of iterations to achieve convergence is an increasing function of time. To test the sensitivity of convergence with respect to the number of considered periods, we re-run the model until 2025. By setting the α parameter equal to 0.8, we find that convergence is achieved at iteration twelve (Table 2.B2).

2010_2025	**Iter 1**	**Iter 2**	**Iter 3**	**Iter 4**	**Iter 5**	**Iter 6**	**Iter 7**	**Iter 8**	**Iter 9**	**Iter 10**	**Iter 11**	**Iter 12**
Max_Diff.	6.129	3.931	1.737	0.523	0.248	0.150	0.056	0.042	0.021	0.008	0.007	0.003

Table 2.B2: Convergence check for an increased number of periods

Moreover, in order to reduce the effects of terminal condition (Equation 2.B8) on expectations, we decide to run the model for more years after the end of the simulation horizon. In particular, for this exercise in which the simulation horizon is 2010-2020, we try to postpone the terminal condition to 2025, instead of being in year 2021. As it is shown in Figure 2.B2, in the long-run, differences in simulation results depend on when the terminal condition has to be satisfied.

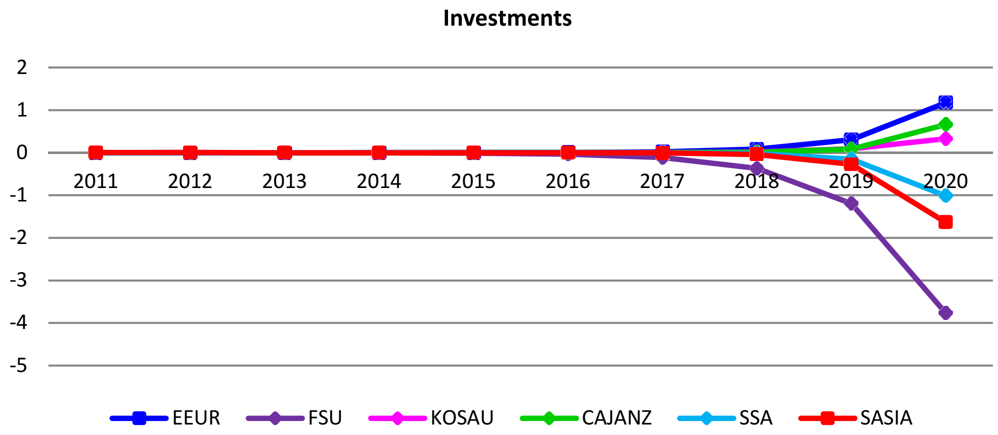

Figure 2.B2: Deviation in investments between ICES_RE_2025 and ICES_RE_2021 for selected countries (Δ%)

It is also important to stress that, by using the Fair-Taylor algorithm, we are only able to approximate rational expectations. Indeed, the expected rate of return is not a solution of the model but instead it is exogenously given by the solution from previous iteration. However, by doing so, we avoid solving the model, considering all periods simultaneously.

Appendix C: Comparing baselines characterized by the same closure

To analyze the effects of the two different assumptions concerning rate-of-return expectations, it is possible to consider the same closure in both models. Differently from what we have done to obtain the two BaU scenarios with similar economic paths, here we assume the same exogenous shocks (e.g. population growths, changes in primary factors stocks and productivities). Even if we use the same calibrated parameters, we expect different economic trends, because of different assumptions related to expectations.

As can be seen from Figure 2.C1, differences between ICES_SE and ICES_RE in terms of expectations tend to be more evident in early periods, compared to the long-run equilibrium. Considering for example 2011, the expected rate of return under rational expectations assumption in the US (light blue line) is almost 0.6 percentage points higher than in the model with static expectations, while in Eastern Europe (green line) is almost 1.2 percentage points smaller. After 2017, the expected rate of return in all regions is smaller in ICES_RE with respect to its value in the model with myopic agents. However, differences become less and less significant. In the last periods in fact divergences between the two modelling approaches are of the order of 0.3 percentage points, on average.

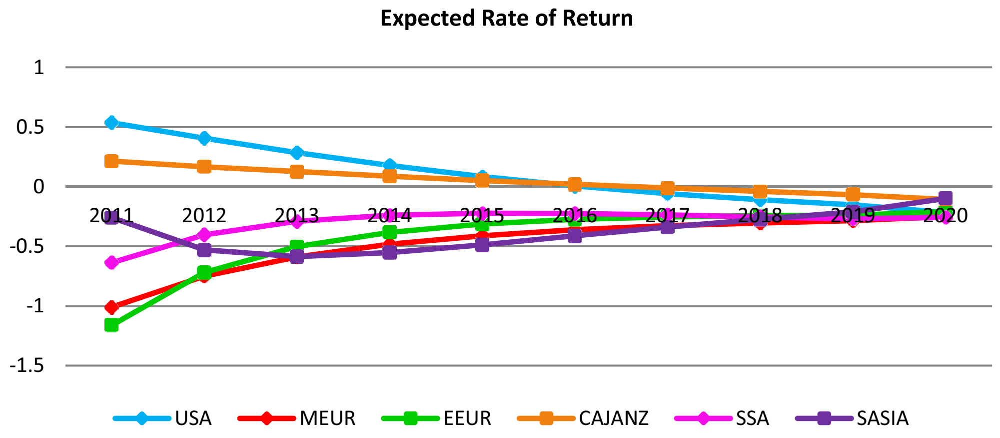

Figure 2.C1: Deviation in the expected rate of return between ICES_RE and ICES_SE for selected countries (percentage points)

Differences in expectations directly affect investment decisions. Although the two models simulate similar trends in terms of investment growth rates, with respect to the base-year (Figure 2.C2), some dissimilarity are observed, especially in the short-run.


USA

MEUR

NEUR

EEUR

FSU

KOSAU

CAJANZ

NAF

MDE

SSA

SASIA

CHINA

EASIA

LACA

Figure 2.C2: Regional real investment (Δ% compared to baseline)

As it is shown in Figure 2.C3, in 2011 real investments in Eastern Europe and Middle East are more than 9% smaller under rational expectations than under static expectations. In the United States instead, investments are almost 8% higher in ICES_RE than in ICES_SE.

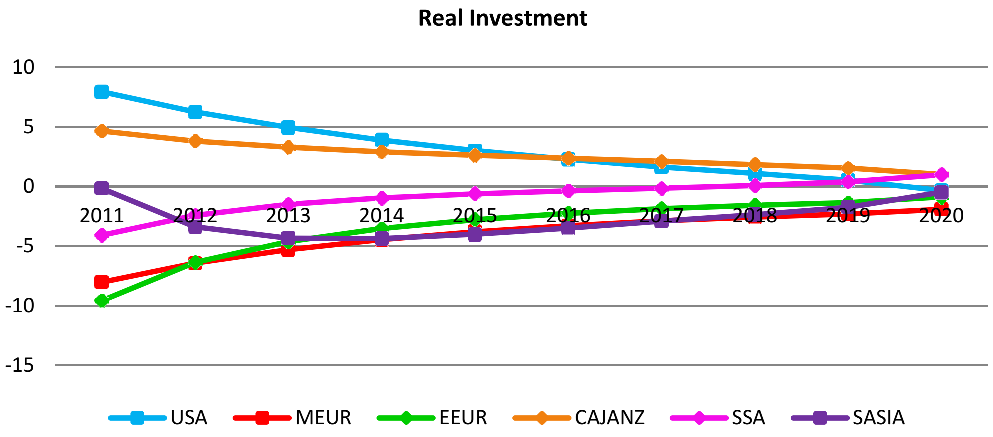

Figure 2.C3: Deviation in real investments between ICES_RE and ICES_SE for selected countries (Δ%)

Looking at Figures 2.C3 and 2.C1, it is possible to notice that differences in investments are driven by divergences in the expected rate of return. If agents expect higher rate of return, they will invest more with respect to the model characterized by less optimistic agents about the future. Although differences between the two models follow similar paths, investments are more strongly affected with respect to expectations on the rate of return. Moreover, changes in investment decisions impact the capital stock accumulation, which in turn directly affects the GDP growth rate. As we have previously said, the model is not calibrated to replicate the same economic growth, hence divergences are expected. In particular, differences between ICES_RE and ICES_SE in terms of GDP are higher in early periods in almost all countries, while the assumption on the expectation formation rule has smaller effects on the long-run equilibrium (Figure 2.C4).

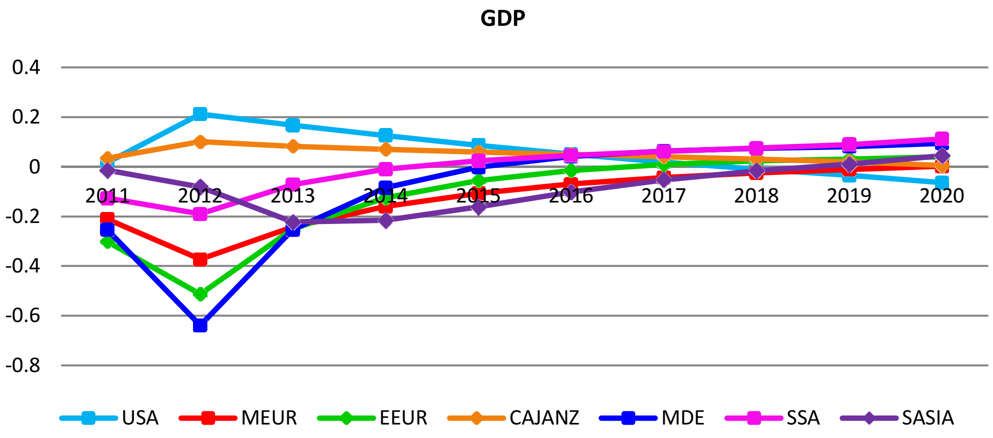

Figure 2.C4: Deviation in GDP between ICES_RE and ICES_SE for selected countries (Δ%)

Appendix D: Other results

	20% Target			30% Target		
	GDP	CO$_2$	Household utility index	GDP	CO$_2$	Household utility index
	(Δ% w.r.t. Baseline)			(Δ% w.r.t. Baseline)		
USA	0.013	0.945	0.056	0.075	1.596	0.126
MEUR	-0.395	-13.122	-0.558	-1.102	-24.281	-1.906
NEUR	-0.320	-14.345	-0.247	-0.890	-26.632	-1.044
EEUR	-0.779	-23.358	-0.072	-2.278	-33.080	-0.837
FSU	-0.094	1.587	-0.474	-0.281	2.458	-0.970
KOSAU	0.056	1.230	0.012	0.221	1.870	0.137
CAJANZ	0.034	0.792	0.088	0.128	1.298	0.182
NAF	-0.096	0.495	-0.744	-0.150	0.596	-0.943
MDE	0.038	0.447	-0.258	0.269	0.825	-0.312
SSA	0.030	0.219	-0.239	0.204	0.723	-0.256
SASIA	0.038	0.419	0.118	0.117	0.616	0.205
CHINA	0.018	0.514	0.038	0.121	0.831	0.082
EASIA	0.024	1.014	-0.039	0.148	1.741	-0.014
LACA	0.005	0.526	-0.045	0.108	0.910	-0.011
EU	-0.381	-15.445	-0.292	-1.085	-26.968	-1.262
Non_EU	0.016	0.752	-0.135	0.104	1.211	-0.161

Table 2.D1: Main macroeconomic variables
under both emission reduction targets with ICES_SE

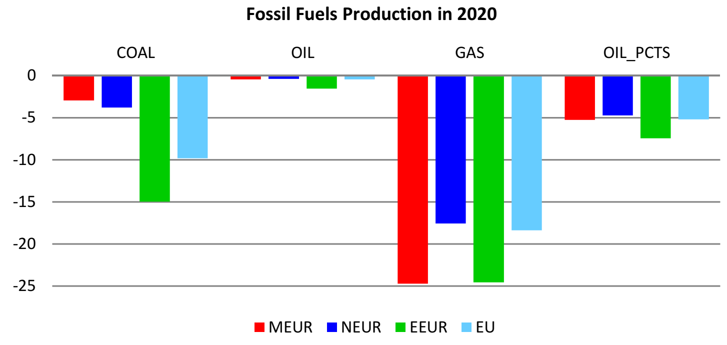

Figure 2.D1: Fossil fuels production in the EU:
% change compared to baseline

Policy Scenario	Fossil Fuels Production (Δ% w.r.t. base-year 2007)
ICES_SE_OP_2020	-11.99 (2020)
ICES_SE_OP_2025	-22.854 (2025)

Table 2.D2: Changes in fossil fuels production under the 20% and the 30% targets: % change compared to base-year 2007

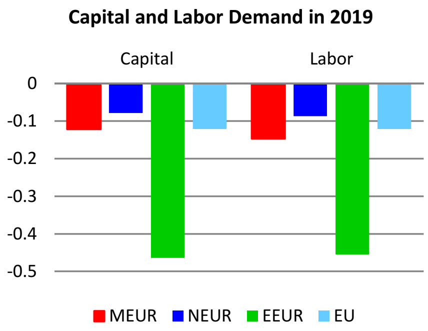

Figure 2.D2: Capital and labor demand by the services sector in the EU: % change compared to baseline

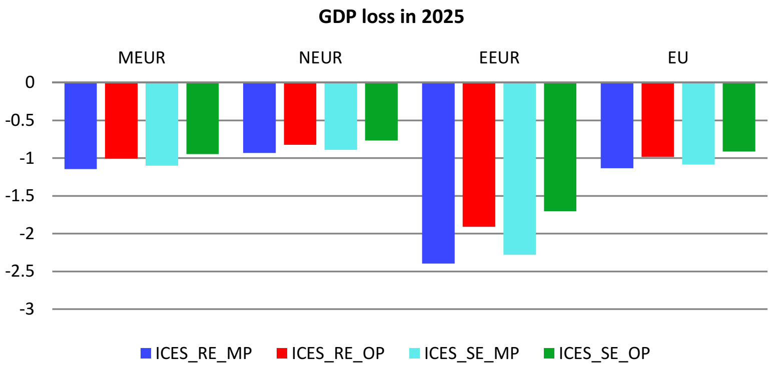

Figure 2.D3: GDP loss in the EU under the four policy scenarios: % change compared to baseline

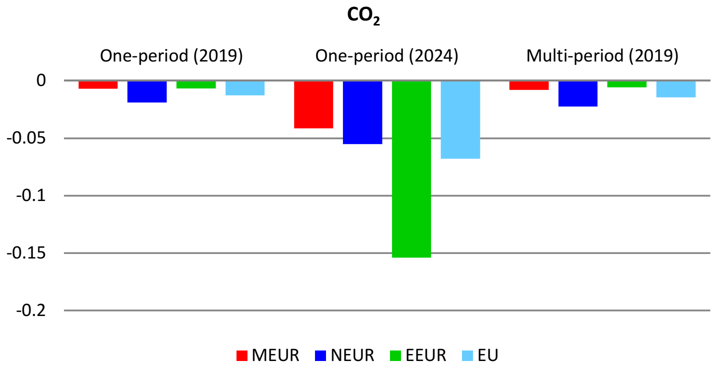

Figure 2.D4: CO_2 emissions within the EU prior to the policy implementation: % change compared to baseline

Chapter 3

The implications of irrigation as a planned adaptation measure on an economy wide context

Anna Dellarole,[⋆] Ramiro Parrado[§]

Abstract

Agriculture is strongly exposed to future climate change. Indeed, changes in temperature, precipitation, rain patterns, water availability and frequency/intensity of extreme weather events would impact on agricultural production. Therefore, adaptation strategies are necessary to cope with the challenges comprised by expected changes in climate patterns. These responses can be driven by self-regulatory mechanism or planned policy intervention. Within this context, the development of irrigation is a key variable to climate change adaptation. Nevertheless, its role as an adaptation strategy is commonly ignored by applied economic models. This paper describes a new modelling approach to include irrigation within the ICES model, a multi-country, multi-sector, recursive dynamic CGE model of the world economy. The new specification distinguishes between irrigable and rainfed land. Moreover, it considers the additional capital, operational and maintenance costs that farmers face when they decide to use irrigable land. The new version of the model has been used to analyze whether irrigation expands as a consequence of climate change impacts. The results indicate that, when climate change negatively affects land productivity, farmers increase the demand of irrigated land. However, the economic costs and benefits of adaptation differ across countries.

JEL classification: C68, Q51, Q54, Q15

Keywords: Computable General Equilibrium Analysis; Climate change; Agriculture; Adaptation

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3.1 Introduction

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

Projected high population growth rate is one of the factors which could put pressure on agricultural production and therefore increase the challenge of poverty reduction. According to the new IPCC (the Intergovernmental Panel on Climate Change) socio-economic scenarios,[39] the world's population will be between 8.5 and 9.9 billion by 2050 (e.g. a 35 percent growth rate from 2000 to 2050 under the SSP2 that is the middle of the road scenario). Despite differences in regional population trends, in all scenarios developing countries, especially Sub-Saharan Africa, will experience the highest population growth during the next 40 years (IIASA SSP Database, 2015). If the world population reaches 9.1 billion by 2050, the FAO says that global food production has to rise by 70 percent between 2005/07 and 2050, and agricultural production in developing countries has to double (FAO, 2009).

However, not only projected population growth rates raise pressure on agricultural production. Indeed, as agricultural activities highly depend on specific climate conditions, agriculture is strongly exposed to future climate change. Changes in temperature, precipitation, rain patterns, water availability and frequency/intensity of extreme weather events would impact on the agricultural production. The consequences of these climate changes are various and include, among others: changes in agricultural productivity, changes in regional distribution and intensity of food production (Fellmann, 2012).

Therefore, adaptation actions are necessary to cope with the challenges comprised by climate change. Human response can occur by a range of actors, such as farmers or governments, and on a range of geographical areas, from local to global level. Adaptation responses can be driven by self-regulatory mechanism (the so-called autonomous reaction) or planned policy intervention. Examples of autonomous adaptation at the farm level are changes in crop management, such as cultivation and planting date adjustment, irrigation and fertilizer optimization, research and development. Examples of autonomous adaptation at the national and international level include price adjustment mechanism. Indeed, changes in the price of agricultural products affect the cost of many other linked production activities, within and between countries.

In addition, climate change impacts on agriculture and autonomous responses can be corrected 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

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

markets and the improvement of trade flows, etc.

In developing countries, agricultural production is highly dependent on rainfall, especially in Sub-Saharan Africa where approximately 97% of total cropland is rainfed (Calzadilla et al., 2013). Such exposure to seasonal rainfall variability would strongly affect their food production and, considering their dependence on this sector, the impacts of climate change would reverberate throughout their economies. Given that water is a major factor to guarantee agricultural production, land productivity can be increased by the expansion of irrigated areas or by higher irrigation efficiency. Hence, the development of irrigation is a key variable to climate change adaptation.

To assess the economic effects of climate change and adaptation on the agricultural sector, two main approaches are usually used: partial equilibrium and computable general equilibrium (CGE) model. The former takes into account equilibrium conditions only for crops sectors, by fixing prices in all other economic activities. The latter instead considers price interaction across markets and shows explicitly linkages between different components of the economic system. Therefore, CGE models enable to analyze the direct and indirect effects of the evaluated phenomenon. Hence, they have been largely used to assess the impact of climate change and autonomous adaptation (e.g. Parry et al., 2004; Iglesias, Quiroga, Diz and Garrote, 2011; Iglesias, Quiroga and Diz, 2011; Bosello et al., 2013). However, few global CGE models explicitly consider water resources in the agricultural sector. Although some papers analyze the role of irrigation as a planned adaptation strategy (e.g., Berrittella et al., 2006; Calzadilla et al., 2013; Koopman et al., 2015), irrigation is treated as an exogenous variable rather than an autonomous farmers' decision, which requires some economic costs.

As discussed above, irrigation may play a key role, especially in developing countries, in addressing future climate change. Nevertheless, it is not thoroughly represented by CGE models. In this sense, the main goal of this paper is to improve the way irrigation is treated in the ICES[40] model that is a multi-country, multi-sector, recursive dynamic CGE model. We have developed a new specification, called ICES-IRR, in which farms face additional capital, operational and maintenance costs (costs for irrigation services) once they decide to use more irrigable than rainfed land. Moreover, we have modified the 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. Given the new specification of the model, we have assessed the impacts of climate change with and without adaptation for the world agricultural sector and the transmitted effects to the whole economy. Our new modelling framework allows addressing important questions such as: if irrigation is a feasible adaptation option to farmers, what will be the economic cost? Do farmers decide to convert rainfed land into irrigated land as a consequence of climate change impacts?

The structure of the paper is as follows. Section 3.2 provides a review of global CGE models used to deal with water resources and irrigation. Section 3.3 gives a brief overview of the standard ICES model and presents a full description of the new modelling approach. To validate the model, we compare the results of ICES-IRR with those obtained by the standard model, by using the same balanced-growth path as reference

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[40] It is the Intertemporal Computable Equilibrium System developed at the Fondazione Eni Enrico Mattei (www.feem-web.it/ices/).

scenario (Section 3.4). Section 3.5 describes the baseline scenario and the climate change scenarios while Section 3.6 focuses on simulation results. Concluding remarks are presented in Section 3.7.

3.2 Water and irrigation in economic models

By focusing on global general equilibrium models, few examples explicitly consider water resources and irrigation as an option in the agricultural sector.[41] Among these, the first one is the GTAP-W1 model (Berrittella et al., 2005), which is a refinement of the GTAP-E model (Burniaux and Truong, 2002) to include water resources in agriculture, and water distribution services. In this modelling framework, water resources are treated as non-marketed goods and they are combined with the composite value-added-energy and the intermediate inputs at the top of the nested CES production function, by assuming perfect complementarity among them (see Appendix A, Figure 3.A1). 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 analyze the economic costs of restricted water supply[42] (Berrittella et al., 2005; Berrittella, Hoekstra, Rehdanz, Roson and Tol, 2007); water price policy[43] (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); investment in irrigation projects in China to increase water supply (Berrittella et al., 2006).

Although GTAP-W1 is the first global CGE model to deal with water resources, several shortcomings can be pointed out. First of all, water is treated as a technology parameter rather than a primary factor and thus water substitutability is limited. Moreover, GTAP-W1 is a static model, hence the adjustment path towards the long-run equilibrium is not observed. Climate change may stimulate further specialization through capital stock adjustments, reducing future economic costs. However, these effects are not sufficiently represented by static models. Furthermore, when investments in irrigation projects are considered, their level is exogenously set and thus it is not a farmers' decision.

By considering the limitations of GTAP-W1, Calzadilla et al. (2011) have developed a new version of the GTAP-W model (GTAP-W2). Firstly, they have distinguished between rainfed, irrigated and pasture land. Secondly, they have introduced substitution possibilities between irrigated land and other primary inputs in crops production. Indeed, water is combined with irrigable land to produce irrigable land-water composite, which in turn is combined with rainfed land, natural resources, labor and capital-energy composite into the

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[41] Because of data requirements, more studies of water resources have been done by using 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; Gómez 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.

[42] 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.

[43] The water saving policy is obtained through a water price tax.

value-added nest through a CES structure (see Appendix A, Figure 3.A2). Rainfed and irrigated land differ as the former is free while the latter is costly (i.e. yields per hectare are higher).

Calzadilla et al. (2011) have used GTAP-W2 to analyze the economy-wide impacts of water saving through increased irrigation efficiency[44] while Calzadilla et al. (2013) have studied the effects of two adaptation strategies for agriculture in Sub-Saharan African, i.e. expanding irrigation and increasing agricultural productivity.[45]

Although GTAP-W2 takes into account water substitutability within the crops production, several limitations can be highlighted, especially related to how adaptation is modelled. The cost of adaptation investments (e.g. investments in irrigation expansion and efficiency, improvements in agricultural productivity) is not incorporated into the model. Therefore, benefits from irrigation strategies could be overestimated. Moreover, limits on water availability and accessibility are not considered. Finally, the transformability of rainfed land into irrigated land is not allowed, since they are treated as two separate stocks.

A similar modelling approach has been followed by Ponce-Oliva (2013), who extended the ICES model to include water, irrigated and rainfed land (ICES-W). However, differently from GTAP-W2, in the crops production function irrigated land is given by land and irrigated capital. Moreover, the productivity of irrigated capital and of rainfed land depends on the level of water and precipitation, respectively. The production structure is represented in Figure 3.A3 in Appendix A.

Ponce-Oliva has the merit of modelling investments in irrigation projects within agricultural sectors. Moreover, he has considered them as an adaptation strategy. However, he did not simulate a counterfactual scenario in which adaptive actions are not taken into account. Hence, it was not possible to use the ICES-W model to quantify the cost and benefit of adaptation, separately.

By using a dynamic model, Ponce-Oliva was able to consider the investment adjustment paths induced by climate change. Moreover, he has modelled explicitly investments in irrigation projects within agricultural sectors and has considered them as an adaptation strategy. However, he did not simulate a counterfactual scenario in which adaptive actions are not taken into account. Hence, it was not possible to use the ICES-W model to quantify the cost and benefit of adaptation, separately. Finally, the approach chosen to split the base-year database to include the new land endowment, is arguable. Indeed, Ponce-Oliva uses the share of area actually irrigated over the total land to disaggregate irrigated and rainfed land, by assuming the average price per hectare of irrigated and dryland to be the same. However, this approach does not consider that better land conditions are usually required for irrigation, which are therefore translated into higher land prices.

A different approach has been followed by Taheripour et al. (2013a) in the GTAP-BIO-W model, which is an extension of the GTAP-BIO model to include water and irrigation (Hertel et al., 2010). Differently from previously described modelling frameworks, they have distinguished between irrigated and rainfed activities, by using different production functions. Moreover, to account for different level of water scarcity and of land

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[44] From a modelling perspective, water productivity is used as a proxy of irrigation efficiency.

[45] 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.

productivity within national borders, in each country several River Basins (RBs) are considered, each of them serves different Agro Ecological Zones (AEZs). Supply of water is exogenously given at the RB level, and only irrigated industries can compete for it. Managed water is immobile between RBs while instead, it is 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. Figure 3.A4 and Figure 3.A5 in Appendix A show the production structure and the land supply structure of GTAP-BIO-W.

Liu et al. (2013) have used the GTAP-BIO-W model to study the impacts of water scarcity on food security and on international agricultural trade. Liu et al. (2014) have analyzed instead the economic implications of future irrigation shortfalls on regional and global food supplies.

Although the GTAP-BIO-W model gives a better representation of climate change impacts at a subnational level, adaptation strategies have not been considered. Moreover, several assumptions have been made to disaggregate the GTAP database, which may affect results. Among these, the strongest hypothesis is that the input-output ratio is the same for both irrigated and rainfed production. However, it is not reasonable to think that the same amount of fertilizer, energy or capital is required to produce one tonne of irrigated rice and tonne of rainfed rice.

Similarly to Taheripour et al. (2013a), Baker (2011) has developed a new specification of the EPPA model (Gurgel et al., 2007), called EPPA-IRC. In particular, he distinguishes between irrigated and non-irrigated crop production and between irrigated and non-irrigated land. The new crop production structure is shown in Figure 3.A6 in Appendix A. Differently from the modelling strategy used in GTAP-BIO-W, water is not treated as a primary factor in the crop production function, but instead it is included in the value of irrigated cropland. Indeed, water resources are explicitly used in the production of irrigated land, and they affect the cost of conversion of rainfed to irrigated cropland. The water resource rent in the production structure of irrigated land is modelled throughout a fixed factor. Figure 3.A7 in Appendix A shows this land conversion structure. Two advantages of this modelling approach can be pointed out. Firstly, Baker explicitly considered the cost of land conversion. Secondly, by using a dynamic model, he was able to treat irrigable land as a stock that is reduced proportionally to the expansion of irrigated land, and limited by the maximum potential increase in irrigable land (i.e. the theoretical limit to irrigation imposed by physical water resources). However, several limitations can be noticed. Among these, and similarly to Taheripour et al. (2013a), many assumptions and additional data are required to disaggregate the original database and they may affect results.

Many challenges still remain and future research has to be done. Firstly, more data are required to include water and irrigation into the GTAP database, by considering a high level of details in terms of crop production sectors and countries. 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.

3.3 The ICES model

Overview of the model

ICES is a multi-region, multi-sector, recursive dynamic computable general equilibrium model of the global economy, derived from the static GTAP-E model (Burniaux and Truong, 2002), which in turn is the energy environmental extension of the standard GTAP model (Hertel, 1999).

The main difference of ICES with respect to the GTAP-E model is the recursive dynamics, featuring capital stock accumulation driven by endogenous investment decision. In particular, investments flowing to a country are determined by its real GDP growth and by the deviation of the country expected rate of return to capital from the world rate of return. Investments then directly affect the evolution of capital stock net of a depreciation rate. Moreover, the model takes into account the possibility that a region can run a foreign debt or a credit position if saving diverges from investment. Specifically, the regional debt accumulation depends on the regional trade balance.

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 the 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 utility function.

As in the standard GTAP model, ICES uses the conceptual device of a "global bank" that collects global net savings and allocates them amongst regions according to relative rates of return to capital. In addition, bilateral trade is specified by assuming imperfect substitutability to consider product heterogeneity by virtue of country origin (Armington, 1969). Moreover, a world sector is considered, i.e. international transportation, which produces transportation services due to goods movements from origin to destination region. Particularly, it determines transport cost margins, given by the difference between prices reported by the importing country (c.i.f.) and prices reported by the exporting country (f.o.b.).

New specification of the ICES model: ICES-IRR

The main innovative feature of the ICES-IRR model is related to crops production. Farms can decide to use both rainfed and irrigable land, or decide to substitute one for the other, according to their relative costs. Irrigable cropland is usually more productive because it requires better conditions in terms of slope, drainage, texture, soil depth, etc. (FAO, 1997). However, in order to use irrigable land, crop industries face additional capital and operational and maintenance costs. Hence, irrigated land is not only more productive, but also more costly; both because the value of irrigable land is higher and because irrigation services are required. Indeed, a new intermediate, called "irrigation services", is included in the production of each crop. Figure 3.1 shows the tree-diagram of the new production structure. Irrigable land and irrigation services are aggregated to determine irrigated land, which in turn is an imperfect substitute of rainfed land in the composite land node.

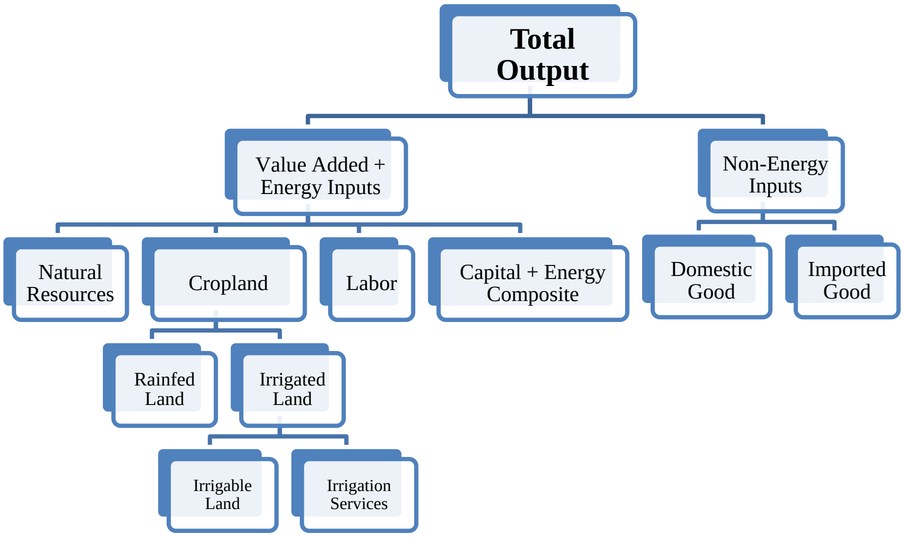

Figure 3.1: Crop production tree

Irrigation services are a new production sector that uses energy, commercial water services (e.g. water distribution services), capital and labor. Moreover, since water availability has a significant impact on the potential used of irrigation services, the supply of this sector is constrained. In fact, a fixed factor is included and it represents the water (scarcity) rents. Figure 3.2 represents the production structure of the new sector.

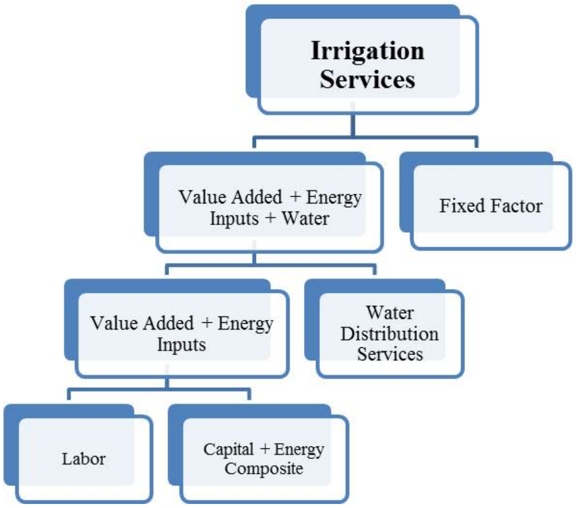

Figure 3.2: Irrigation services production tree

Another significant improvement in the ICES-IRR model is the new land supply structure. In the standard

ICES model, land supply is fixed at the country level, but can be transformed among uses. This means that, land owners decide land allocation among different uses based on relative land rents. In ICES, to take imperfect land transformability into account, a one-level Constant Elasticity of Transformation (CET) function is considered. The elasticity of transformation captures the fact that land mobility is limited by factors such as costs of conversion, region-specific infrastructure, managerial inertia, and unmeasured benefits from crop rotation (Golub and Hertel, 2012). The use of only one-nest to allocate land among uses implies to assume that land is equally easily transformable between different activities (e.g., wheat, rice, millet, livestock, etc.). However, there are many environmental and institutional barriers to land mobility, not only among crops, but also between cropland and pasture land, as well as between irrigable and rainfed land. Moreover, by assuming a one-level CET function, we are not able to consider land rental differentials between cropland and pasture land and between irrigated and rainfed land. Generally speaking, land devoted to cropland and specifically to irrigated production is usually more valuable because it requires better conditions in terms of slope, drainage, texture, soil depth, etc.

In this paper we modify the land supply structure in order to consider different land rents, and imperfect land mobility between pasture and cropland, irrigable and rainfed land and among different crop industries. Following Taheripour et al. (2013a), we extend the land supply structure to a three-level CET function (Figure 3.3). At the bottom level of the nested structure, land in each region is assumed to be transformable among pasture and cropland, while at the second level cropland supply is allocated between composite irrigable land and dryland. Finally at the top, land supply among crops is treated as in the standard ICES model. Differently from Taheripour et al. (2013a), where irrigable land is supplied only to irrigated crop production, in ICES-IRR both irrigable and rainfed land can be used by all crops industries.

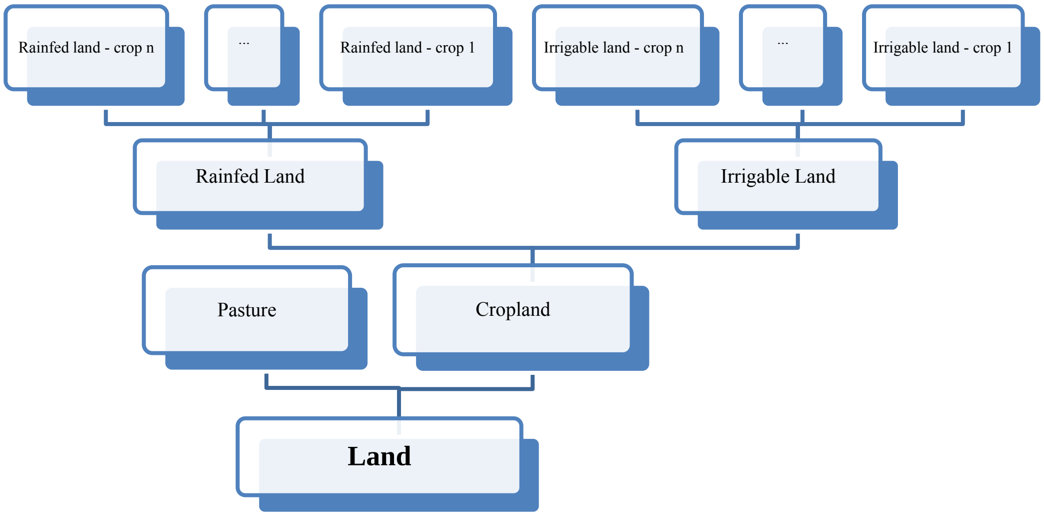

Figure 3.3: Land allocation tree

To include the new “irrigation services” sector and new primary factors, e.g. the fixed factor, irrigable, rainfed and pasture land, changes in the existing base-year database have made. The procedure that has been followed to manipulate data is explained in Appendix B.

3.4 Validation of ICES-IRR

To validate the model, we compare the results of the standard model with those obtained by the new specification, assuming the same balanced-growth path (BGP) as reference scenario.[46] By using both models, the climate change scenario is obtained by a uniform decrease in land productivity reaching 15% in 2050, with respect to 2007. In the ICES-IRR model, both rainfed and irrigated land are affected by the same uniform productivity shock (-15% by 2050). In addition, two variants of the new model are used to consider, not only market-driven adaptation, but also irrigation-adaptation strategies. The first one is the ICES-IRR-ADAP specification, in which farmers are allowed to expand irrigated land to avoid damages due to climate change ("ICES-IRR-Adap" scenario). The second one is the ICES-IRR-NoADAP version, where only climate change impacts are considered, without adaptation responses through changes in irrigated land ("ICES-IRR-NoAdap" scenario). Table 3.1 summarizes the three scenarios, considered in this section, and their differences in terms of modelling strategies.

Scenario Name	Model Variant	Adaptation Strategy	Climate Change Impacts
ICES-CC	ICES (standard model)	market-driven adaptation	uniform shock on land
ICES-IRR-NoAdap	ICES-IRR-NoADAP	market-driven adaptation	uniform shock on all types of land
ICES-IRR-Adap	ICES-IRR-ADAP	market-driven adaptation + irrigation-adaptation	uniform shock on all types of land

Table 3.1: Scenarios used to validate ICES-IRR

This comparison is restricted to the impact on irrigated and rainfed land demand, on their prices, and on the output of each crop. Moreover, we analyze how the new specification affects the macroeconomic costs of climate change, by focusing on changes in GDP.

Regarding land demand and prices, since total land supply is fixed at the regional level in both models, the impact of climate change is reflected by changes in its value, as well as in the distribution of irrigated and dryland due to land conversion.

On average, the uniform decrease in land productivity generates a rise in land price by 89.4% with ICES, by 94.5% with ICES-IRR-ADAP and by 91.5% with ICES-IRR-NoADAP. Because of the new structure of land supply, ICES-IRR determines stronger effects on prices. Indeed, when adaptation is allowed, farmers respond to climate change impacts by substituting rainfed with irrigated land, and these changes increase land rents, at the global level.

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[46] In equilibrium, the economy is annually growing at a rate of 2%.

As shown in Figure 3.4, similar results are observed at the regional level. Stronger impacts on land price are obtained with ICES-IRR, compared to the standard ICES. In this regard, few exceptions are noticed. For example, under the non-adaptation scenario, a smaller increase in land rents is observed in countries characterized by a relatively high share of irrigated land in total cropland (e.g. from 26% to 43% of total land is under irrigation in NAF, CHINA, EASIA, SASIA and MDE). Therefore, in these countries farmers have less incentive to substitute rainfed with irrigated land, avoiding a strong negative impact on total land price. Table 3.2 shows the effects of climate change on land rents in ICES-IRR-NoAdap (column 1) and ICES-IRR-Adap (column 2), both compared to ICES-CC. Column 4 reports the share of irrigated land in total cropland.

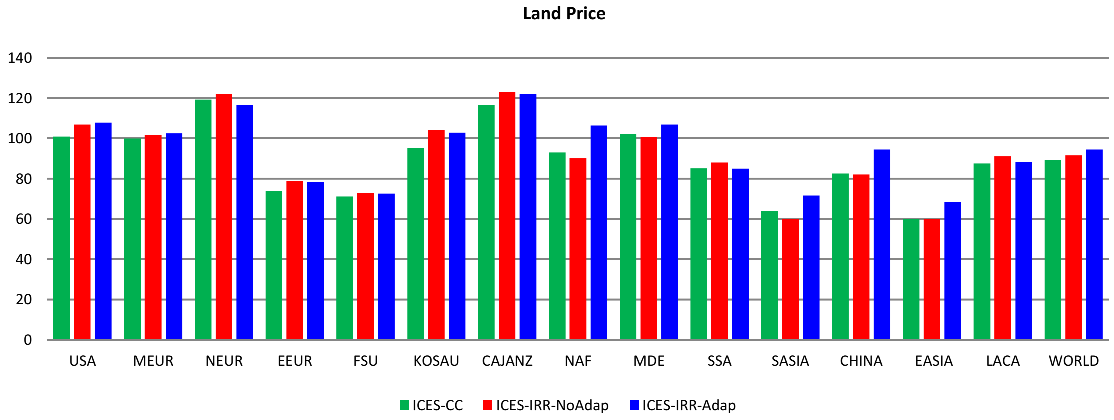

Figure 3.4: Changes in land price at the regional level, under the three scenarios ($\Delta\%$ w.r.t. BGP)

	Total Land Price			Irrigated Land/Cropland (%)
	ICES-IRR-NoAdap vs ICES-CC (Δ)	ICES-IRR-Adap vs ICES-CC (Δ)	ICES-IRR-Adap vs ICES-IRR-NoAdap (Δ)	
	(1)	(2)	(3)	(4)
USA	5.99	6.99	1.00	14.53
MEUR	1.87	2.69	0.81	13.09
NEUR	2.68	-2.60	-5.28	1.77
EEUR	4.84	4.29	-0.55	6.25
FSU	1.85	1.46	-0.39	6.64
KOSAU	8.92	7.59	-1.32	13.99
CAJANZ	6.30	5.27	-1.03	15.27
NAF	-2.97	13.42	16.40	39.20
MDE	-1.63	4.59	6.22	26.21
SSA	2.96	-0.18	-3.15	2.06
SASIA	-3.95	7.60	11.55	37.15
CHINA	-0.36	11.96	12.32	42.81
EASIA	-0.13	8.36	8.49	33.27
LACA	3.67	0.74	-2.93	5.19
WORLD	2.15	5.16	3.01	24.31

Table 3.2: Changes in land prices, under the ICES-CC, the ICES-IRR-NoAdap and the ICES-IRR-Adap scenarios

As said before, adaptation increases averagely land rents, compared to the non-adaptation scenario. However, this is not always true at the regional level. Relevant reductions in land price are observed in NEUR, SSA and LACA (column 3 in Table 3.2). This result is consistent with regional land cost structures. Hence, adaptation stimulates the use of irrigated land, especially in those regions characterized by a relatively low share of irrigated land in cropland cost. The substitution among land types affects their prices, particularly by increasing irrigated land rents and by lowering rainfed land rents (see Figure 3.5). This effect dominates in countries where irrigation is not much developed.

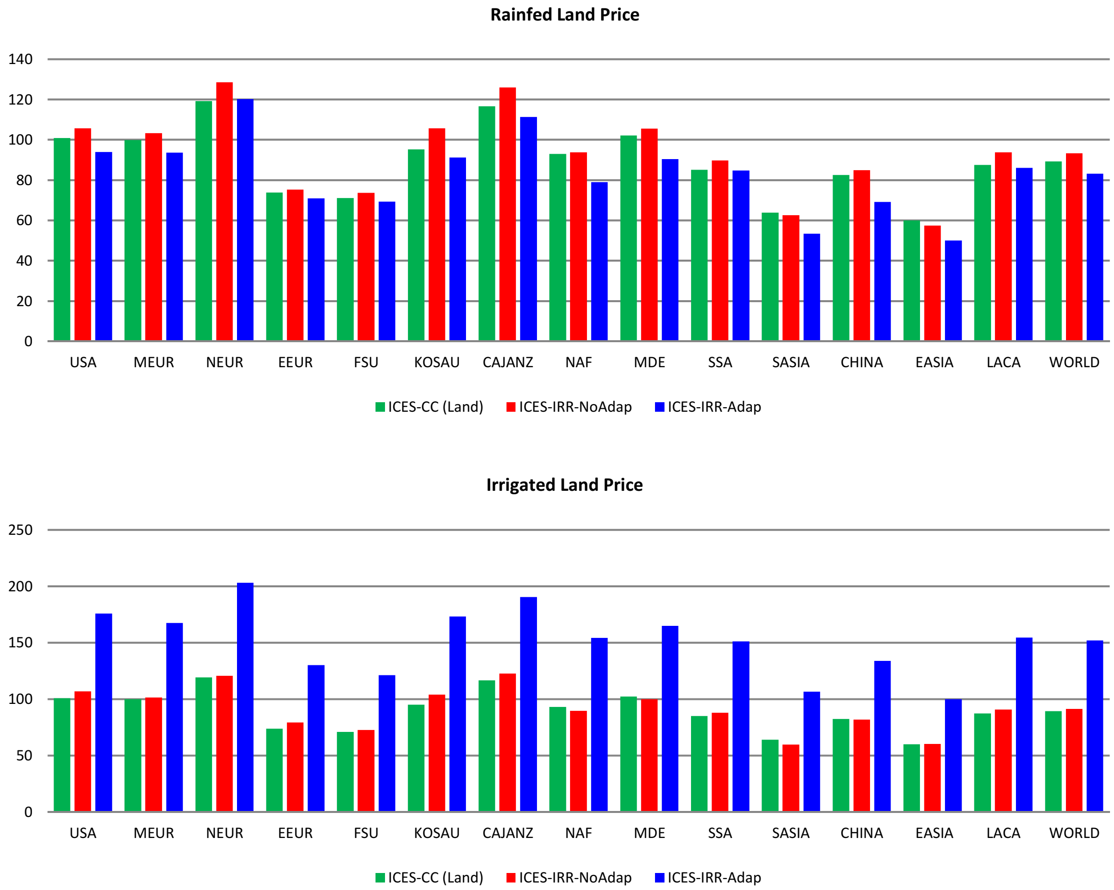

Figure 3.5: Changes in the price of rainfed and irrigated land at the regional level, under the three scenarios ($\Delta\%$ w.r.t. BGP)

Interestingly, striking dissimilarities between ICES and ICES-IRR can be noticed by considering the impact of climate change on the price of different types of land. While land rents in the ICES-CC and ICES-IRR-NoAdap scenario react similarly, land prices are strongly affected under the adaptation scenario. For example, irrigated land price increases on average by more than 60 percentage points in ICES-IRR-Adap, compared to ICES-CC. In ICES-IRR-NoAdap instead, it increase only by 1.87 percentage points. Similar, but smaller, impacts are observed on rainfed land prices. Indeed, they decrease on average by 6.25 percentage points in ICES-IRR-Adap, while they increase by almost 4 percentage points in ICES-IRR-NoAdap, both compared to ICES-CC.[47] Figure 3.5 shows changes in the rents of different types of land, under ICES-CC, ICES-IRR-NoAdap and ICES-IRR-Adap.

In general, in the adaptation scenario, a strong increase in irrigated land rents is observed in all regions. The reason of these changes is the new available substitution options for farmers, as well as land conversion

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[47] Table 3.C1 in Appendix C reports changes in land prices, by using ICES, ICES-IRR-NoADAP and ICES-IRR-ADAP.

options for land owners. Indeed, a more flexible structure, which allows demanding different types of land, strongly affects prices. In particular, in ICES-IRR-Adap, irrigation expands in all regions to the detriment of rainfed land (Figure 3.6). A closer look at the country level shows that in those regions, in which the share of irrigated land in the baseline is small, the substitution is more likely. Examples in this regard are NEUR, SSA and LACA with 1.8%, 2.1% and 5.2% of total land under irrigation in 2007, respectively. Because of negative impacts on land productivity, farmers demand more irrigated land, which is characterized by relatively lower share in total cropland. In fact, in 2050 the demand for irrigated land in those regions increases by 18.6%, 16.6% and 16.4%, respectively, compared to ICES-IRR-NoAdap. The opposite occurs in those countries where the irrigated land share is higher. In SASIA, EASIA, CHINA and NAF, more than 33% of total land is under irrigation. Hence, climate change determines a smaller substitution effect (the increase in irrigated land is between 8.9% and 11.2%).

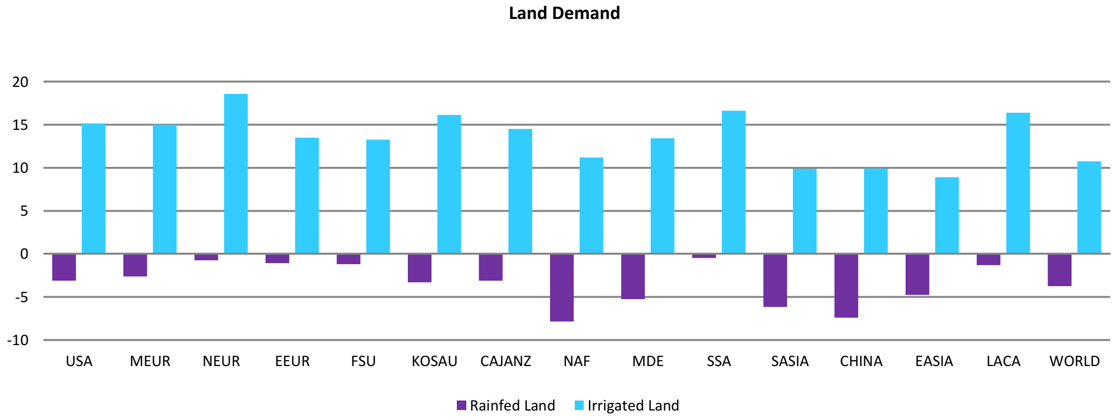

Figure 3.6: Changes in rainfed and irrigated land demand at the regional level in ICES-IRR-Adap (Δ% w.r.t. ICES-IRR-NoAdap)

The picture becomes more variegated when the impact on land demand is considered at the crop level. Figures 3.7 and 3.8 show changes in rainfed and irrigated land demand, respectively, under the three scenarios. By using the standard ICES model, in most countries, the main decrease in land demand is observed in the wheat sector (-1.07% globally). On the contrary, this reduction is compensated by an increase in the land used for rice (+3.15% at the world level). Similar results, both at the regional and at the crop level, are obtained in ICES-IRR-NoAdap. This is particular clear by looking at the demand of rainfed land (Figure 3.7), which is relatively more used in crops production, compared to irrigated land.

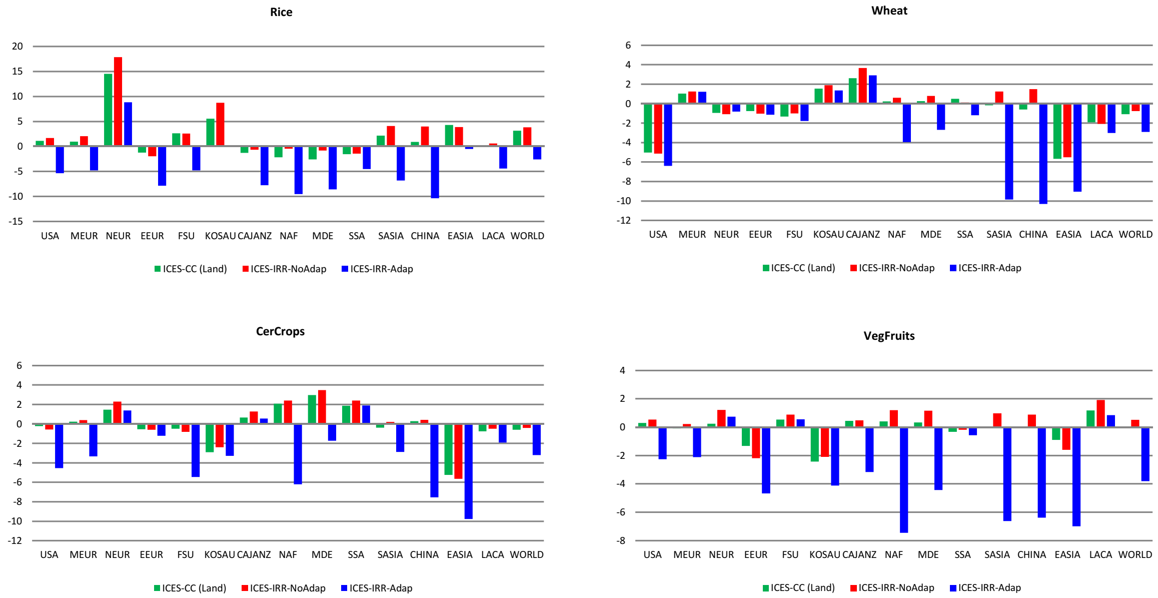

Figure 3.7: Changes in rainfed land demand by crop, under the three scenarios (Δ% w.r.t. BGP)

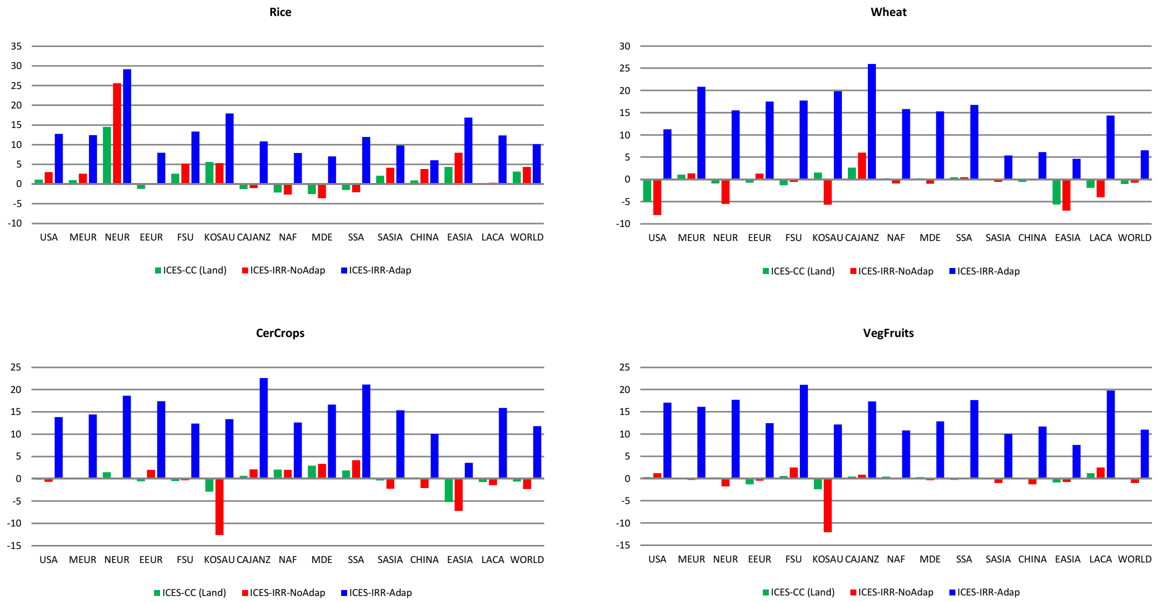

Figure 3.8: Changes in irrigated land demand by crop, under the three scenarios (Δ% w.r.t. BGP)

On the contrary, when irrigation expansion is permitted, there are strong differences between ICES-CC and ICES-IRR-Adap. In almost all agricultural sectors and regions, there is a drop in the demand of rainfed land that goes with an increase in the use of irrigated land. This increase, compared to the non-adaptation scenario, is less significant in those sectors characterized by a high cost share of irrigated land (Figure 3.9).[48]

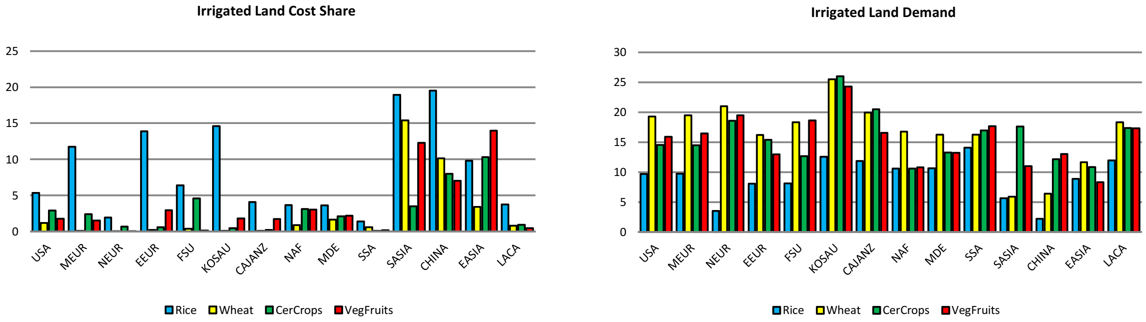

Figure 3.9: Cost share of irrigated land (%) and changes in irrigated land (Δ w.r.t. ICES-IRR-NoAdap)

Because of the increase in land prices, substitution between land and other primary factors is observed. Indeed, there is an increase in labor and capital demand in the production of almost all crops and regions. However, under the adaptation scenario, this substitution effects is less prominent (see Table 3.C3 in Appendix C). Indeed, rainfed land is firstly substituted with irrigated land due to the very high elasticity of substitution among them.

Changes in land demand directly affect crop production. For example, by using the standard ICES model, in NEUR the stronger increase in land demand and production is observed in the rice sector while a smaller output expansion is in the wheat sector, where land demand decreases. In general, under the no-adaptation scenario, impacts on crop production are slightly bigger. However, when substitutability between different types of land is allowed, the standard ICES model and the ICES-IRR under the adaptation scenario present similar results. Therefore, as shown in Figure 3.10, dissimilarities in agricultural production are negligible.

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[48] Cost shares of irrigated land are reported in Table 3.C2 in Appendix C.

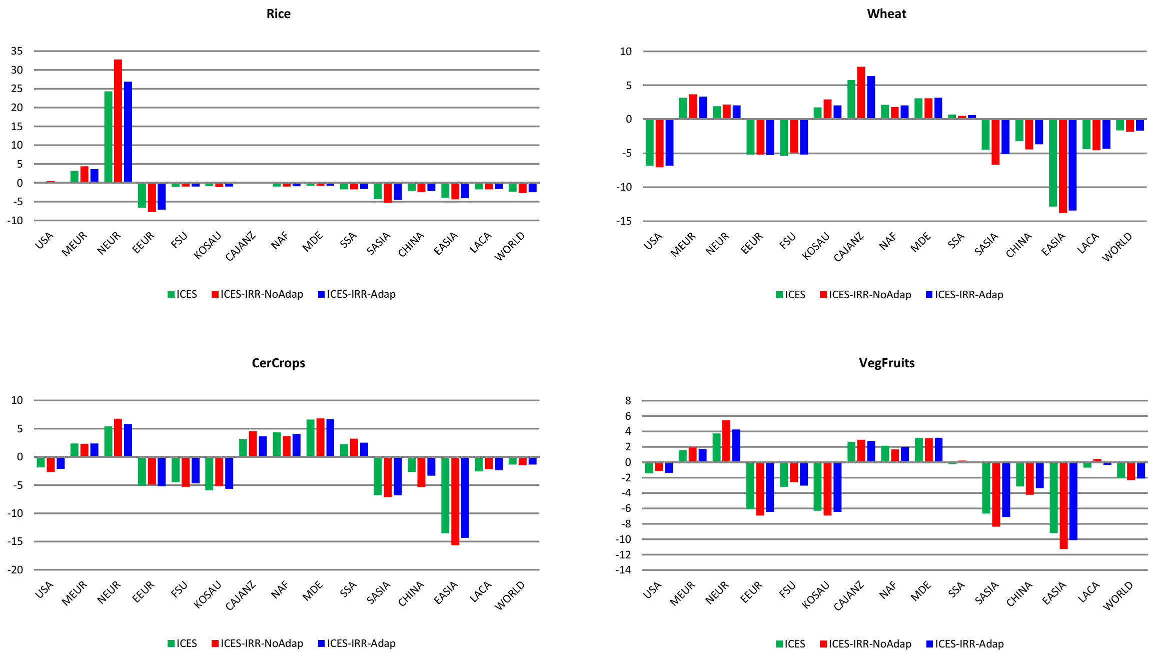

Figure 3.10: Changes in crops production, under the three scenarios (Δ% w.r.t. BGP)

Regarding macroeconomic costs, positive impacts on GDP are expected in those regions characterized by a capital-intensive agriculture (i.e. USA, MEUR, NEUR and CAJANZ). Indeed, they are able to attract more foreign capital, with respect to those regions where agriculture is reliant on land (e.g. SASIA and EASIA). These capital inflows positively affect capital accumulation, and thus economic growth. When irrigation expansion is allowed, differences in climate change costs between ICES and ICES-IRR are negligible (Figure 3.11).

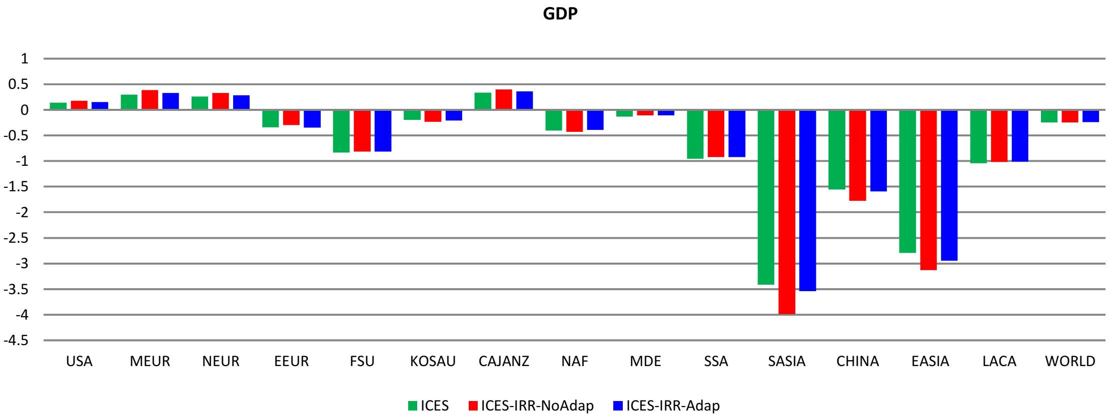

Figure 3.11: Changes in GDP at the regional level, under the three scenarios (Δ% w.r.t. BGP)

In conclusion, even if ICES and ICES-IRR determine similar results in terms of climate change impacts on agricultural production and macroeconomic costs, the main advantage of the new specification is the possibility to quantify both the cost of climate change and the economic effectiveness of irrigation, as a planned adaptation strategy. The former is measured by the GDP loss under the no-adaptation scenario. The latter instead is quantified by the difference between GDP performance in the adaptation and in the no-adaptation scenario (i.e., the avoided GDP loss). As shown in Figure 3.12, adaptation benefits are stronger in those countries which are more impacted by climate change.

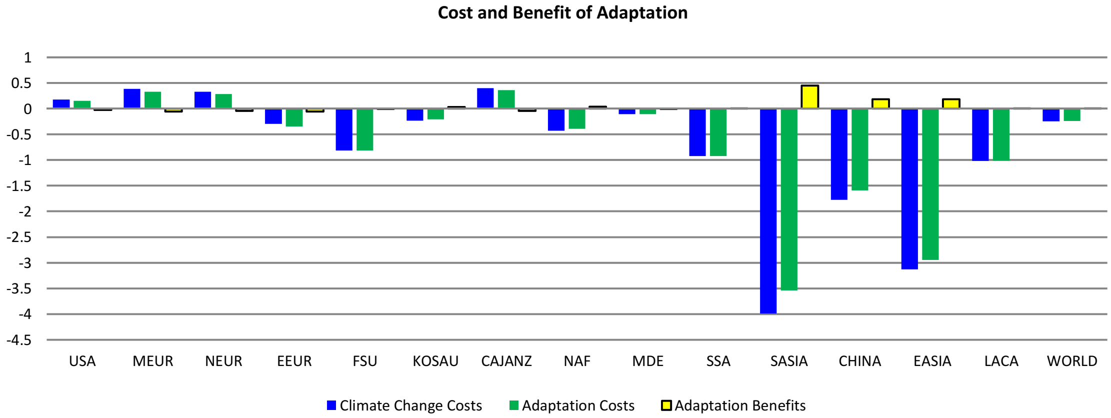

Figure 3.12: Cost and benefit of climate change and irrigation-adaptation at the regional level

3.5 Scenarios

Reference Scenario

ICES-IRR uses the GTAP 8 database, which covers 129 regions and 57 sectors (Narayanan et al., 2012), calibrated in 2007. For the present exercise, the world is grouped into 14 regions, shown in Figure 3.13.

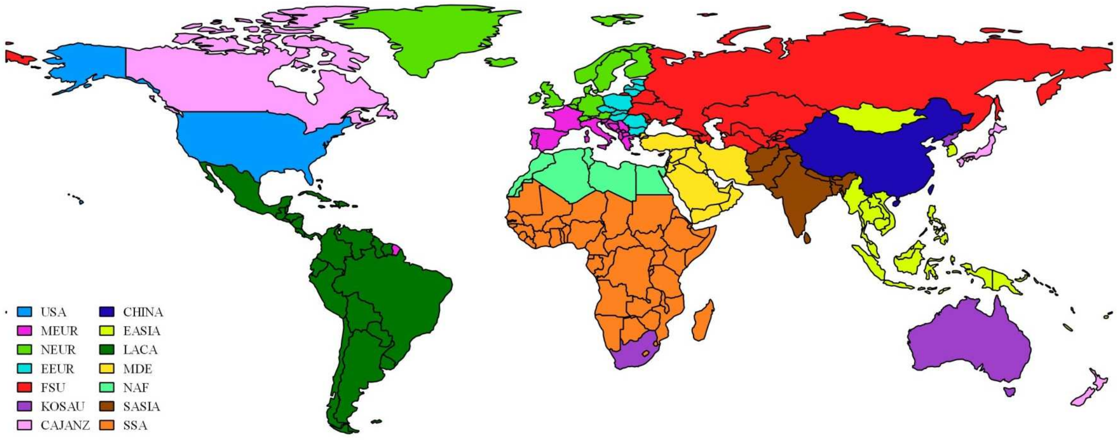

Figure 3.13: The ICES regional aggregation

23 representative industries are considered and reported in Table 3.3. The baseline is a counter-factual scenario which goes from 2008 to 2050, characterized by no climate change effects.

Rice
Wheat
CerCrops
VegFruits
Livestock
Water
MServ
PubServ
IRServ
Coal
Oil
Gas
NuclearFuel
Oil_Pcts
Ely_Nuclear
Ely_Renew
Ely_Other
En_Int_ind
Oth_ind
Construction
RoadTransprt
OthrTransprt
Commerce

Table 3.3: Production sectors

We use the SSP2 socio-economic scenario, that is the "Middle of the Road" (or "Dynamic as Usual", or "Current Trends Continue") of the Shared Social Economic Pathways, developed for Intergovernmental Panel on Climate Change (IPCC) 5th assessment report (O'Neill et al., 2014). This scenario assumes mostly prolongation of currently economic development trends, with reductions in resource and energy intensity at historic rates and a slowly decreasing fossil fuel dependency. To build the business-as-usual scenario (BaU), we use projections on population and economic growth rates for the SSP2, determined by the OECD ENV-Growth model (see Figure 3.14).[49] Labor force growth is assumed to behave the same as that of population.

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[49] The IIASA SSP database is available online at: https://tntcat.iiasa.ac.at/SspDb

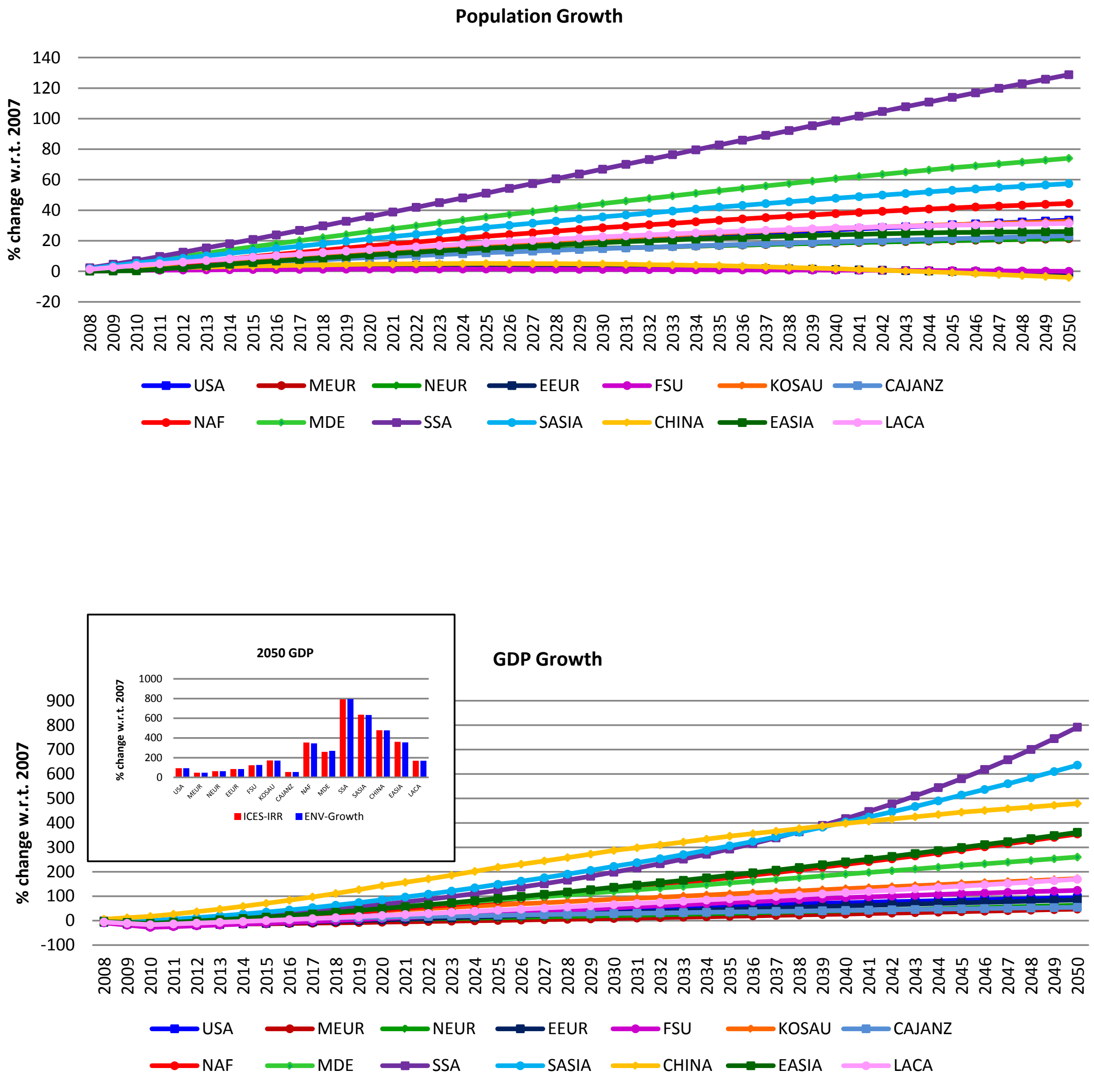

Figure 3.14: Population and GDP trends in the ICES-IRR baseline

Fossil fuels natural resources' stocks are endogenously estimated, by having the quantity replicating in the baseline fossil fuels prices trends, as estimated by simulations performed with the WITCH integrated assessment dynamic optimization model (Bosetti et al., 2009), applied within the FP7 Global-IQ project Figure 3.15).

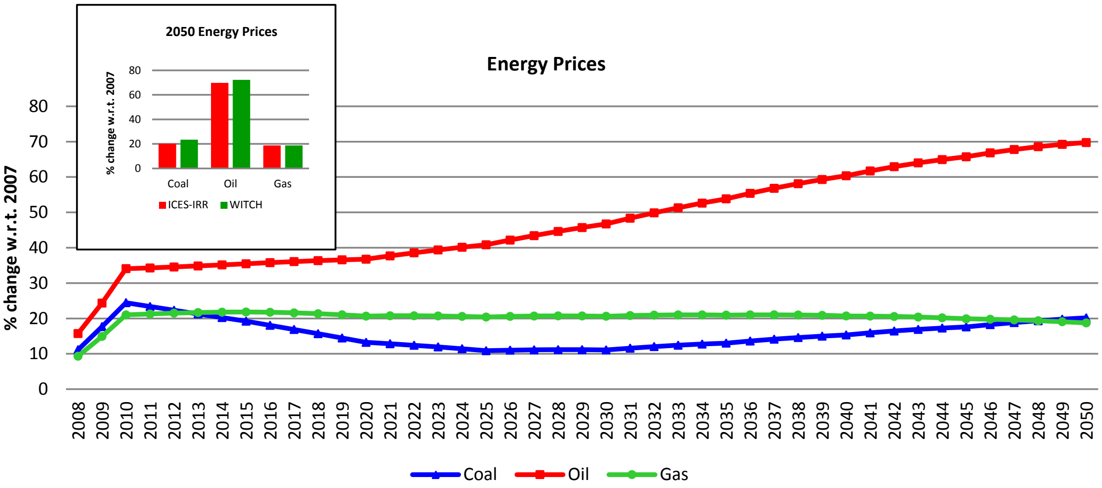

Figure 3.15: Growth in energy prices in the ICES-IRR baseline

Moreover, following Bosello and Parrado (2014), we set the annually growth rates of energy efficiency for developing countries at 0.63%, and for developed countries at 0.56%. Finally, changes in irrigated and rainfed land productivity are taken from the IFPRI baseline scenario ("Baseline Perfect Mitigation"), where today's climate conditions are imposed for the future (Nelson et al., 2010). In particular, the rainfed and irrigated intrinsic productivity rates have been used to simulate land-augmenting or Harrod-neutral technical change within the agricultural sectors (von Lampe et al., 2014). These shocks are introduced to reflect exogenous technological changes.

As shown in Table 3.4, in the reference scenario food production grows strongly by 2050. This increase is particularly significant in those regions where the number of people to be fed puts great pressure on agricultural production. For example, by 2050 in SSA and SASIA, the population is expected to be respectively, 1722 million and 2397 million (with a growth rate of 129% and 57%, compared to 2007 levels). In these regions, agricultural output is projected to grow by 488% and 420%.

	Irrigated Land	Rainfed Land	Cropland	Agricultural Production	Population
USA	34.07	4.46	8.77	125.34	33.53
MEUR	29.00	5.29	8.44	23.44	21.37
NEUR	12.67	5.39	5.51	57.24	21.37
EEUR	12.23	4.15	4.70	39.56	-1.30
FSU	7.70	10.54	10.35	161.74	0.00
KOSAU	42.22	-1.55	4.56	109.68	32.67
CAJANZ	18.83	4.85	6.99	50.50	23.26
NAF	17.25	-3.64	4.55	161.53	44.47
MDE	20.53	-5.53	1.30	226.77	74.03
SSA	18.90	2.74	3.08	487.67	128.80
SASIA	22.64	-6.69	4.20	420.12	57.44
CHINA	23.97	-9.49	4.84	363.19	-4.03
EASIA	18.15	-0.81	5.50	187.65	26.05
LACA	38.79	6.96	8.61	152.58	31.37
WORLD	23.38	0.41	5.93	225.69	40.29

Table 3.4: 2050 baseline results: population, agricultural land and production by region ($\Delta\%$ w.r.t. 2007)

However, this increase is driven by a small expansion of crop harvested area. Indeed, at the world level, agricultural land would grow by 6%, compared to 2007.[50] In those countries where there is the stronger increase in crop production, agricultural land would expand by 3-4.9% (SSA, SASIA and CHINA). Therefore the increase in agricultural output is driven also by other factors. One of this is the increase in irrigated land. Although less than one third of cropland is projected to be under irrigation by 2050, irrigated area grows globally by around 23%, compared to 2007. Figure 3.16 shows the share of irrigated land, over total land, in 2007 and 2050. In the baseline, land under irrigation expands in all countries. In general, the increase in irrigated land does not go with a reduction in rainfed area (+0.4% at the global level).

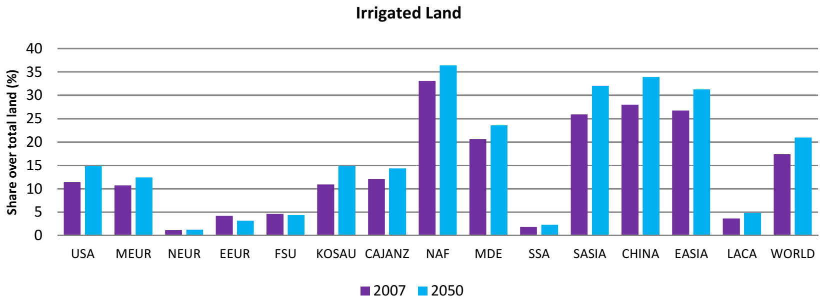

Figure 3.16: Share of total land under irrigation in 2007 and 2050

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[50] This result is slightly lower than those in Schmitz et al. (2014), where similar trends in population, GDP and land productivity are assumed. By comparing four partial and six general equilibrium global agro-economic models, they find an increase of cropland of 10-25% by 2050, compared to 2005. However, they also show a reduction in cropland by using the FARM model (Sands et al., 2014).

Climate Change Scenarios

By using the new specification of the model (ICES-IRR) in its two variants (ICES-IRR-NoADAP and ICES-IRR-ADAP), we consider the effects of adaptation strategies in the agricultural sector under two different climate change scenarios.

The first one is a hypothetical scenario characterized by uniformly reducing the baseline land productivity growth by -10%. This shock is applied to all land types, i.e. irrigated, rainfed and pasture land. Dissimilarly from the validation exercise, climate change would differently affect regions and crops, not only because of market-driven adjustments, but also because of pre-existing differences in terms of economic growth, population dynamics, and primary factors productivities, considered in the baseline.

In the second scenario instead, the climate change impacts on crops' yields are taken from the Agricultural Model Intercomparison and Improvement Project (AgMIP; agmip.org; Rosenzweig et al., 2013). In particular, we use data generated by the LPJmL crop model (Bondeau et al., 2007). Within ICES-IRR, changes in crops' yields are introduced in the same way as in the previous scenario, but this time reducing (or augmenting) the baseline land productivity, by crop and land type, according to LPJmL projections (Elliott et al., 2015; Rosenzweig et al., 2014; Villoria et al., 2014).

Table 3.5 summarizes the climate change scenarios, while Figure 3.17 shows the direct impacts of climate change on land productivity, compared to the baseline levels, under the two climate change scenarios.

Scenario Name	Economic Model Variant	Adaptation Strategy	Climate Change Impacts
ICES-IRR-Adap-CC1	ICES-IRR-ADAP	market-driven adaptation + irrigation-adaptation	negative shock
ICES-IRR-NoAdap-CC1	ICES-IRR-NoADAP	market-driven adaptation	negative shock
ICES-IRR-Adap-CC2	ICES-IRR-ADAP	market-driven adaptation + irrigation-adaptation	PIK – LPJmL model (AgMIP)
ICES-IRR-NoAdap-CC2	ICES-IRR-NoADAP	market-driven adaptation	PIK – LPJmL model (AgMIP)

Table 3.5: Climate change scenarios

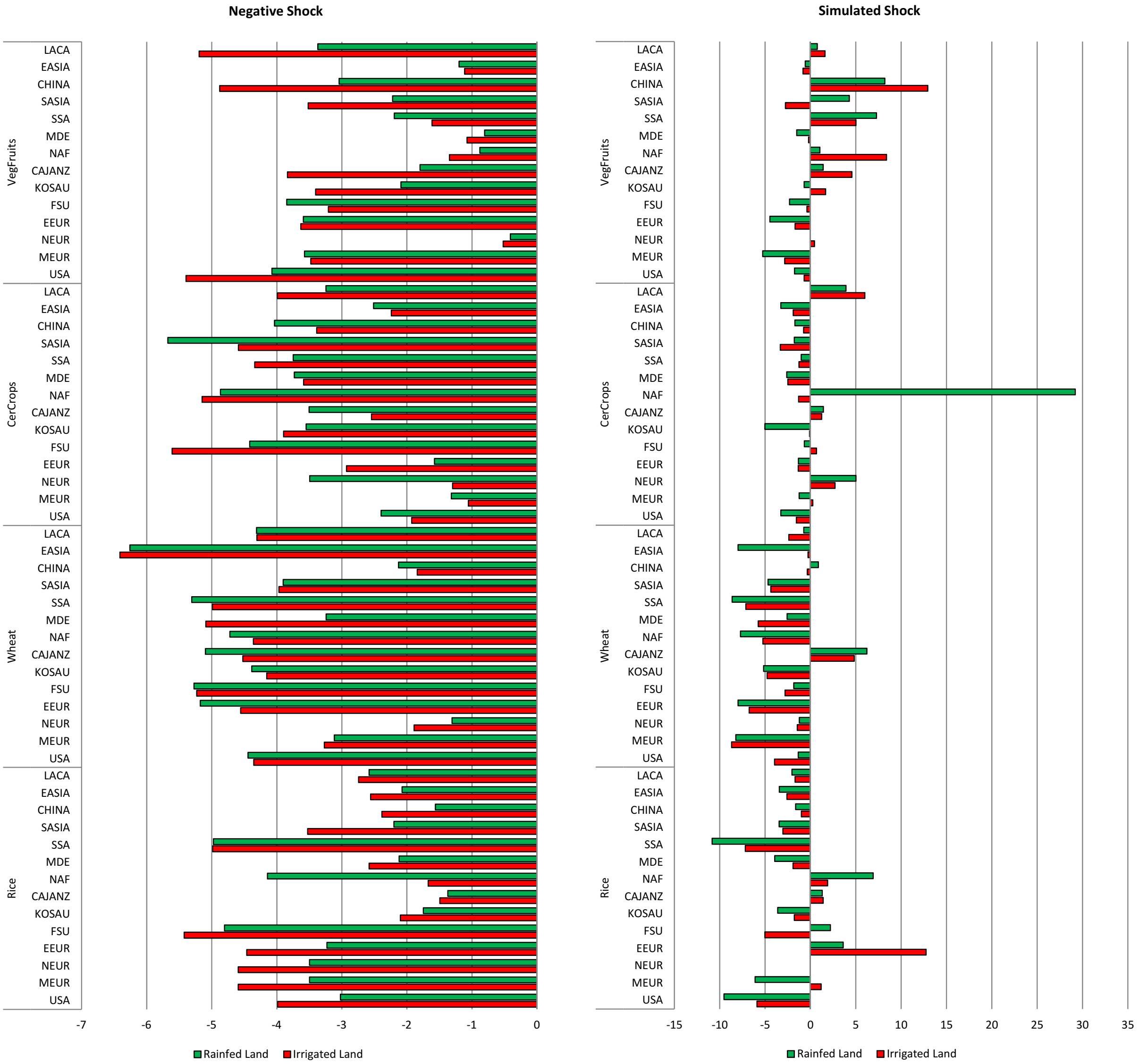

Figure 3.17: Changes in rainfed and irrigated land productivity, in the two climate change scenarios ($\Delta\%$ w.r.t. baseline levels)

3.6 Simulation results

Climate Change Scenario 1: Negative productivity shocks

Although we have imposed a negative uniform shock, dissimilarities in the baseline directly affects results. In fact, differently from the validation exercise, in most countries irrigated land is averagely more productive than rainfed land. Hence, the higher the productivity in the baseline, the higher the climate change impact.

When irrigation-adaptation strategies are not allowed, the decrease in land productivity directly affects production costs in agricultural sectors. Indeed, to produce the same amount of output, famers need more inputs. Hence, they increase land demand, especially irrigated land that is strongly impacted by climate change and less employed, compared to rainfed land. However, since the supply of rainfed, irrigated and pasture land is fixed, the factor market equilibrium is guaranteed through an increase in land prices. As shown in Figure 3.18, in all regions there is a higher increase in the price of irrigated rather than rainfed land. However, the magnitude of this increase is different among countries. Former Soviet Union is the region with the highest increase in irrigated land price, followed by Northern Europe. This result is due to heterogeneity between countries in terms of initial land productivity and share of irrigated land.[51] For example, on average, FSU is characterized by the highest productivity, both in irrigated and rainfed land, which is strongly impacted by climate change, increasing production costs. NEUR is characterized by an initial low productivity, but instead it is the region with the lower share of irrigated land to cropland.

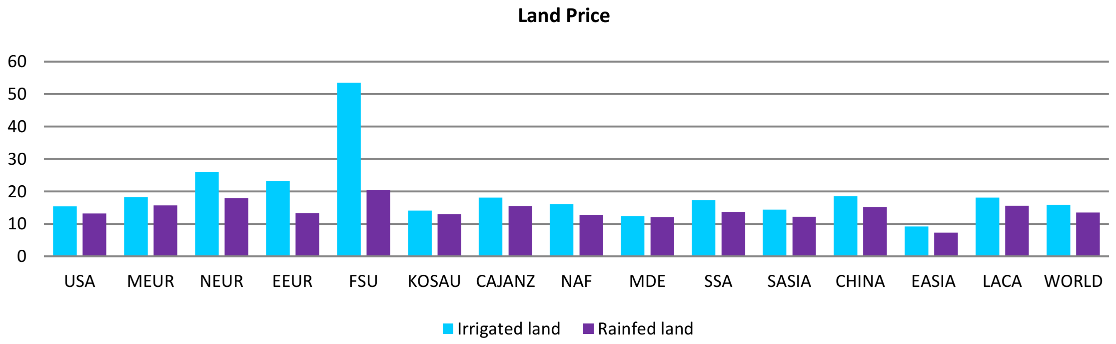

Figure 3.18: Changes in land prices, under the ICES-IRR-NoAdap-CC1 scenario (Δ% w.r.t. baseline)

When irrigation expansion is permitted, not only the demand, but also the supply of land changes. Indeed, in almost all countries landowners convert rainfed land into irrigated land (Figure 3.19), reducing the effects of climate change on land market prices. Therefore, as shown in Figure 3.20 and 3.21, both irrigated and rainfed land prices increases, but less than in ICES-IRR-NoADAP. Differently from the validation exercise, not only land rents, but also the irrigation expansion depends on both, the share of irrigated land in total cropland and the baseline productivity level.

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[51] Shares of irrigated land are reported in column 1 in Table 3.C4 (Appendix C).

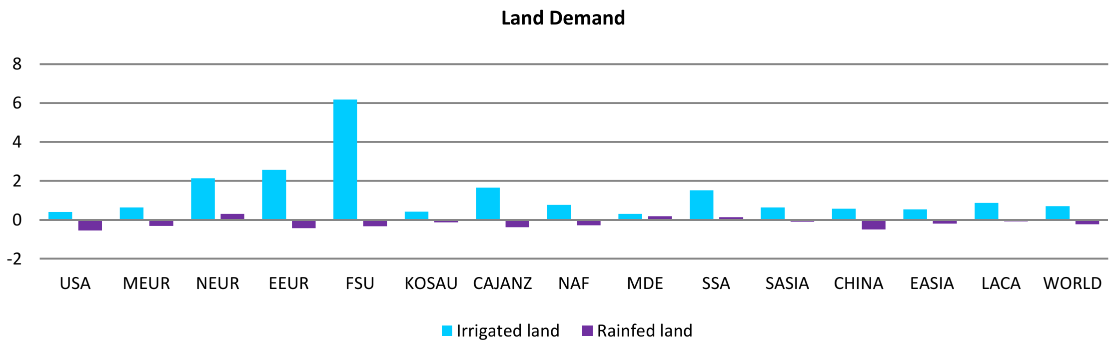

Figure 3.19: Changes in land demand in the ICES-IRR-Adap-CC1 scenario (Δ% w.r.t. baseline)

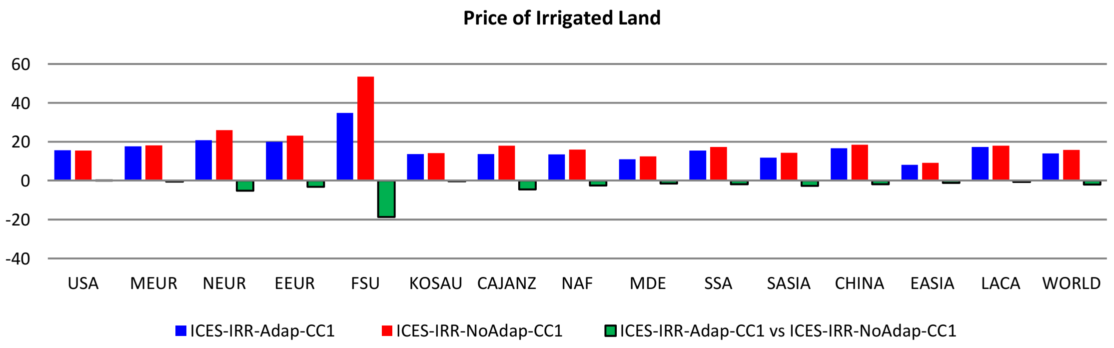

Figure 3.20: Changes in irrigated land prices, under the ICES-IRR-NoAdap-CC1 and the ICES-IRR-Adap-CC1 scenarios (Δ% w.r.t. baseline)

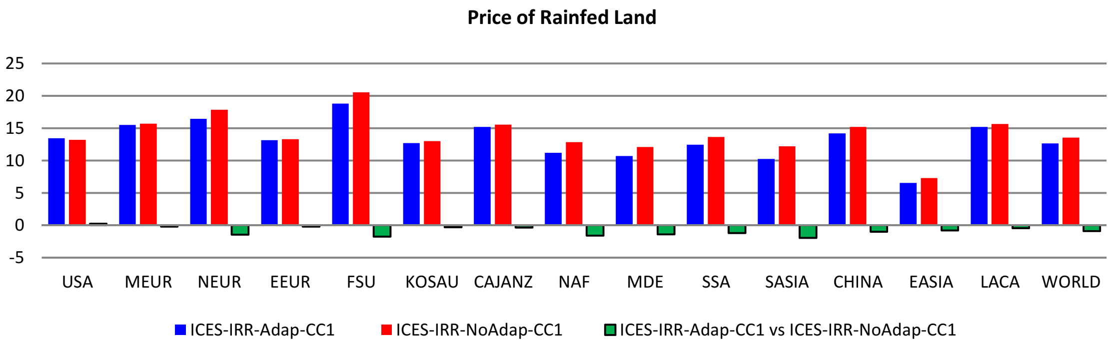

Figure 3.21: Changes in rainfed land prices, under the ICES-IRR-NoAdap-CC1 and the ICES-IRR-Adap-CC1 scenarios (Δ% w.r.t. baseline)

Under both scenarios, the increase in production costs due to climate change impacts determines land reallocation between crops. In particular, when irrigation expansion is not allowed, there is usually an increase in both, irrigated and rainfed land demand in those agricultural sectors, which are strongly impacted by climate change (Table 3.6). For example, in KOSAU land productivity is negatively affected by climate change in wheat production (-4.15% and -4.38% for irrigated and rainfed land, respectively). This determines an increase in both irrigated (+1.8%) and rainfed (1.4%) land demand, stronger than changes in other sectors. Some exceptions can be noticed. For example, in EASIA, the stronger reduction in land productivity is observed in the wheat sector. However, irrigated land demand decreases (-1.33%). This can be explained by looking at changes in both land types. In fact, the negative effect of climate change stimulates an increase of rainfed land (+2.63%) for wheat production, which compensates both productivity shocks.

	Irrigated Land Demand				Irrigated Land Productivity				Rainfed Land Demand				Rainfed Land Productivity			
	Rice	Wheat	CerCrops	VegFruits	Rice	Wheat	CerCrops	VegFruits	Rice	Wheat	CerCrops	VegFruits	Rice	Wheat	CerCrops	VegFruits
USA	1.62	-0.02	-0.78	0.63	-3.99	-4.35	-1.93	-5.40	2.36	-0.64	-0.93	0.82	-3.02	-4.44	-2.40	-4.08
MEUR	2.60	1.85	-0.84	2.39	-4.59	-3.27	-1.06	-3.48	1.69	1.22	-0.79	0.69	-3.50	-3.12	-1.32	-3.57
NEUR	6.03	-5.13	0.12	-5.45	-4.59	-1.89	-1.30	-0.52	10.04	-0.90	1.09	-1.40	-3.50	-1.31	-3.50	-0.41
EEUR	-0.70	3.78	-3.90	1.57	-4.46	-4.56	-2.93	-3.63	-0.12	1.89	-0.56	0.36	-3.23	-5.18	-1.58	-3.59
FSU	1.52	2.96	0.12	-4.36	-5.42	-5.23	-5.61	-3.21	0.22	0.52	0.18	-0.23	-4.80	-5.27	-4.42	-3.85
KOSAU	-0.05	1.80	0.93	0.37	-2.10	-4.15	-3.90	-3.41	0.19	1.40	-0.17	-0.37	-1.75	-4.38	-3.55	-2.09
CAJANZ	-1.87	6.66	10.33	2.45	-1.49	-4.52	-2.54	-3.84	-1.00	0.64	1.31	-0.52	-1.37	-5.10	-3.51	-1.80
NAF	1.70	-4.34	6.61	-0.83	-1.67	-4.36	-5.15	-1.35	-0.99	1.82	1.45	-0.30	-4.14	-4.72	-4.87	-0.88
MDE	0.30	7.82	2.06	-0.51	-2.58	-5.09	-3.59	-1.08	0.04	1.64	1.15	-0.59	-2.12	-3.24	-3.73	-0.81
SSA	2.37	0.86	1.17	-1.17	-4.99	-4.99	-4.34	-1.61	0.72	2.41	1.46	-0.58	-4.97	-5.31	-3.75	-2.19
SASIA	0.24	2.54	5.87	-0.41	-3.53	-3.97	-4.59	-3.52	0.70	-0.68	0.45	-0.31	-2.20	-3.90	-5.67	-2.22
CHINA	-0.32	-0.03	0.17	0.37	-2.38	-1.84	-3.39	-4.88	0.80	-1.09	-1.09	0.17	-1.56	-2.13	-4.04	-3.04
EASIA	0.18	-1.33	0.94	-0.31	-2.56	-6.41	-2.24	-1.11	0.51	2.63	-0.22	-0.42	-2.08	-6.26	-2.51	-1.20
LACA	-0.02	12.40	-0.13	0.01	-2.74	-4.31	-3.99	-5.20	-0.25	0.02	-0.51	0.34	-2.58	-4.31	-3.24	-3.37

Table 3.6: Changes in land demand and productivity, under the ICES-IRR-NoAdap-CC1 scenario (Δ% w.r.t. baseline)

Similar results are also observed when irrigation-adaptation strategies are put in force (Table 3.7). However, since irrigated land is now able to expand at the regional level, almost all agricultural sectors increase their demand for irrigated land, compared to the ICES-IRR-NoAdap-CC1 scenario.

	Irrigated Land Demand				Irrigated Land Productivity				Rainfed Land Demand				Rainfed Land Productivity			
	Rice	Wheat	CerCrops	VegFruits	Rice	Wheat	CerCrops	VegFruits	Rice	Wheat	CerCrops	VegFruits	Rice	Wheat	CerCrops	VegFruits
USA	1.69	0.20	-0.11	0.82	-3.99	-4.35	-1.93	-5.40	1.51	-1.34	-1.20	0.09	-3.02	-4.44	-2.40	-4.08
MEUR	2.77	2.62	-0.17	2.94	-4.59	-3.27	-1.06	-3.48	0.98	1.02	-1.09	0.34	-3.50	-3.12	-1.32	-3.57
NEUR	7.40	-2.43	2.31	-2.58	-4.59	-1.89	-1.30	-0.52	8.72	-0.52	1.42	-0.95	-3.50	-1.31	-3.50	-0.41
EEUR	0.94	4.53	-0.38	3.75	-4.46	-4.56	-2.93	-3.63	-1.57	1.62	-0.87	-0.36	-3.23	-5.18	-1.58	-3.59
FSU	5.40	5.48	5.89	6.17	-5.42	-5.23	-5.61	-3.21	-2.80	0.43	-1.87	-0.17	-4.80	-5.27	-4.42	-3.85
KOSAU	0.38	2.20	1.33	0.73	-2.10	-4.15	-3.90	-3.41	-0.04	1.58	-0.17	-0.47	-1.75	-4.38	-3.55	-2.09
CAJANZ	0.40	7.50	11.34	3.49	-1.49	-4.52	-2.54	-3.84	-2.47	0.80	1.36	-0.79	-1.37	-5.10	-3.51	-1.80
NAF	2.51	-3.56	7.02	-0.04	-1.67	-4.36	-5.15	-1.35	-1.25	1.90	1.34	-0.66	-4.14	-4.72	-4.87	-0.88
MDE	0.53	8.47	2.31	-0.19	-2.58	-5.09	-3.59	-1.08	0.16	1.80	1.29	-0.39	-2.12	-3.24	-3.73	-0.81
SSA	3.51	1.13	2.78	0.43	-4.99	-4.99	-4.34	-1.61	0.59	2.61	1.64	-0.44	-4.97	-5.31	-3.75	-2.19
SASIA	0.63	3.13	6.62	0.34	-3.53	-3.97	-4.59	-3.52	0.27	-1.01	0.58	-0.46	-2.20	-3.90	-5.67	-2.22
CHINA	-0.10	0.56	1.11	1.16	-2.38	-1.84	-3.39	-4.88	-0.36	-1.95	-1.51	-0.32	-1.56	-2.13	-4.04	-3.04
EASIA	0.67	-0.81	1.55	0.24	-2.56	-6.41	-2.24	-1.11	0.25	2.40	-0.30	-0.61	-2.08	-6.26	-2.51	-1.20
LACA	0.68	11.94	0.78	0.88	-2.74	-4.31	-3.99	-5.20	-0.52	0.00	-0.57	0.25	-2.58	-4.31	-3.24	-3.37

Table 3.7: Changes in land demand and productivity, under the ICES-IRR-Adap-CC1 scenario (Δ% w.r.t. baseline)

By increasing production costs, climate change negatively affects agricultural output at the global level (-0.91% compared to the baseline). At the regional level, when irrigation-adaptation strategies are not allowed, the biggest production reduction occurs in SASIA (-2.04%), USA (-1.88%) and CHINA (-1.25%). These regions face large land productivity shocks (between -3.6 and -3.7%, on average) and they have a high share of world cropland (from 20% to 10%).[52] Globally, rice is the most impacted sector by climate change, characterized by an output reduction of -1.19%. On the contrary, the smaller contraction is observed in cereal crops production (-0.55%). At the regional level, the main increase is observed in NEUR for rice (+10.85%), in MEUR for vegetable fruits (1.06%) and in NAF for wheat (2.78%) and cereal crops (3.34%). On the other hand, USA faces the stronger decrease in wheat and cereal crops (-3.01% and -1.82%, respectively), EEUR in rice (-2.39%), and SASIA in vegetable fruits production (-2.07%). These results depend on productivity shocks and changes in land demand (especially rainfed land).

At the global level, irrigation expansion results in a decline of climate change impacts on agricultural output, in almost all crops and countries. This positive effect is more significant where the negative impact of climate change on production is stronger. For instance, significant reduction in output contraction is observed in EEUR and SASIA for rice; in FSU, CHINA and EASIA for cereal crops; in all Asian regions for vegetable fruits; and in SASIA for wheat. Figure 3.22 shows climate change impacts on crops production under both scenarios.

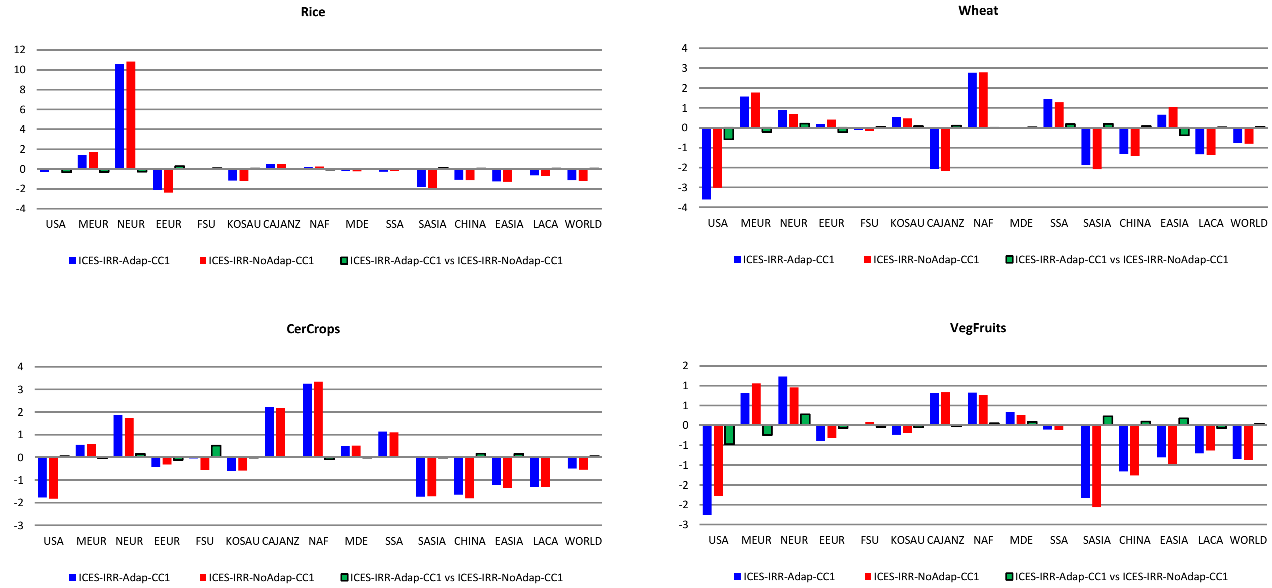

Figure 3.22: Changes in crop production, under the ICES-IRR-NoAdap-CC1 and the ICES-IRR-Adap-CC1 scenarios (Δ% w.r.t. baseline)

A reduction in land productivity negatively affects GDP in almost all regions. At the global level, climate change will cost 0.43% of GDP. At the regional level, the picture is more variegated. Stronger impacts are observed in Asian regions, where the reduction is between 1.04% and 0.68%. This negative effect depends on the regional endowment of cropland, compared to the global stock, and on the role of agriculture on the

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[52] Shares of cropland land are reported in column 2 in Table 3.C4 (Appendix C).

regional economic system.[53] On the contrary, positive impacts are observed in MDE, CAJANZ and NEUR, which are characterized by low share of world cropland (smaller than 4%). When irrigation expansion is one option to farmers, the negative effects of climate change on global GDP is slightly reduced (-0.02 percentage points). At the regional level, stronger positive impacts are observed where irrigated land is already developed (Figure 3.23).

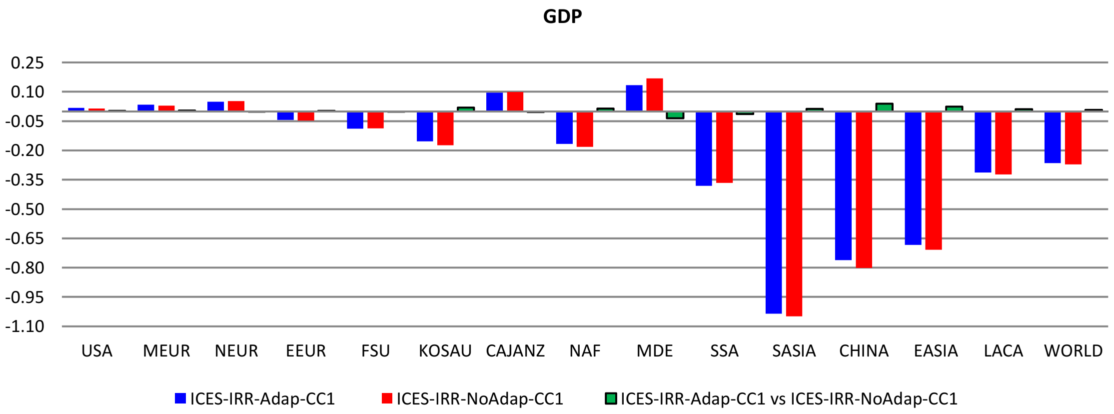

Figure 3.23: Changes in GDP under the ICES-IRR-NoAdap-CC1 and the ICES-IRR-Adap-CC1 scenarios (Δ% w.r.t. baseline)

Climate Change Scenario 2: Simulated productivity shocks

To illustrate the new features of the ICES-IRR model, we now present the results of a simulation in which both, the baseline and the climate change scenarios, are based on data simulated by a crop model. In particular, the land productivity shocks in the climate change scenario have been taken from LPJmL ((Bondeau et al., 2007), developed at the Potsdam Institute for Climate Impact Research (PIK) and that have been produced within the AgMIP project (Rosenzweig et al., 2013). Although for the AgMIP project there are several sets of climate change impacts produced using five climate models, for illustrative purposes we have used the output, based on climate data from the HadGEM2-ES general circulation model (GCM), under the RCP8.5 high-emission scenario and the SSP2 socio-economic scenario. The crop model has been run without considering possible growth-enhancing effects from CO_2 fertilization, which are subject to large uncertainties (Long et al., 2006; Tubiello et al., 2007).

Differently from previous scenarios, climate change has either positive or negative impacts on land productivity, depending on region, crop and land type (Table 3.8). Hence, different results are obtained, compared to the validation exercise and the negative uniform shock simulation.

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[53] The contribution of agriculture to GDP is reported in column 3 in Table 3.C4 (Appendix C).

	Rice		Wheat		CerCrops		VegFruits		Agriculture	
	Irrigated Land	Rainfed Land	Irrigated Land	Rainfed Land	Irrigated Land	Rainfed Land	Irrigated Land	Rainfed Land	Irrigated Land	Rainfed Land
USA	-5.91	-9.53	-3.97	-1.35	-1.57	-3.28	-0.69	-1.75	-1.28	-2.24
MEUR	1.17	-6.10	-8.70	-8.24	0.26	-1.25	-2.83	-5.26	-1.01	-4.11
NEUR	0.00	0.00	-1.45	-1.24	2.71	5.01	0.45	-0.04	2.51	2.83
EEUR	12.75	3.61	-6.77	-8.00	-1.36	-1.33	-1.70	-4.47	-1.65	-4.02
FSU	-5.03	2.20	-2.80	-1.85	0.67	-0.68	-0.38	-2.31	0.26	-1.88
KOSAU	-1.79	-3.62	-4.79	-5.16	-0.12	-5.02	1.67	-0.70	-0.50	-2.39
CAJANZ	1.39	1.30	4.84	6.21	1.24	1.43	4.56	1.40	3.20	1.91
NAF	1.90	6.92	-5.25	-7.73	-1.32	29.20	8.39	1.03	4.84	3.03
MDE	-1.92	-3.94	-5.76	-2.57	-2.50	-2.62	-0.21	-1.53	-1.25	-1.94
SSA	-7.18	-10.84	-7.14	-8.64	-1.27	-1.02	5.03	7.27	-0.74	3.60
SASIA	-3.04	-3.46	-4.38	-4.69	-3.33	-1.77	-2.76	4.29	-3.08	0.56
CHINA	-1.00	-1.64	-0.35	0.87	-0.76	-1.73	12.94	8.20	9.27	7.47
EASIA	-2.59	-3.44	-0.27	-7.99	-1.90	-3.28	-0.83	-0.58	-1.46	-2.17
LACA	-1.71	-2.04	-2.39	-0.73	5.99	3.92	1.61	0.74	2.83	1.76

Table 3.8: Changes in rainfed and irrigated land productivity, by crop and region (Δ% w.r.t. baseline)

In some countries, the productivity of both irrigated and rainfed land averagely increases (NEUR, CAJANZ, NAF, CHINA and LACA). In those regions, climate change reduces agricultural production costs and thus, in the no-adaptation scenario, land rents fall (Figure 3.24 and 3.25 for irrigated and rainfed land prices, respectively). Production costs, and land prices also decline in SSA. This is driven by the strong productivity increase in rainfed land only (+ 3.6%, on average), which in turn covers almost 98% of total Sub-Saharan African cropland.

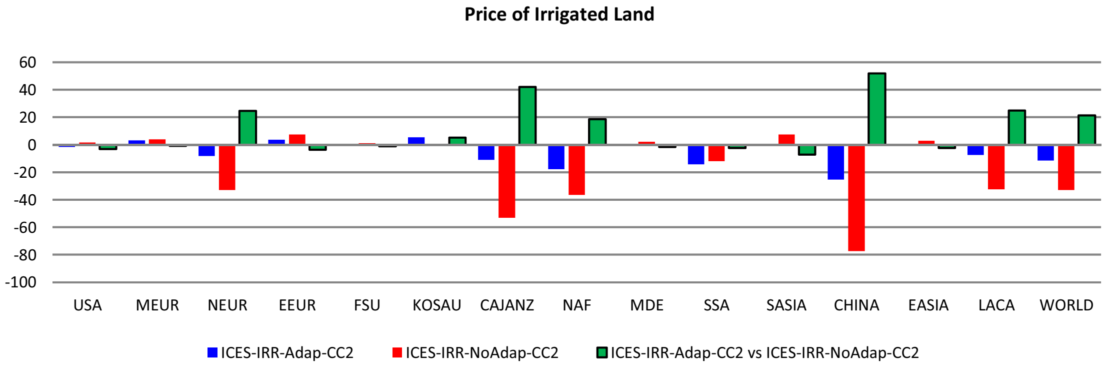

Figure 3.24: Changes in irrigated land prices, under the ICES-IRR-NoAdap-CC2 and the ICES-IRR-Adap-CC2 scenarios (Δ% w.r.t. baseline)

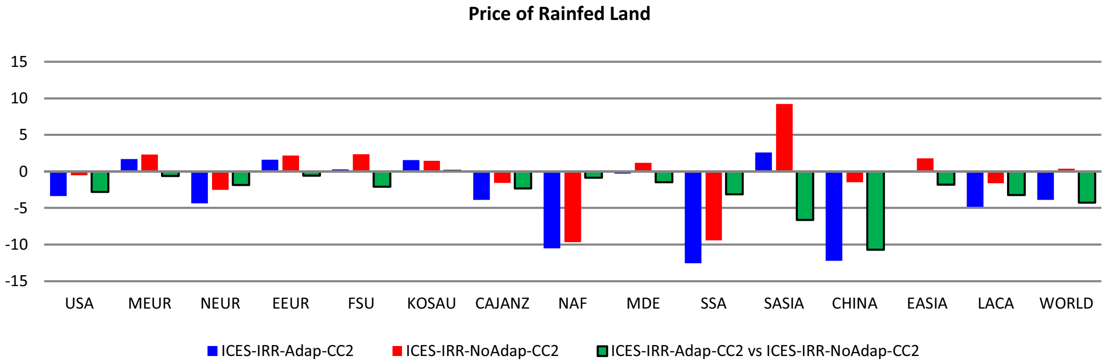

Figure 3.25: Changes in rainfed land prices, under the ICES-IRR-NoAdap-CC2 and the ICES-IRR-Adap-CC2 scenarios (Δ% w.r.t. baseline)

When irrigation-adaptation is allowed, instead, there are changes in land supply (Figure 3.26). In particular, irrigation expansion is observed at the expense of rainfed land, only in those regions where climate change increases agricultural production costs. Indeed, farmers decide to substitute rainfed with irrigated land, which is relatively less abundant and it is characterized by higher baseline productivity levels. On the contrary, in those countries where climate change reduces production costs, landowners convert irrigated land into rainfed land. One exception is SASIA where climate change negatively affects irrigated land productivity, and positively, rainfed land productivity. However, the former impact dominates since the shock is much stronger and 40% of total cropland is under irrigation. Therefore, agricultural production costs rise and thus, to produce the same amount of output, farmers demand more of both types of land.

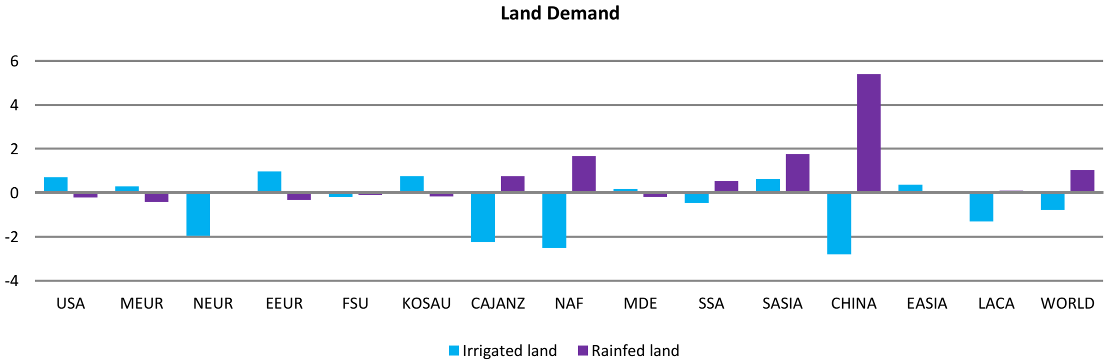

Figure 3.26: Changes in land demand in the ICES-IRR-Adap-CC2 scenario (Δ% w.r.t. baseline)

Changes in landowners' behavior can either reduce or increase the impacts of climate change on land rents. Indeed, in those regions where climate change decreases agricultural production costs, the expansion of rainfed land determines a stronger fall in its rents. On the contrary, the increase in irrigated land price is lower where landowners convert rainfed land into irrigated land to satisfy the rise of farmers' demand for land.

Climate change impacts agricultural production (Figure 3.27). In particular, agricultural output expands in CHINA, NEUR, LACA, SSA, NAF and CAJANZ where climate change reduces production costs. At the global level, the positive effect of climate change dominates. Indeed, crop production increases by 0.51%, compared to the baseline.

The picture changes when irrigation expansion is allowed. In almost all regions, adaptation has negative effects on crops production, compared to the no-adaptation scenario. The only exceptions are CHINA, SASIA and EASIA, in which adaptation strategies determine positive effects, compared to the ICES-IRR-NoAdap-CC2 scenario. Therefore, regardless of the sign of climate change impacts, agricultural sectors can benefit from adaptation only if irrigation is already developed.

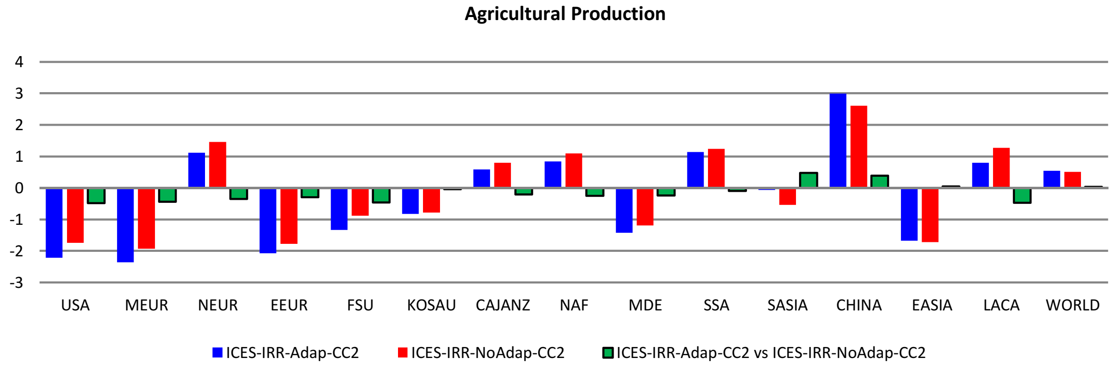

Figure 3.27: Changes in agricultural production, under the ICES-IRR-NoAdap-CC2 and the ICES-IRR-Adap-CC2 scenarios (Δ% w.r.t. baseline)

Changes in production costs, and thus in market price of agricultural products, affect international trade. Indeed, for those countries facing a decrease in production costs due to climate change, there is an increase in their exports and a decrease in their imports (Table 3.9). In line with previous results on agricultural production, when irrigation-adaptation strategies are allowed, negative effects on exports are observed in almost all countries, except CHINA and SASIA.

	ICES-IRR-Adap-CC2				ICES-IRR-NoAdap-CC2			
	Agricultural Production	Market Prices	Agricultural Exports	Agricultural Imports	Agricultural Production	Market Prices	Agricultural Exports	Agricultural Imports
USA	-2.22	-0.41	-4.52	1.49	-1.74	0.71	-2.76	1.83
MEUR	-2.37	0.94	-6.64	2.23	-1.93	1.05	-4.70	1.23
NEUR	1.11	-1.27	2.66	-0.70	1.46	-0.85	3.38	-0.91
EEUR	-2.08	1.20	-5.93	1.28	-1.78	1.37	-4.49	0.79
FSU	-1.34	0.46	-2.96	0.53	-0.88	0.89	-0.81	-0.19
KOSAU	-0.83	1.96	1.47	1.82	-0.79	1.77	1.27	2.76
CAJANZ	0.59	-1.23	2.96	-0.28	0.80	-0.69	3.30	-0.75
NAF	0.84	-1.90	6.12	-0.77	1.09	-1.79	9.54	-0.95
MDE	-1.43	0.53	-4.62	0.87	-1.19	1.07	-2.80	0.32
SSA	1.14	-2.71	3.05	0.80	1.24	-1.80	4.06	1.11
SASIA	-0.06	0.47	-5.19	0.76	-0.54	3.09	-8.23	3.01
CHINA	2.99	-5.49	15.47	-6.24	2.61	-4.65	13.13	-0.65
EASIA	-1.67	1.37	-8.16	2.04	-1.72	2.64	-7.06	1.32
LACA	0.79	-2.07	1.55	-1.63	1.27	-0.92	3.49	-1.65
WORLD	0.54	-1.85	-0.84	-0.91	0.51	-0.75	0.27	0.28

Table 3.9: Changes in agricultural production, market price, export and import, under the ICES-IRR-NoAdap-CC2 and the ICES-IRR-Adap-CC2 scenarios (Δ% w.r.t. baseline)

By looking at macroeconomic costs of climate change (Figure 3.28), positive effects on GDP are observed at the global level (0.23%, compared to the baseline). These are driven by the crops production expansion in those regions where agriculture plays a key role in the regional economic system. Given that land is more productive with climate change, farmers can demand less land and more of other inputs, particularly more capital. Therefore they increase their production. In those countries where the weight of agriculture is significant, changes in capital demand determine a strong increase in the capital rental rates. This stimulates foreign capital inflows, which positively affect capital accumulation, and thus economic growth. In particular, at the regional level, positive impacts are observed in CHINA, SSA, NAF and LACA. Although agricultural production does not expand, positive impacts of climate change on GDP are also observed in SASIA. In this region, more than 10 percent of GDP is derived from agriculture. Hence, the reduction in land productivity determines an increase in both, land and capital demands, within crop sectors. This is strong enough to increase regional capital rental rates, and thus to stimulate foreign investments.

An interesting result is noticed when adaptation strategies are allowed. The effect (either positive or negative) of climate change on GDP is reduced, both at the regional and the global level. Indeed, farmers substitute rainfed with irrigated land (and vice versa), before increasing (or decreasing) their demand for other primary factors. Therefore, changes in capital markets are smaller, and consequently variations in international capital inflows/outflows.

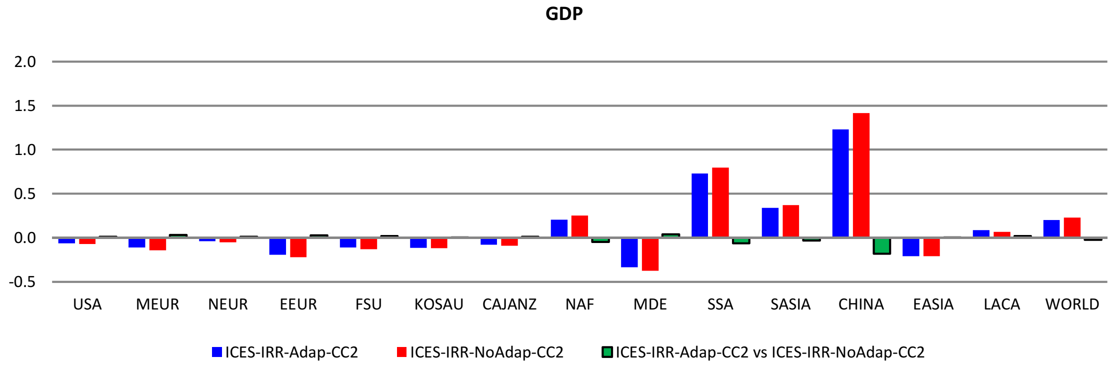

Figure 3.28: Changes in GDP under the ICES-IRR-NoAdap-CC2 and the ICES-IRR-Adap-CC2 scenarios (Δ% w.r.t. baseline)

3.7 Conclusions

Agricultural activities highly depend on specific climate conditions, such as temperature, precipitation, rain patterns, water availability and frequency/intensity of extreme weather events. Hence, it is expected that climate change will put strong pressure on agricultural productivity, and thus on food production. Therefore adaptation strategies are necessary to cope with climate change impacts.

Given that water is a major factor to guarantee agricultural production, land productivity can be increased by the expansion of irrigated areas or by higher irrigation efficiency. Hence, irrigation will play a key role in climate change adaptation. However, it is not thoroughly represented in applied economic models.

In this regard, the paper describes a new 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 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.

The relevance of this new modelling approach is explained by two reasons. Firstly, it allows to study whether farmers decide to substitute rainfed land with irrigable land, as a consequence of climate change impacts. In the literature, few studies analyze the role of irrigation as an adaptation strategy (Berittella et al., 2006; Calzadilla et al., 2013). However, in these papers irrigation is treated as an exogenous variable rather than an autonomous farmers' decision, which requires some economic costs. On the contrary, in this new specification, the optimal level of irrigated land is defined by the interaction between landowners and farmers.

Secondly, by using two variants of the new model, it is possible to analyze the cost of climate change and the economic effectiveness of planned adaptation. In fact, two climate change scenarios can be considered: an adaptation scenario, in which farmers are allowed to expand irrigated land to avoid damages due to climate change; and a non-adaptation scenario, where only climate change impacts are taken into account.

We apply this modelling framework to different scenarios of climate change, highlighting effects on the demand for irrigation land, as well as the price and production of agricultural commodities; and finally on country GDP.

The results indicate that if climate change negatively affects agricultural production costs, the demand for irrigation will increase. Moreover, when land productivities decreases in all crops and countries, irrigation expansion determines a reduction in climate change impacts on agricultural output, as well on GDP. Results are more diversified when either positive or negative shocks on land productivity are considered. In general, the final economic outcome depends on the initial endowment of irrigated land, the type of agriculture (capital-, labor- or land-intensive), the role of this sector in the economic system and the interaction between different changes in productivities (by land types and crops). Moreover, by considering various scenarios, we show that the economic cost of climate change impacts can be different, both at the global and at the regional level, depending on the impact of climate change.

We can think of at least two directions along which our analysis could be extended. Firstly, to better address uncertainty at sectoral and regional level, we can use the same modelling framework under different climate change scenarios, and by using various crop models. Secondly, in order to analyze planned policy intervention, future work can be done to extend the current version of ICES-IRR, to incorporate strong investments in irrigation projects, making irrigation a more feasible option for developing countries.

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Appendix A: Crop production and land supply structure in selected global CGE models

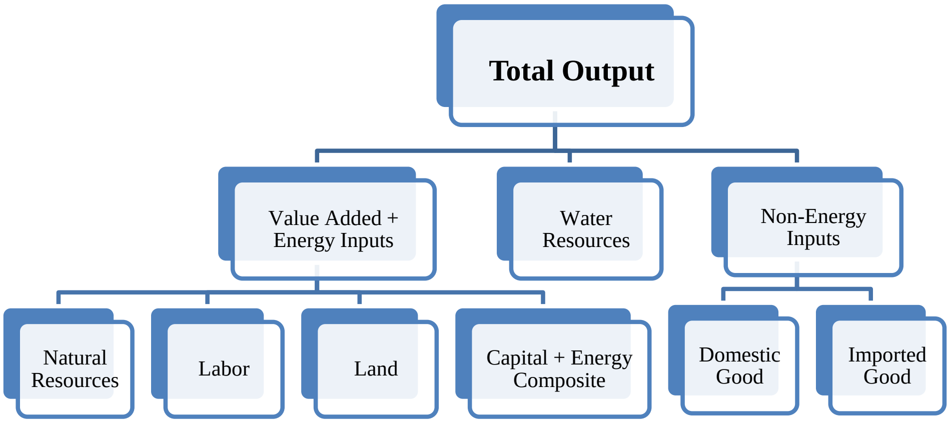

Figure 3.A1: Production structure in GTAP-W1 (Truncated)
[Source: Adapted from Berittella et al. (2007)]

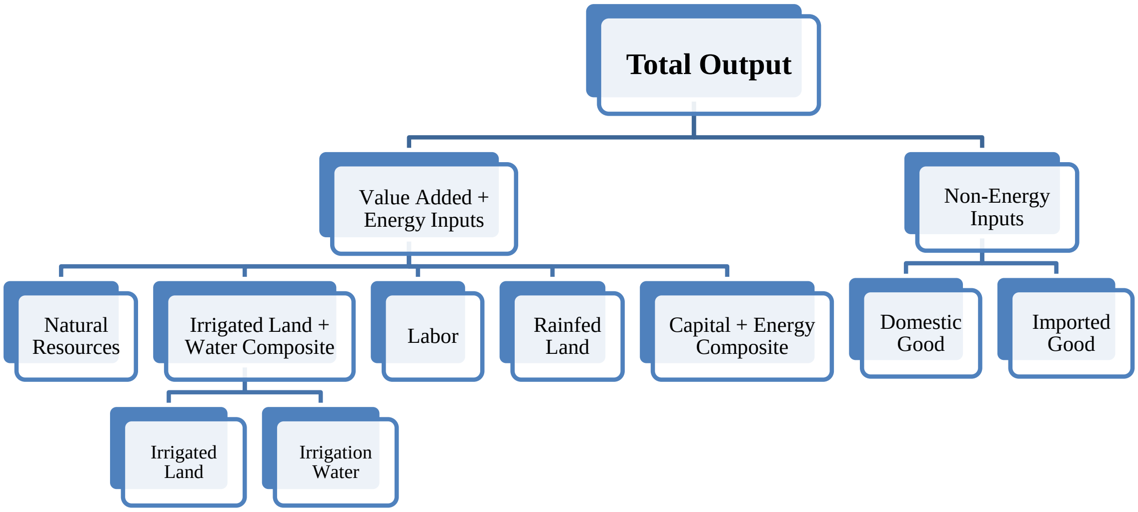

Figure 3.A2: Production structure in GTAP-W2 (Truncated)
[Source: Adapted from Calzadilla et al. (2011)]

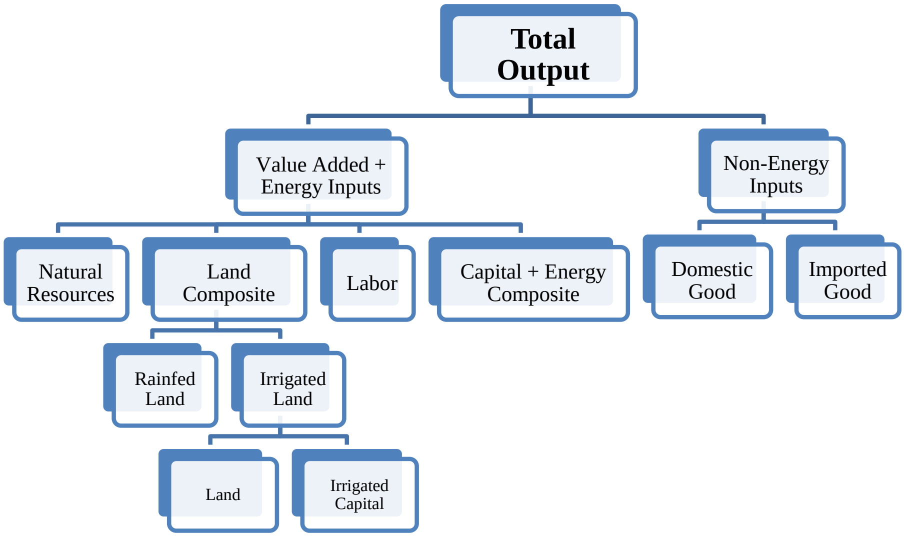

Figure 3.A3: Production structure in ICES-W (Truncated)
[Source: Adapted from Ponce-Oliva (2013)]

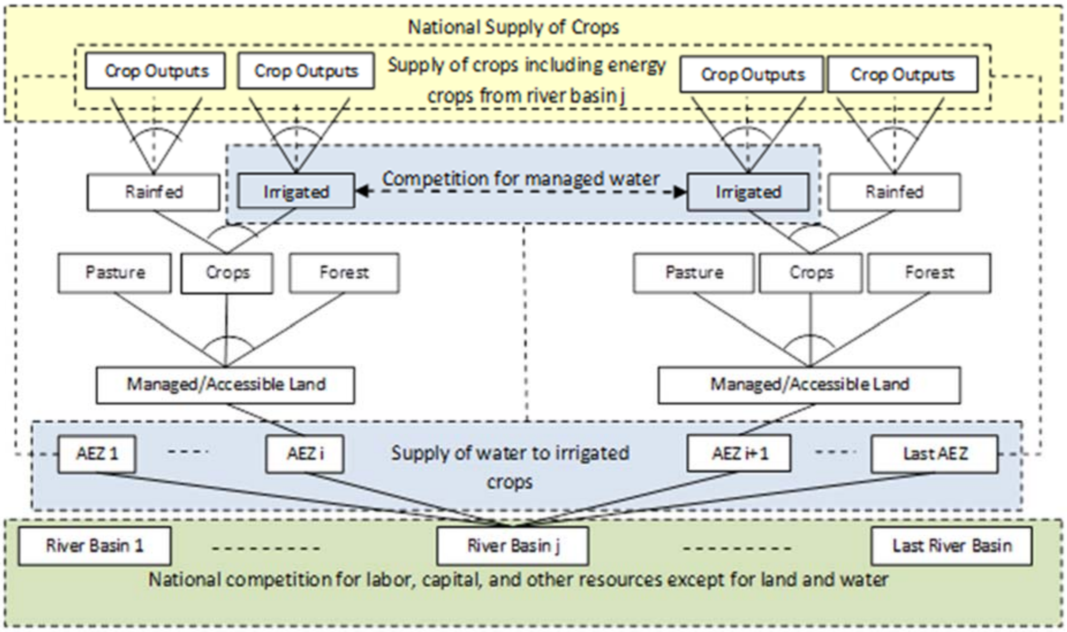

Figure 3.A4: Production structure in GTAP-BIO-W
[Source: Taheripour et al. (2013a)]

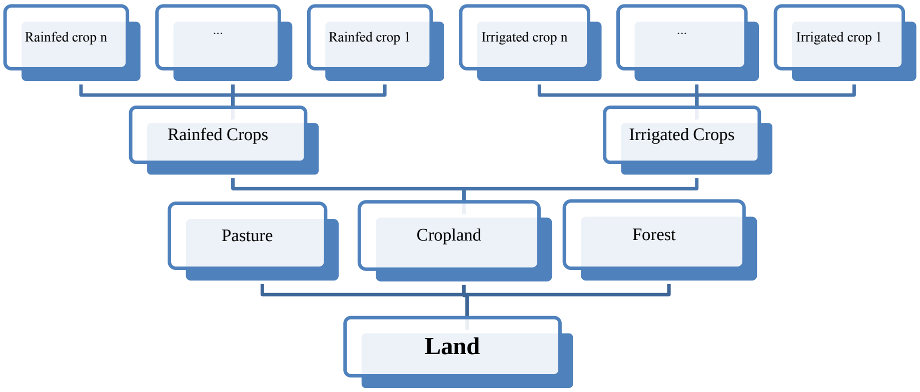

Figure 3.A5: Land supply structure in GTAP-BIO-W
[Source: Adapted from Taheripour et al. (2013a)]

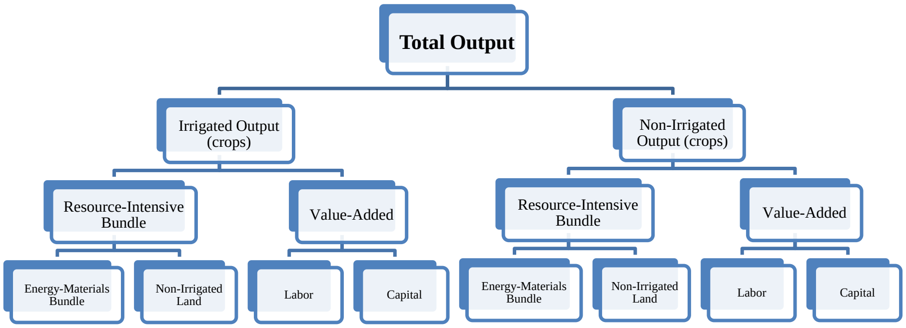

Figure 3.A6: Production structure in EPPA-IRC (Truncated)
[Source: Adapted from Baker (2011)]

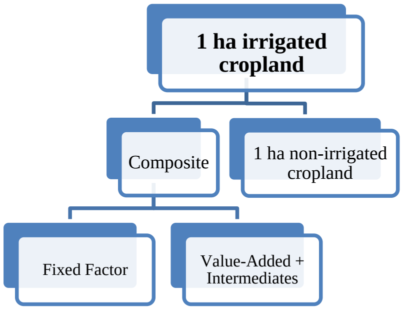

Figure 3.A7: Land conversion structure in EPPA-IRC
[Source: Adapted from Baker (2011)]

Appendix B: Data manipulation

To include the new "irrigation services" sector and new primary factors, e.g. the fixed factor, irrigable, rainfed and pasture land, changes in the existing base-year database have made.

In the GTAP database, land is one homogenous factor, used for agricultural and livestock sectors. The header $EVFA_{\text{``}Land\text{''},j,r}$ represents land rents that are paid by firm in sector j of region r, evaluated at agent's prices. To take the new land supply structure into account, the value of original land endowment is split into the value of pasture and cropland.[54] The former is given by the value of land used in the production of animals and animal products, while the latter is given by land rents, paid in crops production:

$$\begin{aligned} EVFA_{\text{``}PastLand\text{''},j,r} &= \begin{cases} EVFA\_OLD_{\text{``}Land\text{''},j,r} & if\, j \in ANIMALS \\ 0 & otherwise \end{cases} \\ EVFA_{\text{``}CropLand\text{''},j,r} &= \begin{cases} EVFA\_OLD_{\text{``}Land\text{''},j,r} & if\, j \in CROP\_IND \\ 0 & otherwise \end{cases} \end{aligned} \tag{3.B1}$$

where $\_OLD$ stands for original GTAP values.[55]

The value of cropland is then split between rainfed and irrigable land. Because of the lack of land values, both at the sectoral and regional level, it was not possible to use prices and quantities to disaggregate $EVFA_{\text{``}CropLand\text{''},j,r}$.

The ICES-W model has used the share of area actually irrigated over the total cultivated area, by assuming the average price per hectare of irrigated and dryland to be the same. However, that approach does not take into account (typically large) differences in prices between the two types of land. Irrigable cropland is usually more valuable because it requires better conditions. To accomplish this, we split the value of cropland into irrigable and rainfed land, by using its proportionate contribution to total production (Calzadilla et al., 2011). Moreover, we assume that the value of irrigable land includes the intrinsic value of water. Because of the lack of market price of water used in irrigation, following Baker (2011) we impose a value share of 10% for USA in the production of irrigable land and readjust it for all other regions, by using the ratio of irrigated yield to rainfed yield as a proxy of land rents ratio (Equation 3.B2). These ratios are computed for different countries by using irrigated and rainfed yields/ha data from the IFPRI database, assuming data for 2010 under the baseline scenario ("Baseline Perfect Mitigation") being a proxy of 2007 base-year (Nelson et al., 2010).

$$FF\_CS_{\text{``}IrrServ\text{''},r} = FF\_CS_{\text{``}IrrServ\text{''},\text{``}USA\text{''}} \frac{YS_r}{YS_{\text{``}USA\text{''}}} \tag{3.B2}$$

Where $FF\_CS_{\text{``}IrrServ\text{''},r}$ is the fixed factor share and YS_r is the ratio of irrigated to rainfed yield, both in region r (see Table 3.B1).

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[54] 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.

[55] In the GTAP8 database four primary livestock production sectors are included (Bovine cattle, sheep and goats, horses (ctl); Animal products nec (oap); Raw milk (rmk); Wool, silk-worm cocoon (wol)), and eight crop industries are considered (Paddy rice (pdr); Wheat (wht); Cereal grains nec (gro); Vegetables, fruit, nuts (v_f); Oil seeds (osd); Sugar cane, sugar beet (c_b); Plant-based fibers (pfb); Crops nec (ocr)).

	YS_r	$FF\_CS_{\text{"IrrServ"},r}$
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 3.B1: Ratio of irrigated to rainfed yield and the fixed factor share, by region

The actual value for irrigable land and rainfed land is then given by the following equations:

$$EVFA_{\text{“}IrrLand\text{”},j,r} = (1 - FF\_CS_{\text{“}IrrServ\text{”},r})\, IRR\_PS_{j,r} EVFA\_OLD_{\text{“}Land\text{”},j,r} \tag{3.B3}$$

$$EVFA_{\text{“}RfLand\text{”},j,r} = RF\_PS_{j,r} EVFA\_OLD_{\text{“}Land\text{”},j,r} \tag{3.B4}$$

Where $IRR\_PS_{j,r} = \frac{IRR\_Y_{j,r}}{TOT\_Y_{j,r}}$ and $RF\_PS_{j,r} = \frac{RF\_Y_{j,r}}{TOT\_Y_{j,r}}$ are respectively the shares of irrigated and rainfed production in total production in sector j ($j \in CROP\_IND$) and region r. These shares are computed for different countries and crop industries by using data from the IFPRI database (Nelson et al., 2010), reported in Table 3.B2.

	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 3.B2: Share of irrigated production in total production

Figure 3.B1 shows the results of this procedure in terms of base-year irrigated land as percentage of total agricultural land, at the crop level.

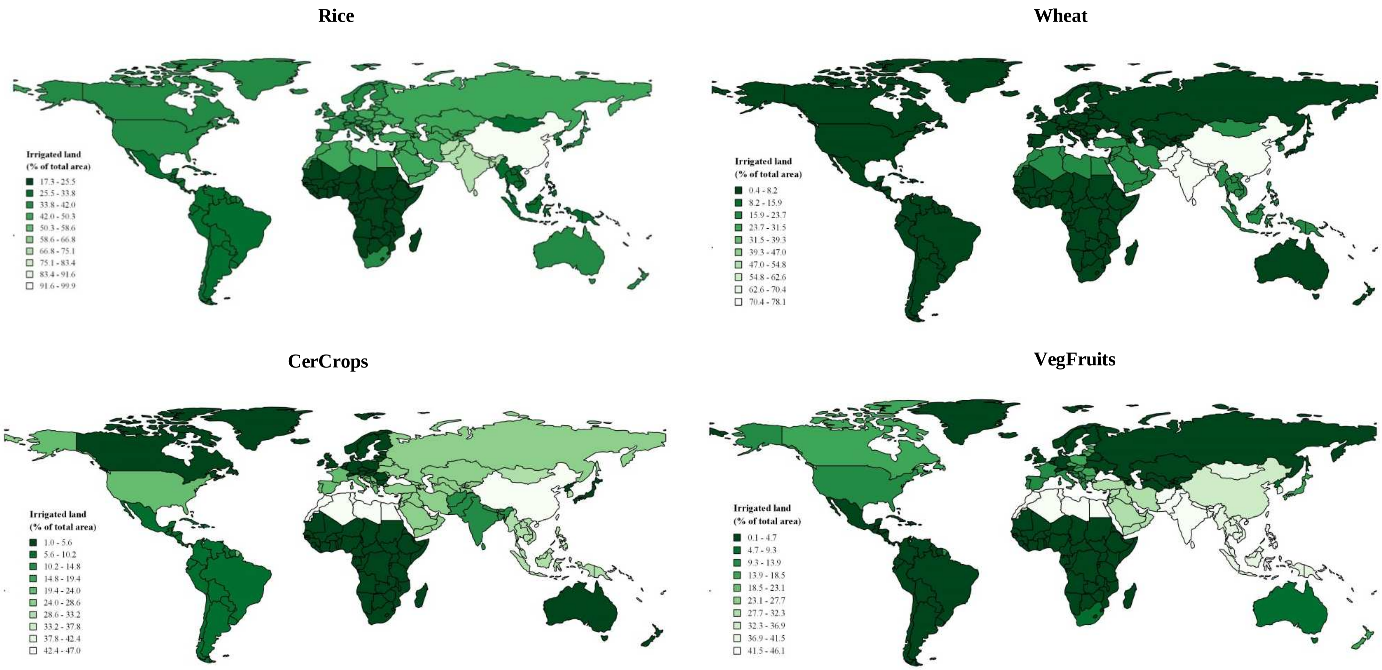

Figure 3.B1: Irrigated land as a share of cropland (%), by crop sector

The value of irrigable land is only one component of the actual value of irrigated land. Costs of irrigations services have to be considered too. 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 ($VFA_{\text{``}IrrServ\text{''},j,r}$) is given by labor, capital, water services, energy costs and water scarcity rents.

By using crop budget data for the US, we assume that 60% of the irrigated land value is given by land and 40% by irrigation services. Since water rents are included in the irrigable land value, we subtracted them from $EVFA_{\text{``}IrrLand\text{''},j,r}$ and added to $VFA_{\text{``}IrrServ\text{''},j,r}$. Finally, by using the cost shares in crop production, taken from the GTAP database, the value of irrigation services is given by the following equation:

$$\begin{aligned} VFA_{\text{``}IrrServ\text{''},j,r} = {} & FF\_CS_{\text{``}IrrServ\text{''},r} IRR\_PS_{j,r} EVFA\_OLD_{\text{``}Land\text{''},j,r} + \\ & L\_CS_{j,r} EVFA\_OLD_{\text{``}Lab\text{''},j,r} + K\_CS_{j,r} EVFA\_OLD_{\text{``}Capital\text{''},j,r} + \\ & W\_CS_{j,r} VFA\_OLD_{\text{``}Water\text{''},j,r} + E\_CS_{j,r} VFA\_OLD_{\text{``}Energy\text{''},j,r} \end{aligned} \tag{3.B5}$$

Where $L\_CS_{j,r} = \frac{EVFA\_OLD_{\text{``}Lab\text{''},j,r}}{TC\_OLD_{j,r}}$ is the labor cost share in crop $j$ production, in region $r$; $K\_CS_{j,r} = \frac{EVFA\_OLD_{\text{``}Capital\text{''},j,r}}{TC\_OLD_{j,r}}$ is the capital cost share in crop j production, in region r; $W\_CS_{j,r} = \frac{VFA\_OLD_{\text{``}Water\text{''},j,r}}{TC\_OLD_{j,r}}$ is the water cost share in crop $j$ production, in region $r$; $E\_CS_{j,r} = \frac{VFA\_OLD_{\text{``}Energy\text{''},j,r}}{TC\_OLD_{j,r}}$ is the energy cost share in crop j production, in region r; and $TC\_OLD_{j,r} = EVFA\_OLD_{\text{``}Lab\text{''},j,r} + EVFA\_OLD_{\text{``}Capital\text{''},j,r} + VFA\_OLD_{\text{``}Water\text{''},j,r} + VFA\_OLD_{\text{``}Energy\text{''},j,r}$.

The value of primary factors and intermediates used in the irrigation services sector is subtracted from the costs of each cropping sector, keeping total agricultural output unchanged (see Equation 3.B6 for labor, Equation 3.B7 for capital, Equation 3.B8 for water services and Equation 3.B9 for energy goods).

$$EVFA_{\text{``}Lab\text{''},j,r} = (1 - L\_CS_{j,r})\, EVFA\_OLD_{\text{``}Lab\text{''},j,r} \tag{3.B6}$$

$$EVFA_{\text{``}Capital\text{''},j,r} = (1 - K\_CS_{j,r})\, EVFA\_OLD_{\text{``}Capital\text{''},j,r} \tag{3.B7}$$

$$VFA_{\text{``}Water\text{''},j,r} = (1 - W\_CS_{j,r})\, VFA\_OLD_{\text{``}Water\text{''},j,r} \tag{3.B8}$$

$$VFA_{\text{``}Energy\text{''},j,r} = (1 - E\_CS_{j,r})\, VFA\_OLD_{\text{``}Energy\text{''},j,r} \tag{3.B9}$$

The cost structure of the new irrigation services sector is summarized in the following equations:

$$EVFA_{\text{``}Lab\text{''},\text{``}IrrServ\text{''},r} = \sum_{j \in CROP\_IND} L\_CS_{j,r} EVFA\_OLD_{\text{``}Lab\text{''},j,r} \tag{3.B10}$$

$$EVFA_{\text{``}Capital\text{''},\text{``}IrrServ\text{''},r} = \sum_{j \in CROP\_IND} K\_CS_{j,r} EVFA\_OLD_{\text{``}Capital\text{''},j,r} \tag{3.B11}$$

$$EVFA_{\text{``}FF\text{''},\text{``}IrrServ\text{''},r} = \sum_{j \in CROP\_IND} FF\_CS_{j,r} IRR\_PS_{j,r} EVFA\_OLD_{\text{``}Land\text{''},j,r} \tag{3.B12}$$

$$VFA_{\text{“}Water\text{”},\text{“}IrrServ\text{”},r} = \sum_{j\in CROP\_IND} W\_CS_{j,r} VFA\_OLD_{\text{“}Water\text{”},j,r} \tag{3.B13}$$

$$VFA_{\text{“}Energy\text{”},\text{“}IrrServ\text{”},r} = \sum_{j\in CROP\_IND} E\_CS_{j,r} VFA\_OLD_{\text{“}Energy\text{”},j,r} \tag{3.B14}$$

Moreover, we assume that water services and energy used in irrigation services industry is only domestically produced:

$$VFA_{\text{“}Energy\text{”},\text{“}IrrServ\text{”},r} = VDFA_{\text{“}Energy\text{”},\text{“}IrrServ\text{”},r} \tag{3.B15}$$

$$VFA_{\text{“}Water\text{”},\text{“}IrrServ\text{”},r} = VDFA_{\text{“}Water\text{”},\text{“}IrrServ\text{”},r} \tag{3.B16}$$

Once we have readjusted $VDFA_{i,j,r}$ and $EVFA_{i,j,r}$, other three headers have to be split: $VFM_{i,j,r}$, i.e. producer expenditure on primary factor i by sector j in region r, valued at market prices; $EVOA_{i,r}$, i.e. the value of commodity i in region r; and $VDFM_{i,j,r}$, i.e. expenditures on intermediate i by sector j in region r, valued at market prices. Assuming the same tax rates as in the original database, we use the previously described shares to disaggregate the new endowments and intermediates.

Since the procedure we have just described only split the original database, we do not run into problems related to model calibration.

Appendix C: Other results

	Land Price	**Rainfed Land Price**		**Irrigated Land Price**		**Rainfed Land Price**		**Irrigated Land Price**	
	ICES-CC	**ICES-IRR-NoAdap**	**ICES-IRR-Adap**	**ICES-IRR-NoAdap**	**ICES-IRR-Adap**	**ICES-IRR-NoAdap**	**ICES-IRR-Adap**	**ICES-IRR-NoAdap**	**ICES-IRR-Adap**
	Δ% w.r.t. BGP					**Δ w.r.t. ICES-CC**			
USA	100.81	105.69	94.01	106.98	175.70	4.89	-6.80	6.17	74.89
MEUR	99.85	103.30	93.58	101.45	167.39	3.45	-6.27	1.60	67.54
NEUR	119.21	128.61	120.22	120.60	203.16	9.40	1.01	1.39	83.95
EEUR	73.87	75.25	70.96	79.36	130.29	1.37	-2.91	5.48	56.42
FSU	71.09	73.71	69.28	72.79	121.19	2.62	-1.81	1.71	50.10
KOSAU	95.20	105.67	91.17	103.86	173.28	10.47	-4.03	8.66	78.08
CAJANZ	116.72	126.01	111.35	122.54	190.50	9.29	-5.37	5.81	73.78
NAF	93.01	93.82	78.93	89.61	154.36	0.81	-14.08	-3.40	61.34
MDE	102.24	105.63	90.48	99.91	164.91	3.39	-11.76	-2.33	62.67
SSA	85.13	89.73	84.78	87.77	151.12	4.61	-0.34	2.64	65.99
SASIA	63.93	62.52	53.48	59.69	106.46	-1.41	-10.45	-4.24	42.53
CHINA	82.46	85.00	69.22	81.80	133.96	2.54	-13.25	-0.66	51.49
EASIA	60.05	57.44	50.06	60.24	99.95	-2.61	-10.00	0.18	39.90
LACA	87.47	93.78	86.06	90.65	154.48	6.31	-1.41	3.18	67.01
WORLD	89.36	93.30	83.11	91.23	151.91	3.94	-6.25	1.87	62.55

Table 3.C1: Changes in land prices, under the ICES-CC, ICES-IRR-NoAdap and ICES-IRR-Adap scenarios

	Rice	**Wheat**	**CerCrops**	**VegFruits**
USA	5.36	1.16	2.91	1.79
MEUR	11.76	0.08	2.41	1.51
NEUR	1.92	0.04	0.67	0.01
EEUR	13.88	0.22	0.60	2.96
FSU	6.41	0.37	4.59	0.11
KOSAU	14.61	0.09	0.45	1.83
CAJANZ	4.08	0.08	0.20	1.75
NAF	3.65	0.88	3.11	3.05
MDE	3.62	1.65	2.11	2.18
SSA	1.39	0.59	0.08	0.16
SASIA	18.92	15.38	3.48	12.29
CHINA	19.53	10.15	8.00	7.02
EASIA	9.82	3.41	10.29	13.95
LACA	3.76	0.82	0.94	0.48

Table 3.C2: Cost shares of irrigated land, by crop (%)

	Rice				**Wheat**				**CerCrops**				**VegFruits**			
	ICES-IRR-NoAdap		**ICES-IRR-Adap**		**ICES-IRR-NoAdap**		**ICES-IRR-Adap**		**ICES-IRR-NoAdap**		**ICES-IRR-Adap**		**ICES-IRR-NoAdap**		**ICES-IRR-Adap**	
	Δ% w.r.t. BGP															
	Labor	**Capital**	**Labor**	**Capital**	**Labor**	**Capital**	**Labor**	**Capital**	**Labor**	**Capital**	**Labor**	**Capital**	**Labor**	**Capital**	**Labor**	**Capital**
USA	9.03	9.18	7.53	7.67	-0.99	-0.85	-1.12	-1.00	5.29	5.45	5.06	5.20	6.92	7.09	6.03	6.18
MEUR	8.53	8.75	7.16	7.35	7.14	7.30	6.67	6.82	5.89	6.07	5.55	5.71	5.70	5.91	5.21	5.39
NEUR	37.34	37.58	30.59	30.79	6.82	7.00	6.51	6.67	11.32	11.52	10.09	10.26	9.93	10.16	8.51	8.70
EEUR	0.84	0.84	0.39	0.36	1.08	1.06	0.84	0.80	1.70	1.69	1.20	1.17	-0.02	-0.03	0.00	-0.03
FSU	6.83	6.66	5.60	5.42	0.80	0.64	0.25	0.07	1.19	1.02	1.10	0.92	3.20	3.03	2.59	2.41
KOSAU	16.41	16.41	13.71	13.72	8.71	8.71	7.41	7.42	2.73	2.74	1.60	1.61	2.24	2.24	1.93	1.94
CAJANZ	7.14	7.34	6.01	6.18	13.22	13.42	11.46	11.64	9.98	10.15	8.68	8.83	8.95	9.13	8.15	8.32
NAF	2.65	2.58	2.09	2.04	4.90	4.84	4.89	4.85	7.47	7.41	7.32	7.27	5.42	5.36	5.19	5.14
MDE	3.13	3.19	2.56	2.62	6.36	6.39	6.12	6.15	10.33	10.36	9.78	9.80	6.66	6.69	6.23	6.26
SSA	1.62	1.81	1.39	1.53	3.86	4.04	3.79	3.93	6.79	6.99	5.91	6.05	3.42	3.62	2.95	3.10
SASIA	7.24	6.26	5.64	4.85	2.04	1.13	1.86	1.13	1.78	0.84	1.48	0.72	2.16	1.20	1.97	1.18
CHINA	9.16	8.71	6.48	6.11	4.61	4.21	3.38	3.04	3.22	2.80	3.94	3.59	4.25	3.82	3.89	3.53
EASIA	7.30	6.26	6.59	5.65	-6.50	-7.41	-6.71	-7.53	-6.83	-7.74	-6.26	-7.09	-0.76	-1.72	-0.69	-1.57
LACA	5.48	5.18	4.63	4.34	1.88	1.59	1.72	1.42	4.00	3.71	3.39	3.10	7.30	7.00	6.07	5.77

Table 3.C3: Changes in labor and capital demand

	Irrigated Land/Cropland (1)	**Cropland/Global Cropland** (2)	**Crop production/GDP** (3)
USA	18.16	8.30	1.50
MEUR	16.03	5.95	1.86
NEUR	1.37	3.95	0.87
EEUR	7.43	3.43	3.05
FSU	6.74	5.81	7.28
KOSAU	18.43	3.74	1.87
CAJANZ	17.05	2.47	1.26
NAF	43.90	0.91	6.35
MDE	31.54	2.03	3.84
SSA	2.39	3.45	14.58
SASIA	43.70	19.28	10.27
CHINA	50.07	20.40	6.38
EASIA	37.24	10.74	4.66
LACA	6.62	9.56	4.97
WORLD	28.66	100.00	4.22

Table 3.C4: Shares of irrigated land, cropland and the contribution of agriculture to GDP (%)