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Tiziano Distefano

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The dissertation of Tiziano Distefano is approved.

Program Coordinator: Prof. Fabio Pammolli, IMT Advanced Studies Lucca

Supervisor: Prof. Massimo Riccaboni, IMT Advanced Studies Lucca

Supervisor: Dr. Giovanni Marin, CERIS-CNR Milano

Tutor: Dr. Massimiliano Onorato, IMT Advanced Studies Lucca

The dissertation of Tiziano Distefano has been reviewed by:

Prof. Douglas Crawford-Brown, University of Cambridge

Dr. Valeria Andreoni, Liverpool Hope University

IMT Institute for Advanced Studies, Lucca

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Vita

14 March 1987	Born, Viareggio (LU), Italy
2009	Bachelor in Bank, Finance and Insurance (Laurea triennale) Final mark: 110/110 cum laude Università di Pisa, Pisa (Italy)
2011	MA in Economics (Laurea magistrale) Final mark: 110/110 cum laude Università di Pisa, Pisa (Italy)
2014-15	Visiting Research Scholar (September-February) Department of Land Economics, Centre for Climate Change Mitigation Research University of Cambridge, Cambridge under the supervision of Dr Scott Kelly

Presentations

1. T. Distefano (with M. Riccaboni and G. Marin) "Integrating Structural Decomposition Analysis with Network Theory. The Blue Water case study" at:
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   - Global Sustainability Institute Research Conference 2015, The Interface between Sustainability Research and Policy Anglia Ruskin, University of Cambridge, UK (January 2015).
2. T. Distefano (with S. Kelly) "Are we in deep water? Water scarcity and its limits to economic growth" at The Complexity of Economics and the Economics of Complexity CNR, Rome, Italy (May 2015).
3. T. Distefano (with S. DAlessandro) "An Evolutionary approach to International Environmental Agreements", at The Governance of a Complex World, GCW, Nice, France (July 2015).

Abstract

Ecological Economics (EE) is a novel, wide and heterogeneous branch of research which aims at studying the relationships between Ecological and Economic Systems, which are composed of large number of entities (state variables or stocks), that interact through the flows of matter, energy, and information passing through the systems' boundaries. The two systems are strictly interwoven and each one have an impact on the other, i.e. the exploitation of natural resources for productive purposes and the potential economic losses due to environmental disasters (e.g. climate change). The current dissertation provides a set of both theoretical and empirical studies to tackle the problem of natural resource scarcity (e.g. water), climate change, economic growth, international agreements and environmental consciousness with different methodologies, in line with the purposes of EE.

The dissertation is composed by two main blocks: the first one based on empirical investigations of water resource exploitation and the other based on theoretical studies. The first block (chapters 2 and 3) employs a sector-level approach to investigate, at Global level, the main drivers of (Blue) water exploitation and the vulnerability of inter-sectoral linkages to external shocks (chapter 2), and the extent to which OECD GDP growth forecasts are sustainable under the current water resource availability and future climate change (chapter 3). The second block (chapter 4) describes a novel theoretical framework to analyse the International Environmental Agreements, combining a static 2x2 game (macro-level) with an Evolutionary Game (micro-level). The Appendix A provides the Supplementary Materials in which are explained in

depth the mathematical details of the models employed in the Chapters 2 and 3. Moreover, it has been introduced a brief survey, part of a work in progress, that touches some of the basic principles, epistemological assumptions and methodological issues underpinning Ecological Economics.

Chapter 2

Chapter 2 discusses the empirical distribution of Blue virtual water trade and it assesses the vulnerability of inter-sectoral trade by integrating the Input-Output tables with Network Theory. This paper applies the Global Multi-Regional Input-Output (GMRIO) model to quantify the interdependencies of different sectors, within the global economy, and to determine the overall Blue water consumption of each country. This procedure allows the measurement of Virtual Water Trade (VWT), that is the volume of water embedded in traded goods. Firstly, I present the results from the Structural Decomposition Analysis (SDA) at different level of aggregation: spatial and sectoral. This procedure allows to identify and quantify the impact of the main drivers of Blue water use: technological development, international trade, evolution of production functions, population growth and changes in the product mix of final demand. SDA is integrated with the analysis of the topology of the inter-sectoral Blue VWT in order to assess the vulnerability of the system to external shocks. This paper offers a novel framework because it combines two different, but analogous, methodologies that allow to set up a broad framework in which assessing the effect of the key factors in water exploitation and the resilience of the system to (micro–level) shocks.

All in all, SDA showed a substantial contribution to reducing water demand exerted by the composition of final demand and by improvements in the water efficiency of production, while demographic and economic growth and changes in the intermediate input mix has more than compensated such reduction. Network theory extends the information provided by the IO assessment, confirming that the system is particularly exposed to the propagation of local (supply-side) shocks due to 'cascade effects'. The 'duality' of trade is determined by the apparent minor role played, evidenced by the SDA, coupled with the potential risks related to the propagation of shocks in water supply. The main policy implication of these findings is that a cross-country coordination of water management policies is needed to increase the resilience of the water supply system to negative shocks to some crucial sector, that would otherwise propagate to a large number of countries.

Chapter 3

Chapter 3 integrates measures of social water scarcity and physical renewable water constraints, in order to structure a consistent set of scenarios under which evaluate the likely economic impacts caused by future water scarcity, the technological development needed to follow a sustainable growth and the role of VW trade in providing an extra-amount of (virtual) water per capita. The problem of quantitatively evaluate water resources vulnerability derives from the fact that is also used, both directly and indirectly, in production processes across many different sectors of the economy, through supply chain. This is simulated with an assessment of very long-run implications (2100), using a Dynamic Multi-Regional Input-Output (D-MRIO) model. I simulate the joint impact of climate change, economic and population growth, as provided by the Intergovernmental Panel on Climate Change (IPCC), under four alternative scenarios. In order to overcome the limitations of the Falkenmark indicator, I assess both the direct water footprint of national consumption and total water footprint that also allows for VW water trade between different regions of the world.

Results suggest that under OECD GDP growth rates, there should be an over-exploitation of available freshwater resources (Wa) in almost every country across all scenarios. It is shown that, for most countries, water-stress is mostly affected by socio-economic variables rather than directly from climate change. The comparison of the results using alternative, internally consistent, climate change scenarios is essential to guide future environmental policy decisions, both at national and international levels, to achieve sustainable and equitable water management strategies.

Chapter 4

Chapter 4 contributes to explain the observation of two facts at odds: starting from the meeting held in Stockholm in 1972 till the last one arranged in Lima on December 2014, the number of signatories of international environmental agreements (IEA) has grown in time. Meanwhile, the aggregate global level of greenhouse gas emissions is increasing at exponential rate worldwide. I propose a novel multi-scale framework, composed by two tied games, to show under which conditions a country is able to fulfil the IEA: Game 1 is an Evolutionary Game that models the economic structure of 'isolated' economies, where the interaction of households and firms' strategies determine the level of greenhouse gas discharge. Game 2 deals with the IEA with a 2x2 static one-shot game, in which two asymmetric nations bargain on the maximum level of emissions.

Countries might have different environmental performances based on their economic structure, without the need to impose any 'free–riding' behaviour. Consumer's environmental consciousness (micro level) together with global income (and technological) inequality (macro level), are found to be the key variables towards the green transition path. IEA alone appears to be a weak incentive, unable to stimulate a green transition if not paired with local action and high level of environmental awareness among consumers. Due to the complexity of the game, not any result can be showed analytically, therefore I run four simulations. The current approach is able to offer a multi-scale level of analysis necessary to deal with the complex issues at stake, that is climate change and global/local actions.

Appendix A

This chapter is a brief methodological note on the models employed in Chapter 2 and 3, in particular it offers the detailed mathematical system of equations at the base of the Structural Decomposition Analysis (Chapter 2), the algorithm with which I computed the sustainable rate of technological progress (Chapter 3) and an extension of Chapter 3 based on the computation of the potential economic losses in case of un-sustainable exploitation of water resources. Finally, I provide a brief overview of the epistemological and methodological foundations of Ecological Economics. I pass through some key concepts (i.e. entropy law, incommensurability, complexity and irreversibility) in order to frame the strengths and the limits of this novel, wide and heterogeneous branch of research.

Chapter 1

Introduction

Increasing international trade, at global level, motivates the elaboration of critical information about the direct and the indirect effects of inter-sectoral linkages and increasing consumption on resource exploitation, in particular water use. Recognizing water as an important factor of production, required for economic output and growth, is crucial when dealing with the vulnerability of future economic activity to climate change and resource constraints. Globalization of economic activities implies that countries should deal with the issue of resource exploitation and climate change through international agreements in which coordinating their activities in a sustainable manner. The current dissertation touches some of these aspects with both a theoretical and empirical perspective.

Content of the dissertation

Chapter 2 reports the measurement of direct and indirect (through trade) Blue water (BW) use, which refers to the consumptive use of ground or surface water, the identification and the evolution of the main drivers of BW exploitation, through the SDA, and the analysis of the topology of the inter-sectoral Blue VWT, with Network tools, in order to assess the resilience of the system to external shocks.

The focus of chapter 3 is, instead, an ex-ante simulation, based on a Dynamic Multi Regional Input–Output Model, of the sustainability of the OECD GDP growth rates forecasts when water constraints are included. Moreover, I integrated measures of social water scarcity and physical renewable water constraints in order to frame a consistent set of scenarios under which to evaluate the likely economic impacts caused by future water scarcity.

Chapter 4 moves to the theoretical perspective to offer a novel approach when studying the success of IEA. The 'micro' (country's economic structure) and 'macro' (international agreements) levels are coupled to offer a multi-scale perspective, necessary to deal with the complex issue of climate change and global/local actions. In particular, I combine two games: the first one is an Evolutionary Game that show the dynamic evolution of each economy (country-level), while the second one is a classical one-shot Game with 2 asymmetric countries.

Research questions

To summarize, the current dissertation aims at dealing with the following research questions:

1. Which are the key drivers of blue water use and what is their impact over time? (Chapter 2)
2. Does International Trade make the inter-sectoral exchanges more vulnerable to exogenous shocks? Which are the most critical geographical areas? (Chapter 2)
3. Is economic growth (based on OECD's forecasts) hampered when water constraints are taken into account? (Chapter 3)
4. Which is the rate of technological progress needed to follow a sustainable economic growth? On the other hand, what is the potential economic loss due to the impact of climate change on water resources? (Chapter 3)
5. Under which economic conditions a country fails to respect the IEA? (Chapter 4)

6. Are local actions and environmental consciousness relevant for the success of international environmental agreements? (Chapter 4)

Main results

The theoretical results and the empirical evidence related to the previous set of research questions of each chapter is summarized as follows.

Chapter 2

An important features observed is that international VWT, in many cases, does not follow the spatial pattern of fresh water resource availability, as confirmed by two water abundant countries, such as USA and Russia, which are net (virtual) water importers. SDA allowed to disentangle and quantify the main drivers of water use over the time span considered. Overall, improvements in water efficiency of production activities and changes in the mix of consumption bundle allowed to reduce world water footprint by about 50 percent. On the other side, these beneficial effects, were superseded by changes in per capita level of affluence (in real terms), demographic growth and in the mix of intermediate inputs that required, jointly, an increase of more than 80 percent of blue water.

Network theory revealed the heavy-tail behaviour of the in– and out– node strength, of virtual water of intermediate goods, which follows a power law distribution. The fat-tail and scale-free behaviour are further confirmed by the results from the $first$– and $second$– order connectivity measures, which show that the potential benefit of water redistribution through international trade might carry the risk of propagation of local (supply-side) shocks due to 'cascade effects'.

Chapter 3

Numerical simulations showed that climate change alone seems to have a smaller impact than socio-economic drivers for most countries, except Turkey, Mexico and Brazil. Countries already experiencing water stress will be the most impacted in the future under the combined effects of socio–economic shifts and climate change. China and India must deal with severe and imminent water shortage problems, to which they are not able to pursue economic growth without over-exploiting natural water resources. The same holds for the most advanced economies, although this occurs later in time (around 2050), while only Russia, Japan and Brazil seem to be the less vulnerable. It appears that water constraints represent a physical limit to economic growth in both developing and developed countries. A possible alternative to these pessimistic scenarios is to boost technological progress via investment in water efficiency, even though the speed of progress must be far greater than what observed in the recent years.

The Falkenmark indicator is found to be a misleading indicator, therefore I extended the analysis to assess the actual countries ability to alleviate social water stress through virtual water trade. The use of I-O data allowed to trace different sources of virtual water consumption, for each water category, economic sector and country. Finally, international trade seems efficacious in redistributing the water resources, allowing to almost each country, with the exception of India, to provide at least 1700 m^3 of water per capita.

Chapter 4

This mathematical framework shows that 'global solutions' negotiated at international level, if not backed up by a variety of efforts at national, regional, and local levels to prompt environmental consciousness, are not guaranteed to work well. From the *micro* point of view, the model is able to identify five alternative Regimes under which each economy reaches different equilibria. Each of them defines the possibility of success of global standards bargained between countries. From the *macro* point of view, I define, both analytically and with numerical simulations, the impact of inequality, asymmetric risks and opportunity costs distribution among countries. Given a certain level of inequality countries will establish more environmental friendly standards inasmuch the benefit-risk ratio is high. Moreover, historical inequality, in terms of different level of profits generated by the industries and different technological development of both green and polluting firms, and heterogenous risks play a key role to the establishment of sustainable environmental standards.

All in all, increasing environmental consciousness could reduce the costs of environmental policy, while increasing global inequality has a negative influence on the level of environmental standards.

Contribution to the literature

This last section of this introductory chapter aims at stressing the most important innovative contributions to the economic literature of the current dissertation chapter-by-chapter.

Chapter 2

The economic empirical literature on virtual water trade has followed two separate, but analogous, strands of research, such as Input-Output (IO) Analyses and Network Theory. Chapter 2 is, to my knowledge, the first attempt to fill this gap. The novelty introduced by the present study is given by the combination of the SDA with Network measures of systematic vulnerability to exogenous (climatic) shocks. It goes beyond the previous contributions because I ground the analysis on intersectoral (virtual water) trade, and not simply on final consumption. This step is essential to understand whether the current global supply-chain is vulnerable to external shocks and whether the evolution of international trade is yielding riskier systems of VW exchanges. Moreover, the analysis is based on the most recent tools developed in the literature of Complex Economy.

Chapter 3

The main innovative contributions of chapter 3 are: the consistent integration of different databases coming from different fields, such as hydrology, economy and climate science; the combination of both social and physical indicator of water-stress in the simulation of several economic and climatic scenarios; the use of a dynamic MRIO with which building a set of different economic path consistent with the OECD GDP forecasts and, more importantly, the quantification of the (expected) impact of each driver of water stress.

Chapter 4

The innovative contribution to the Game Theory literature of chapter 4 regards the model I employed. To my knowledge, chapter 4 is the first attempt to consider at the same time the $micro$ and the $macro$ level by combining, in a consistent manner, two different games. It differs from the previous literature in three respects. First, the analysis is not based on a stylized model where parties are modelled 'as if' they were individual rational agents, but I ground their actions on a given economic structure. Second, I offer a micro-foundation of the economic system with an Evolutionary Game where consumers and firms interact, determining the level of emissions for any given level of environmental standards fixed by the IEA. Finally, the complexity of the model limits the possibility to analytically derive every results, therefore I provide (parameterise) numerical simulations, using a handy Maple algorithm, to determine the alternative evolutionary equilibria that each country reaches when IEA is enforced.

Chapter 2

Integrating Structural Decomposition Analysis with Network Theory. The Blue Water case study.

2.1 Introduction

Global trade virtually transfers large amounts of water resources from areas of production to far consumption regions, a phenomenon that has been named 'the globalization of water' (Hoekstra and Chapagain, 2008), that is especially important for food security (Konar et al., 2012), conflicts for water (Barnaby, 2009) and overpopulation (Schade and Pimentel, 2010). Antonelli et al. (2012) notice that VW is an 'inherently economic concept', which is consistent with standard international trade theory (Reimer, 2012). Water is cheap where it is abundant, but the opposite is not necessarily true: water resources may not be correctly priced and property rights may not be adequately enforced, so that the cost of water could be kept inefficiently low. The capacity to engage in trade enables water-scarce countries to achieve food security and, more generally, to satisfy its demand of water-intensive products. The quantification and assessment of VW and the evaluation of the vulnerability of the VW network are particularly relevant as climate change is likely to alter the geographical distribution of water availability and to cause shocks to the VW network.

The two major methodological approaches to assess and evaluate VW are Input-Output (IO) Analyses and Network Theory. IO tables express the value of economic transactions occurring between different sectors of an economy, so that it is possible to account for sectoral interdependencies in the economic system. In the vast literature of environmentally extended input output analysis, the attention has been directed towards the attribution of the responsibility of producers and consumers for the exploitation of natural resources and the release of pollutants, by computing the net balance of pollution and of resource 'embedded' in traded goods. In contrast to the bottom-up accounting, which only considers direct water withdrawal in production, input-output models include both direct and indirect water use along the complex supply chain of producing a specific product for final consumption (Lenzen et al., 2013). Serrano and Dietzenbacher (2010), using a multi-regional input-output (MRIO) model, demonstrate that the trade emission balance and the responsibility emission balance yield the same result. MRIO models have been widely used to calculate footprints and to analyse the environmental consequences of trade (Lenzen et al., 2013, Wiedmann et al., 2010). Although these models have been mainly used to analyze CO2 emissions, there are also some applications to water footprint and virtual water embodied in trade of specific countries. An important contribution is represented by Arto (2012) who quantified the environmental responsibility in a production and in a consumption-based approaches. WIOD data and a Multi-Regional Input-Output model have been used to estimate the Use, the Footprint and the Virtual Trade of Water, GHG Emissions, Materials and Land for 41 world regions in the period 1995-2008. As noticed by Hoekstra et al. (2011) these studies are particularly useful as they assess the effect of international trade on domestic water resources, the effect of water availability on international trade and the role that the latter can play in increasing global water-use efficiency.

Extending the findings based on input-output models, the literature has developed a variety of Structural Decomposition Analysis (SDA)[1] in order to unravel and quantify the main drivers of change in pollution or in resource and water use. There are several examples of studies on structural decomposition analysis of energy use (Ang and Liu, 2001, Su and Ang, 2012), emissions (Serrano and Dietzenbacher, 2010, Xu and Dietzenbacher, 2014) or water use Cazcarro et al. (2013), Roson and Sartori (2015) in a specific region or macro-area. European countries are characterized by very different patterns of water consumption. Roson and Sartori (2015) showed that the productive structure in most economies has shifted away from water intensive industries (most notably agriculture), that changes in the water footprint induced by changes in the pattern of consumption are generally negative and remarkable, and that fast-growing countries are also countries in which the share of agriculture shrinks at a faster pace, possibly because of the expansion in manufacturing and services (e.g. China).

On the other hand, Network Theory has been extensively used to analyse bilateral trade flows (Carvalho, 2012, Zhu et al., 2014) because it enables to find non-linear relationship among the nodes involved in international trade and to grasp useful information on the topology of exchanges. Network Theory is particularly suitable to deal with economic complexity, where hierarchies of economic sub-systems and the synergic interactions between sub-systems can be detected (Sonis and Hewings, 1998). Classical Macroeconomics have got rid of the possibility of cascade effects, based on the alleged diversification argument Lucas (1977). However, the recent bulk of economic studies have shown that the interconnections between different firms and sectors play a key role in the potential propagation of idiosyncratic shocks throughout the economy.

This Chapter extends this approach to study the potential impact on the water resource management. A number of papers applied network analysis to study Virtual Water Trade as a global network (Barrat et al., 2008), unveiling the main characteristics of its topological structure

[1] See Rose and Casler (1996), Dietzenbacher and Los (1998) and Hoekstra and van den Bergh (2003) for overviews of the literature.

(D'Odorico et al., 2012, Konar et al., 2012, Tamea et al., 2014), as well as its temporal and geographical evolution (Carr et al., 2013, Dalin et al., 2012). They find that the total volume of virtual water trade is likely to shrink as a consequence of climate change due to higher crop prices under scenarios of declining crop yields and due to decreased virtual water content of crops under high agricultural productivity scenarios. Moreover, they show that international trade in food-related commodities has contributed to substantial savings in global water resources over time. The current approach is in line with the recent studies that integrate the information provided by IO table with Network indexes (Aldasoro and Angeloni, 2015, Carvalho, 2012, Hewings et al., 2009), particularly useful for a deeper understanding of the vulnerability of a system to external shocks (Acemoglu et al., 2012, Contreras and Fagiolo, 2014). As many other global networks, the global VW trade system has the feature of being both interconnected and interdependent, which poses a problem of network vulnerability to exogenous perturbations (Sartori and Schiavo, 2014). Another key property of networks is the community structure, i.e. the partition of a network into clusters, with many edges connecting nodes in the same cluster and few connecting nodes between different ones. Communities in networks are groups of nodes that share a close relation. The identification of the communities of a network leads sometimes to non-trivial clustering between nodes which helps in describing the topology of the network. D'Odorico et al. (2012) is the only attempt to define a Community Structure analysis of the virtual water embedded in crops and animal products. Differently from them, I included data on inter-sectoral intermediate trade providing an additional contribution to the current literature.

The novelty introduced by the present study is given by the combination of the SDA with Network measures of systematic vulnerability to exogenous (climatic) shocks. It goes beyond previous contributions because I grounded the current analysis on inter-sectoral (virtual water) trade and not simply on final consumption. This step is essential to understand whether the current global supply-chain is vulnerable to external shocks and whether the evolution of international trade is yielding riskier systems of VW exchanges. In particular: (i) I take into account the heterogeneous composition of each country with a 35-sector level of disaggregation, (ii) I assess the evolution of blue water use and the key drivers of its evolution, (iii) I evaluate the stability of the Blue IO Network, and (iv) the geographical distribution of trade, through the Community Detection analysis.

The present research is organised as follows: Section 2.2 describes the World Input Output Database (WIOD) and introduces the main concepts. Section 2.3 explains the Input-Output methodology, while Section 2.4 discusses the drivers of blue water use by means of a Structural Decomposition Analysis (SDA). Section 2.5 introduces the Network methodology and the fundamental topological properties of the global virtual water trade. In particular the Community Detection describes the geographical distribution of inter-sectoral exchanges, giving further information on the spatial distribution of trade and risks. Finally, Section 2.6 discusses the results and the potential for further research.

2.2 Data and definitions

The World Input Output Database (WIOD[2] gives the opportunity to assess the environmental impact of economic activity in terms of water, material, land and energy use and a series of air emissions, by exploiting information on world interindustry flows of intermediate goods. The database contains data for 40 countries (EU, USA and other important developing country, i.e. India, China and Brazil among others), plus the Rest of the World, and 35 sectors for each country. For every year it provides the square matrix of 1435x1435 bilateral (industry-country) flows of intermediate inputs (input-output). WIOD is composed by a set of harmonized supply and use tables and symmetric I-O tables, valued at current and previous year's prices. Sectoral water use is derived from

[2]World Input Output Database, http://www.wiod.org, updated to May 2013. The most recent version proposed on November 2013 does not contain the values in previous year's price, then for the sake of consistency here it is used the previous version. For a description of alternative IO databases see Andreoni and Miola (2014).

the estimations of Mekonnen and Hoekstra (2010)[3], FAOSTAT (2010) and EXIOPOL. Population data are available from the World Bank website (http://data.worldbank.org/).

Before moving to the set of empirical applications, it is useful to discuss the most common definitions of Virtual Water present in the existing literature. In the early 1990s, the geographer Tony Allan coined the term 'Virtual Water' (henceforth VW) to draw attention to the total volume of water needed to produce and process a commodity or service. Recently, Chapagain and Hoekstra (2007) referred to it as to the amount of water 'embedded' in traded goods within and across national borders. The concept has both an intensive and an extensive component (Allan, 2003). The former describes the role of water in food production and the role of trade in providing food security; the latter refers to the 'invisible' link between the source of water demand and the site of water consumption.[4] Note that the actual 'direct' water content of a product is generally far lower than the virtual water content, which includes the volume of water required by the manufacturing, transformation or processing of the product (Zimmer and Renault, 2003). There is no standard methodology to compute such indicator. The traditional approach to assessing VW embedded in a product is to multiply the trade volume of the product by the product's water intensity. Both water withdrawal and water consumption embedded in VW can be analysed within this framework by using different water withdrawal or consumption coefficients per unit output. The sum of direct and indirect water use coefficients gives a vector of total water demand multipliers, equivalent to virtual water content in $m^3/\$$. The total water demand multipliers are indicators of total water use that take into account supply chain effects, in contrast to the direct water coefficients that focus only on water use intensity from local pro-

[3]There are uncertainties related to input data used and limitations on the estimations taken from Mekonnen and Hoekstra (2010) who explain that the uncertainties related to unit water footprints are in the range of ±10-20% compared to observed data and ±5-10% compared to the other modelling exercises. They claim that the differences are due to data regarding cultivated and irrigated areas, growing periods, crop parameters, soil and climate used in their model.

[4]See Antonelli et al. (2012) and Velazquez et al. (2011) for a review of the literature on VW concept.

duction activities using local water resources.

The adoption of water footprint (WF), originally proposed by Hoekstra and Hung (2002), in analogy to the ecological footprint (Rees, 1992), originates from the concept of virtual water proposed by Allan (1993). The methodological relation between VW and WF is summarised by Van Oel et al. (2009). VW is defined as the amount of water needed to produce an unit of good, while WF is the sum of the VW in each production process and of the VW related to the 'distribution' phase.
Blue water (henceforth **BW**) refers to the consumptive use of ground or surface water and, normally, its supply is costly, because it requires infrastructure. Blue water is mobile, it can be abstracted, pumped, stored, treated, distributed, collected, and recycled, thus each m^3 saved can be directed toward alternative uses by industry and households. Finally, as a proxy of Water Availability (**Wa**),[5] following Chapagain and Hoekstra (2007), I used the Total Actual Renewable Water Resources[6] which shows the maximum theoretical yearly amount of water actually available for a country at a given moment.

Table 1 compares the total amount of water used both at absolute level and per capita. Given the stability of the distribution and of the ranking across countries in terms of water use during the considered time span, Is present the amount of Blue water consumed in years 1995 and 2009. These volumes stem from the estimation of water used by households, on the basis of the average domestic water supply, and industry, reported in Hoekstra et al. (2011). There are three facts that emerge from the results reported by the table:

1. there is an uneven distribution of direct water use both in terms of absolute level and per capita. The first three countries in the rank-

[5]The issue of analysing green water scarcity is largely unexplored mostly because there is no consensus on how to measure green availability. For a deeper discussion see Chapagain and Hoekstra (2007) (pag.34) and Hoekstra et al. (2011).

[6]It is the sum of internal renewable water resources (IRWR) and external actual renewable water resources (ERWR), in particular it is computed as the sum of total renewable surface water and total renewable groundwater, minus the possible overlapping. For more information see FAO AQUASTAT (http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en).

Table 1: Total and per capita blue water use (column 1 and 2) and Wa at country level in 2009.

BLUE Water Statistics 2009					
km^3		$1000m^3$ per capita		Wa in Km^3	
China	315 (16.22%)	Canada	2.76	BRA	8647
India	305 (15.71%)	Sweden	1.75	RUS	4508
USA	182 (9.39%)	Austria	1.21	USA	3069
Brazil	113 (5.80%)	Australia	0.63	CAN	2902
Canada	93 (4.80%)	Finland	0.61	CHN	2840
Russia	61 (3.15%)	USA	0.59	IDN	2019
Turkey	25 (1.32%)	Brazil	0.58	IND	1911

ing, China, India and USA, were responsible of the 41.31% (39.18%) of the total amount of blue water use worldwide, in 2009 (1995);

2. the rank of countries in terms of absolute water use and per capita water use remains rather stable over the period 1995–2009;

3. blue water use (absolute and per capita) has increased substantially over time.

In what follows I assess the impact of inter-sectoral exchanges, international trade, technological shifts and change in size and composition of final demand to explain the above facts, providing further policy insights.

2.2.1 Methodology

The Russian economist Wassily Leontief won the Nobel Prize due to the introduction of the Input-Output (IO) system to describe the economic process; it is composed by a matrix summarizing the inter-sectoral relationships existing between several industrial activities. A modern definition is provided by Miller and Blair (2009): “The input-output modelling approach consists of a system of linear equations, each one of which describes the distribution of an industry’s product through the economy” (pag. 1). The input of energy and matter transformed into final output, within an economy, are used to describe the links across sectors, industries, products and final consumption. The main hypothesis is that in the short-term the production system is fixed and that total production is constrained by existing capacities, equipment and infrastructures. Among its strengths I recall the possibility to recover feedback effects through simple linear algebra and to incorporate socio-environmental variables to shed a light on the extra-economic effects of industrial production.

I opted for an input-output model because it offers a variety of tools to ascertain several features of economic activity both at local and global level. Input-output analysis does not incorporate any specific behavioural assumption for individuals, firms or the government. Moreover, it offers the possibility to trace the trade structure between countries and the related impacts on economic systems, environmental pressures and society. Input-output analysis permits the determination and quantification of key drivers that cause changes over time in economic, social or environmental variables and the evaluation of the economic (and other) consequences of shocks that hit an industry (short-run analysis) or of natural disasters. Recently, the literature on footprint has focused on the calculation of the volume of emissions, employment, or value added that is embodied in exports and imports to provide a systematic view of the impact of global production/value chains (Andreoni and Miola, 2014) on environmental resources (e.g. water). However, any analytical model stands on a set of assumptions which necessarily bring about some limitations. Andreoni and Miola (2014) identify the following shortcomings for what concerns input-output models: i) limited flexibility given by linearity and rigid structure with respect to input, import substitution and price changes; ii) lack of explicit resource constraints and lack of responses to price changes, and iii) reliance on constant technical coefficient which limits the suitability of input-output model for long run scenarios.

Though designed to keep track of the inter-industrial links, the IO system has been extensively applied in the field of network science. The

MRIO system can be viewed as an interdependent complex network, where nodes are thought as country-sector pairs in different economies and edges are the flows of (virtual) water between industries. Complex networks has been proved to be fruitful for the description of a variety of economic issues (Carvalho, 2012, Zhu et al., 2014). In this Chapter, I considered the global MRIO system as a world input-output network, in order to assess the evolution of VWT and the vulnerability of the system to (potential) exogenous shocks. The field of input-output networks, though relatively new, is fast expanding. The recent bulk of literature in economics stresses that the structure of this production network is key in determining whether and how microeconomic shocks, affecting only a particular firm or technology, can propagate throughout the economy yielding aggregate outcomes. Studying the mechanisms through which shocks diffuse, in economic and ecological systems, is of a foremost importance to devise policy measures that can help water management strategies. Whereas most papers have analyzed the mechanisms of contagion in financial (Elliott et al., 2014, Glasserman and Young, 2015) and economic networks (Acemoglu et al., 2012, Contreras and Fagiolo, 2014), much less is known about how the topology of interdependencies between the sectors of an economy could affect the access and the distribution of natural resources. An interesting feature, found in many networks, is the presence of a highly heterogeneous structure, with degree distributions characterized by large variability and heavy tails. This feature, in a context of inter-sectoral input-output linkages, has been proven to be fundamental to understand how microeconomic idiosyncratic shocks may lead to aggregate effects. Acemoglu et al. (2012) showed that higher-order interconnections capture the possibility of cascade effects whereby local shocks propagate to the rest of the economy.

2.3 International VWT

2.3.1 Global Multi-Regional Multi-sectoral Input Output Model

Global trade involves all countries, each of which has a technology of production given by the different mix of sectors. A natural approach to deal with this framework is the application of Global Multi-Regional Multi-sectoral IO Model (Miller and Blair, 2009) (G-MRIO) in which there are R regions (countries in this case) composed by the same number (S) of sectors s. The matrix of intermediate exchanges is composed by $(R{\cdot}S)^2$ elements. This approach allows to exploit both information about the exchange within a country from sector i to sector j (z_{ij}^{RR}) and international trade from country B to country M (z_{ij}^{BM}), with possibly $i = j$.[7] In what follows, I describe the logic of the MRIO model, the notation and the main equations derived in Section 2.4, which define the evolution of the international trade structure and final demand, and their impact on Virtual Water.

Let assume, without loss of generality,[8] that there are two countries (M,B) composed by two sectors each (i,j). The aggregate IO table Z of intermediate exchanges has, on the diagonal, the square matrices Z^{MM} and Z^{BB} which represent domestic interindustry flows, while off-diagonal matrices Z^{MB} and Z^{BM} record the interindustry flows across countries (i.e. international trade in intermediates). In particular, each element z_{ij} indicates the amount of intermediate exchange from sector i to sector j, i.e. the entry z_{ij}^{BM} is the volume of trade from sector i of country B to sector j of country M.

[7] In the present case, given the high level of aggregation, each sector is actually composed by several firms and sub-sectors. For this reason, positive (and large) values are found in the main diagonal.

[8] See Miller and Blair (2009) for a full description of the IO methodology.

$$\left(\begin{array}{cc|cc} z_{ii}^{BB} & z_{ij}^{BB} & z_{ii}^{BM} & z_{ij}^{BM} \\ z_{ji}^{BB} & z_{jj}^{BB} & z_{ji}^{BM} & z_{jj}^{BM} \\ \hline z_{ii}^{MB} & z_{ij}^{MB} & z_{ii}^{MM} & z_{ij}^{MM} \\ z_{ji}^{MB} & z_{jj}^{MB} & z_{ji}^{MM} & z_{jj}^{MM} \end{array}\right) \tag{2.1}$$

Let x be the vector of total output, given by the row sum of intermediate exchanges (Z) plus the matrix of final demand (F) which includes domestic consumption and international trade of final goods. It is possible to split the system among different regions, hence also x is composed by x^B and x^M given the presence of two countries. The vector f of total final demand (row sum of F) is composed by domestic demand and exports. The matrix of technical coefficients (A) shows how the product of each row is distributed across other sectors, that is $A = Z \cdot \hat{x}^{-1}$, where $\hat{x}$ is a diagonal matrix composed by the inverse of the elements in x, $\frac{1}{x_i}$ $\forall i \epsilon x$. Given that A has the same structure of Z, it is split into the domestic matrix block A^{BB}, A^{MM} and those with the international intermediate trade: A^{MB} and A^{BM}. The Leontief matrix L solves the linear system: $x = A \cdot x + f$, and it is thus given by $L = (I - A)^{-1}$. Each element $l_{ij} \epsilon L$ indicates how much the production of sector j must increase given an unitary increase in the demand of good i. Matrix L captures not only the direct links (A) but also the indirect ones. In order to compute the indirect use of water at the global level, let define the water intensity vector γ with respect to total output (x) and to the vector of total water consumption of each sector (w), then $\gamma = w \cdot \hat{x}^{-1}$. Total water use of each sector can now be defined as:

$$w = \hat{\gamma} \cdot L \cdot f \tag{2.2}$$

that is the vector of water intensity coefficients which expresses the amount of water (m^3) in terms of (1000 dollar worth of) total output. Combining γ and L, I define the matrix of the indirect use of water due to to intermediate exchanges, that is:

$$\Theta = \hat{\gamma} \cdot L \tag{2.3}$$

Each element θ_{ji} of the matrix Θ measures the overall water impact of an increase of final demand for each sector in each region. Therefore, the row sum returns the global increase that sector j must satisfy to supply all other (intermediate) sectors.

2.3.2 VWT: evidence

In what follows, I show how the international trade of intermediate and final goods, with the relative water footprint, allows some country to indirectly use water coming from other countries. As expected, only the Agriculture, Hunting, Forestry and Fishing (AFF) sectors and the Electric, Gas and Water supply (EGW) sectors show a great direct usage of blue water, where the first represents in 2009 (1995) 56.15% (57.82%) of total and the latter 41.02% (40,02%) of total. Let define the water footprint of exports (Θ_{Exp}) and imports (Θ_{Imp}) of both intermediate and final goods, from which the water trade balance Θ_{BAL} = Θ_{Exp} - Θ_{Imp} is derived, e.g. for country C:

$$\Theta_{Exp}^{C} = \sum_{k=1}^{R} \Theta_{Ck} \cdot (f_k - f_{kC}) \tag{2.4}$$

$$\Theta_{Imp}^{C} = \sum_{k=1}^{R} (\tilde{\Theta}_k - \Theta_{Ck}) \cdot f_{kC} \tag{2.5}$$

where

$$\tilde{\Theta}_k = \sum_{j=1}^{R} \Theta_{jk} \tag{2.6}$$

where R is the number of countries (40 + ROW). Here f_{CC} is the domestic final demand, while f_{kC} represents the vector of export from country k to C, and f_k is the row sum for each sector in country k. Let Θ_{ij} be a square sub-matrix which shows the Leontief inverse for country i, when it exports to j, multiplied by their water usage, as in equation 2.3. Note that $\Theta_{CC} \cdot \sum_{k \neq C}^{N} f_k$ returns the water needed in country C when producing goods and services for final use which are exported to all the other countries. Whilst, given $k \neq C$, it is possible to recover the water needed in country C when producing the intermediate exports that are used abroad to produce final goods and services consumed by country k: $\Theta_{Ck} \cdot \sum_{k \neq C}^{N} (f_k - f_{kC})$. Country C is a 'water debtor' if and only if $\Theta_{Imp,C} > \Theta_{Exp,C}$.

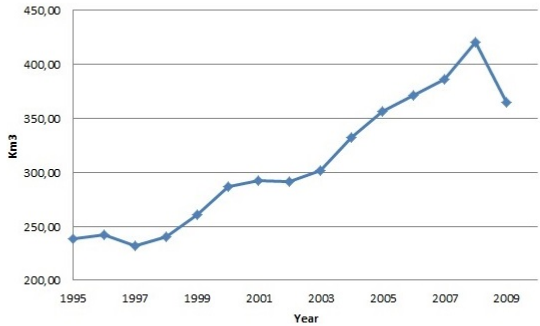


Figure 1: Global Blue water export dynamics: 1995 to 2009.

Figure 1 shows the increasing relevance of export of blue water that grew from 238 to 365 km^3 over the 1995-2009 period. The impact of the international crisis is evident since export reaches the peak in 2008, showing a decrease of more than 10% in 2009 with respect to 2008. The figure shows the non-linear dynamics of the level of export of virtual water. An important conclusion from studies on VWT is that international VWT in many cases does not follow the spatial pattern of fresh water resource availability. Indeed, Figure 2 tells that international trade has an high impact on the possibility of a country to face its domestic requirements. The findings of Arto (2012) are confirmed, with a progressive diversion of virtual water from the developing (Asian) to developed countries (see Table 14 in Appendix A.2). There is a tendency of globalization to move the production from the wealthier countries to emerging countries making them the core of production and, consequently, export. The main net importers are: USA, Japan, Germany and Great Britain. Note that, once compared with water availability (Wa), there are only few largely water endowed countries (China, India, Canada and Brazil) which cover the greatest part of the export of virtual water. Bigger countries are rather heterogeneous: some of them are net exporters (Brazil, China, India and Canada) while USA imported an amount of (virtual) water of almost 40 km^3 in 2009. Interesting to note the case of Russia which was an important exporter in 2001 (+13.39 Km^3) but became a net importer (-1.38 Km^3) in 2009, although it is a water abundant country.

Inasmuch a country is less endowed with water, it becomes more dependent on foreign freshwater resources. From a systemic point of view, these facts raise the question about the vulnerability of VW trade in case negative (climatic) shocks hit the main nodes of the virtual water network. In what follows, I assess the evolution of industrial structure and final demand and their impact on virtual water through SDA. This analysis will be complemented by network-based measures to unravel the topology and the connections between the industrial sectors and thus the resilience of VWT network.

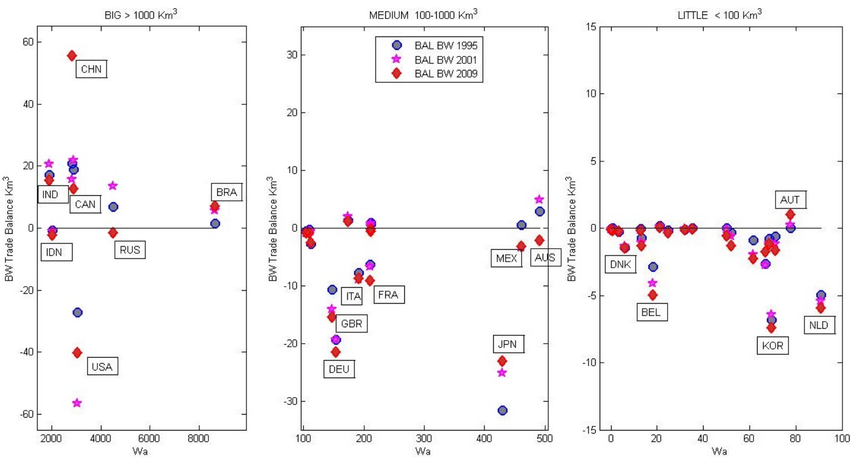


Figure 2: Relation between Water Availability and net trade balance (BAL) of BVW in 1995, 2001 and 2009.

Note that, in Figure 2, points above zero stand for 'net' exporter of Blue (virtual) water, while the 'water debtors' lie below. BIG stands for water abundant countries (> 1000 km^3 of Wa), MEDIUM stands for countries endowed with an amount of renewable freshwater between 100-1000 km^3 and LITTLE are countries with less than 100 km^3 of Wa.

2.4 Structural Decomposition Analysis

As discussed in the previous section, trade in virtual water has increased substantially in recent years. The existing literature (e.g. Arto et al., 2012) agrees that this dynamic has been driven by a variety of factors such as changes in 'water efficiency', structural change, composition of final demand and scale effects. In this section I dig deeper into the drivers of virtual water by decomposing recent trends of virtual water in their various components. I apply a simplified version of the structural decomposition analysis (SDA) used by Xu and Dietzenbacher (2014) to quantify the contribution of various driving forces to changes in water embodied in exports. Differently from Xu and Dietzenbacher (2014), I do not evaluate changes in environmental pressures embodied in export (either of final goods or of intermediates) but I evaluate directly the water footprint of final demand of each country. This is particularly suitable for purposes of this Chapter as it grasps the importance of the different driving forces of total water footprint. Methodological details about the decomposition are discussed in the Appendix A.1. The change of total water footprint from time t to $t+1$, $\Delta w = w_{t+1} - w_t$, is a function of the above drivers, that is:

$$\Delta w = \Theta(IE, T, H, POP, Q_C, Q_{cap}, D^*) \tag{2.7}$$

where the intensity effect (IE) stands for change in water intensity coefficients (γ), T and H are the impact of trade and change in the 'sectoral' composition of intermediate inputs, respectively, captured by the Leontief inverse. The impact of final demand is decomposed into four components: impact of international trade (D), change in the product mix (Q_C) and change in consumption per capita (Q_{cap}) and population size (POP). Here, the results at the global level (figure 15) are compared with those derived for a selection of countries: United States, India, China, Italy, Russia, Brazil and Japan. These countries represent together 51.78

percent of global GDP (source: World Bank) and 52.06 percent of total blue water direct use (source: WIOD) in 2009. The selection of countries includes both high-income and emerging countries which allows to compare the drivers of changes in water demand across rather heterogeneous regions.

The 'water intensity' component IE describes the role played by changes in the vector of direct water use per unit of produced output. More specifically, this component describes how changes in water intensity in all countries affect the water footprint of a specific country. Overall (Figure 15), improvements in water efficiency of production activities allowed to reduce world water footprint by about 40 percent over the period 1995-2009. The contribution of this component has been rather small in the first years of the series (1995-1999) and then accelerated substantially up to 2008. Results for specific countries (figure 16) show that the water footprint of China's final demand would have increased by about 60 percent over the period 1995-2009 in absence of improvements of water efficiency in production occurred in China and in its trading partners. Changes in water intensity contributed to an overall reduction in water footprints for all countries (at least for the period 1995-2008, while the water footprint for Brazil and Italy in 2009 would have been higher than in 1995 due to worldwide changes in water intensity) but with much smaller magnitudes than for China (in the order of 10-20 percent). It is also interesting to note that while the overall cumulative trend goes in the direction of a negative contribution (i.e. smaller water use) of water intensity, many years have been characterized by (even substantial) increases in average water use per unit of output.

There are several institutional barriers that might impede a more efficient use of water: regulatory uncertainty, cross-country heterogeneity in water-related regulation (including property rights), high upfront costs, and principal-agent issues in water markets. Another possible explanation is that water is not always priced effectively (if not at all) resulting in many countries not considering water as a scarce limited resource. Note that IE includes, for each country, the effect of an (in-)efficient water management of all the other countries. Therefore, to overwhelm those institutional barriers, a global coordination is needed, as suggested below.

The component H should be interpreted as the contribution to water footprint of changes in the technical coefficient matrix (i.e. mix of intermediate inputs) with no consideration of the geographical origin of intermediate inputs. A positive sign reveals a systematic increase in the relative importance of water-intensive (above average) sectors. Overall, this component has driven up the world water footprint by about 8 percent over the period 1995-2009: virtual water related to final consumption has increased due to a systematic shift of intermediate inputs towards more water-intensive sectors. Results for single countries, reported in figure 17, highlight a substantial degree of heterogeneity. The component is positive, in the order of 15-20 percent over the period 1995-2009, for Brazil and China and in the order of 5-10 percent for Italy. It is interesting to note, however, that for Brazil and Italy the contribution of the component H has been steadily increasing since 1995 while for China it is estimated a substantial increase starting form 2003. At the other extreme, there is a negative contribution of the component in the order of 15-20 percent for India, Russia and the United States and basically no change due to H for Japan. Overall, the production technology has changed, in recent years, in the direction of requiring an increasing amount of virtual water.

The component T accounts for changes in the 'geographical' composition of the mix of intermediate inputs for a fixed average mix of intermediates (i.e. H). A positive sign should be interpreted as a systematic shift of the purchase of intermediates towards more water-intensive countries. At the aggregate level, this component is very small and contributed positively to water footprint. Results for selected countries, reported in figure 18, denote a generally smaller contribution of this component relative to the H component. Similarly to the 'water efficiency', trends are not systematically upward or downward. Looking at the overall 1995-2009 cumulative contribution of the T component, the only country that shifted its demand of intermediate inputs towards systematically less 'water efficient' countries is China, with a predicted increase in the order of 10 percent of its water footprint. The contribution of this component is very small (smaller than 5 percent) for India, Brazil, Japan and the US, while it is negative and in the order of 5 and 10 percent for, respectively, Italy and Russia. Quite surprisingly, the composition of trade of intermediates has remained rather stable in the considered period, especially when compared to changes in production technology (H). Trade links seem to be persistent in time and are likely to be strictly linked to bilateral relationships between countries, comparative advantages, trade costs, factor endowments and historical bilateral links. This is particularly interesting as shocks in water availability, that might drastically reduce the supply of water-intensive goods of a specific country hit by the shock, are likely to influence the demand for water quite substantially due to the 'rigidity' of bilateral trade patterns.

Final demand is split into four different components to capture both the scale and the intensity effects. The first two components, Q_C and D^*, are the counterparts for final demand of the components H and T, respectively. The component Q_C quantifies the role played by changes in the product mix of final demand for a given level of final demand and for a given 'geographical' composition of final demand. The aggregate result (Figure 15) highlights a negative contribution of this component to total water demand, in the order of about 18 percent over the period 1995-2009. Results for selected countries, reported in figure 19, confirm a general transition of final demand towards sectors with a systematically smaller water footprint per dollar, the only exception being Japan, for which basically no change is visible. The component is particularly big in magnitude for China and India, for which changes in the sectoral composition of final demand contributed to a reduction of water footprint of about 45 percent over the period 1995-2009. As highlighted in the recent literature (Arto, 2012, Roson and Sartori, 2015) this evidence is linked to the relative decrease in the share of final demand directed to food products, which are particularly water-intensive. The magnitude of the reduction is much smaller for the United States and Russia (about 15 percent) and even smaller for Italy and Brazil (about 5-10 percent).

The role of changes in the 'geographical' distribution of final demand is described by the component D^*. Results for this component are very similar to the ones found for T, that described the geographical composition of intermediate consumption. The geographical distribution of final demand contributes positively to the overall demand of virtual water, even though the effect is rather small. Looking at the evidence for selected countries (Figure 20), China was the only country that experienced a big increase in water use due to shift of demand (now of final goods) towards more water-intensive countries. The size of the effect is here much bigger than for T, accounting for about 20 percent increase in water footprint of China (about two times the contribution of factor T for the same country). For five other countries the contribution is close to zero while the contribution is negative and between 5-10 percent for Italy and Russia. These results are in line with the ones discussed for the component T, denoting a substantial rigidity of the geographical distribution of trade patterns.

The last two components refer to more aggregate driving forces, that are: changes in per capita total final demand (in real terms) and demographic growth. The role played by changes in total final demand per capita, strongly correlated with affluence, is by far the biggest component that drives virtual water, accounting for a 55 percent increase (worldwide) in virtual water over the period 1995-2009. This effect was particularly important for emerging countries (Figure 21) such as China (about +120 percent), India (about +80 percent) and Russia (+60 percent) over the period 1995-2009, while the increase due to affluence in Brazil, Italy and the United States has raised the water footprint by about 20 percent and no change is observed for Japan. These differences reflect asymmetric macroeconomic growth across countries, with evidence of a substantial convergence of emerging countries towards high-income countries both in terms of affluence and in terms of water demand.

Finally, the role of demography has been very stable over the period, contributing to an increase in water footprint of about 20 percent worldwide. When looking at the selected of countries (Figure 22), the contribution of the demographic component was about 20 percent for India and Brazil, 15 percent for the United States and China, 5 percent for Italy and

Japan and basically no change for Russia, over the period 1995-2009.

To summarize, the structural decomposition has highlighted that while $size$-related components (population and affluence) and $technological$-$structural$ components (water intensity and structure of final demand and intermediate input mix) have contributed substantially to changes in the demand for water, while the geographical-related components (both in terms of final demand and intermediate inputs) had very little influence on the demand for water. The interpretation of this last result is that heterogeneity in water availability and water efficiency across countries played a minor role as determinant of trade patterns vis-a-vis other determinants such as trade policy, comparative advantage, and factors (other than water) endowment. However, there is another possible implication: if the geographical structure of trade patterns was not responsive to differences in water endowment and efficiency across countries, what would happen in case of shocks to water availability that are likely to occur due to climate change? How would these shocks propagate across different countries and sectors and how vulnerable is the VW trade network? To answer these questions a comprehensive knowledge about the topology and the property of the VW trade network is needed as classic input-output analysis, with its strong assumptions of linearity, perfect complementarity and immediate adjustment of supply to demand, is not an utterly suitable methodological tool.

2.5 Network Analysis of Virtual Water Flows

The topology of the VWT network is described by the matrices Ω and Φ, both containing the amount of direct virtual water exchanged for intermediate and the final consumption, respectively as:

$$\Omega = \hat{\gamma} \cdot Z \tag{2.8}$$

$$\Phi = \hat{\gamma} \cdot F \tag{2.9}$$

such that the row sum of both matrices must be equal to the total amount of water used in each sector: $\Omega \cdot e + \Phi \cdot e = w$, where e is the summa-

tion vector. I investigate the Directed and Weighted Graph of the actual exchanges,[9] among the sectors of all the countries, of (virtual) water embedded in each product. In this way it is possible to complement the evidence arising from the SDA, which quantifies the role played by a variety of drivers of virtual water at the aggregate level, with useful information on the topology of the linkages among countries and sectors. Each combination of country-sector pair is considered as a node of the Network. Links between nodes are directed on the basis of the flow of trade, e.g. from exporter to the importer, and they are weighted by the volume of virtual water traded. In particular, in line with Acemoglu et al. (2012), I present the results for matrix Ω only, assessing the topological structure of intermediate trade, giving a better understanding of the technological evolution and its spatial distribution.
Ω is the weighted adjacency matrix whose elements ω_{ij} represent the links between node i and j, that is the flow of VW that goes from i to j. Strictly-positive self loops $\omega_{ii} > 0$ captures the idea of a sector using its own products as inputs (in case of heterogeneous firms' activity). Directed networks are typically asymmetric, meaning that $\omega_{ij} \neq \omega_{ji}$, so they allow to recover the information both from the importer and the exporter side. Let $k_{in,i}$ be the $in-$node degree, that is the number of sectors that are exporting to sector i; while $S_{in,i} = \Sigma_j \omega_{ij}$ is the $in-$node strength of node i, that is the total amount of intermediate input purchased by sector i.[10] Symmetrically, I define the $out-$node degree $k_{out,i}$ and strength $S_{out,i}$, of node i, by summing the entries in the row i of matrix Ω. These indicators provide a first overview, albeit incomplete, of the structure of VWT network and of the presence of hubs (big importer or exporter), which influences the resilience of the whole system. Results in table 2 refer to the Graph composed by 1400 nodes, each of which trades virtual water. ROW has been removed because, by definition, it includes a great variety of countries, and then it does not represent an homogeneous entity. The topological structure is not affected by that, with the

[9] I filter the edges such that the minimum amount of virtual water traded is 1000 m^3. This simplifies the computation without affecting the results in a substantial way.

[10] This computation reminds the backward linkage index which returns the column sum of matrix L to assess the importance of a node.

exception of the ranking, because ROW covers a big share of the virtual water globally traded. In what follows I showe some statistics of interest for the whole graph Ω, while the last part of this Section is focused to an higher level of aggregation in order to assess the evolution of the community structure of VWT. It is also offered a comparison with the 'pure' international trade (IT), that is by excluding each domestic trade in the matrix Ω. Table 2 shows some statistics of interest that give important information about the topological structure of the Network.[11]

Table 2: Fundamental properties of BVWT Network for intermediate goods in 1995, 2001 and 2009.

Ω	BW_{1995}	BW_{2001}	BW_{2009}	BW_{1995}^{IT}	BW_{2001}^{IT}	BW_{2009}^{IT}
VWT Km^3	621.05	655.48	837.61	25.83	32.29	32.14
VWT %	41.00	41.07	42.72	4.15§	4.92§	3.86§
edges	99864	110122	117595	90847	101015	108479
density	5.10	5.62	6.00	90%§	91.7% §	92.2% §
max(k_{in})	238	243	241	230	235	233
max(k_{out})	1202	1237	1260	1168	1203	1203
max(S_{in}) Km^3	43.30	49.54	52.67	2.35 (5.3% $^{\sharp}$)	2.64 (5.33% $^{\sharp}$)	2.48(4.70% $^{\sharp}$)
max(S_{out}) Km^3	90.03	87.80	143.86	6.69 (7.4% $^{\sharp}$)	6.86 (7.8% $^{\sharp}$)	8.86 (6.16% $^{\sharp}$)
$LogN_{S_{in}}$: μ	10.18	10.23	10.27	7.28	7.65	7.78
(σ)	(2.84)	(2.90)	(2.85)	(2.38)	(2.36)	(2.22)
$LogN_{S_{out}}$: μ	9.99	10.09	10.19	7.79	7.96	8.16
(σ)	(3.44)	(3.44)	(3.44)	(2.9)	(2.97)	(2.91)
FIT S_{in} vs k_{in} (ξ)	2.38	2.42	2.41	2.15	2.16	2.16
(σ)	(0.056)	(0.055)	(0.059)	(0.064)	(0.069)	(0.082)
FIT S_{out} vs k_{out} (ζ)	1.99	2.00	1.98	1.73	1.77	1.74
(σ)	(0.076)	(0.08)	(0.078)	(0.07)	(0.08)	(0.097)

It appears a great increase in the volume of blue VWT of intermediate goods, which represents more than 40% of total blue water. Although the number of edges (or links) is quite large, the share of active linkages, with the respect to all possible combinations (1400^2) is very low, that is around 5.5%. This is not surprising because many sectors are characterized by a null direct water intensity coefficient.[12] The weight of links ranges from

[11] In Table 2 σ stands for the standard deviation, § stands for percentages computed with the respect to intermediate exchanges only, while $^{\sharp}$ means percentages of $\max(S_{in-/out-})$.

[12] This is a specific feature of the data collected in WIOD, with the bulk of direct water usage concentrated in a reduced number of water-intensive sectors. If also direct water

10^3 m^3 to a maximum of 52 Km^3 in case of $in-$node strength and up to 143 Km^3 in case of $out-$node strength, indicative of high link weight heterogeneity. The main importers (with higher S_{in}) and exporters (with higher S_{out}) are almost the same during the whole time span considered.[13] When looking at the whole network the main importer was the Food and Beverage (Fd) sector of USA, India and China representing the 18% of the whole BVWT (intermediate goods). The main exporters were the AFF and EWG sector of China and the AFF sector of USA and India representing more than 50% of the whole BVWT (intermediate goods). However, when the focus is narrowed toward 'pure' international trade, the picture is barely different: the Fd sector of China superseded the USA and Japan in 2009 as the main importer, with a share of almost 8% (the three together represents again the 18% of the whole BVW from IT in intermediate goods). The main exporters were the AFF sector of USA and India and the EWG sector of Canada (again with a share slightly above the 50%, confirming the scale-free behaviour of the system).

It is now worth to investigate the distribution of $in-$ and $out-$ node degree and strength to assess the heterogeneity of the network connectivity. As expected max(S_{out}) $>$ max(S_{in}) always, because only few sectors are providing virtual water to all the others. Figure 3 draws the natural logarithm of nodes strength as a function of their degree. It emerges a power-law relationship that follows the form $S_{in} \sim k_{in}^{\xi}$ and $S_{out} \sim k_{out}^{\zeta}$ (estimated coefficients are reported in Table 2). The power law coefficients of the $in-$ degree distribution is relatively stable (less than 10% change) and of about 2.4. The same holds also for ζ which, in all cases, floats around 2, revealing a highly non-linear relationship. This high values indicate that there is a strong relationship between the volume

use of much less water-intensive sectors was considered, the number of active links would have been greater, even though these additional links would have been characterized by a very small average 'weight'.

[13]Note that by including self-loops and intra-country trade, the terms import and export not necessary refer to transfers abroad but in most of the cases they are led by domestic exchanges.

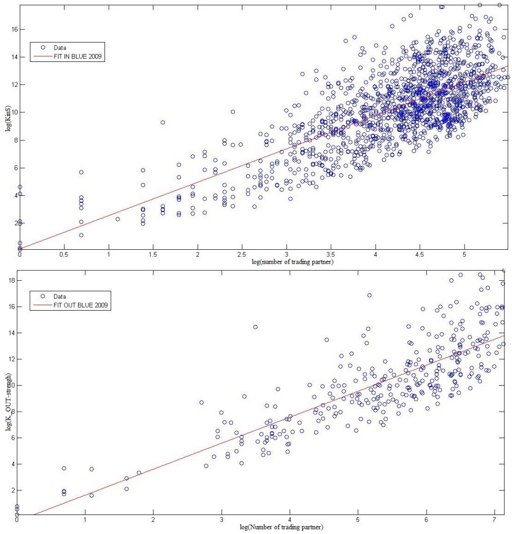


Figure 3: Plot of S^{in} against k^{in} (above) and of S^{out} against k^{out} (below).

of virtual water that each nation trades and the number of commercial partners. In other words, the weight $in-/out-$ degree grows faster than simple $in-/out-$ degree, so the more trade connections a country has, the much more it is able to participate in the exchange of virtual water in a highly nonlinear way. This finding suggests a remarkable policy implications: more 'openness to trade' is an efficacious channel for countries to improve access to water resources. On the other hand, the rate of decay is far slower than in a Gaussian distribution (where the exponent is 0.5), meaning that shocks to sectors, that take more central positions in the inter-sectoral network, have a more than proportional effect on the whole system.

The distributions of both S_{out} and S_{in} are well fitted by a lognormal[14] distribution (see Figure 23 and 24 in the Appendix A.4). These results are in line with the findings of Konar et al. (2012), despite the fact that this

[14]It was applied the Kernel density smoothing function given in Matlab. It returns a probability density estimate, f, for the sample in the vector x. The estimate is based on a normal Kernel function, and is evaluated at 100 equally spaced points, x_i, that cover the range of the data in x.

study accounts for self-loops and that it focuses on inter-sectoral trade only (Ω). Given the stability of the distributions over time, I report only the fits for three years of interest (1995, 2001 and 2009). The scale-free behaviour allows to conjecture similar findings even when more data and details for the ROW will be available. Indeed, the system is stable at different levels of aggregation and the absence of the half of the VWT (represented by the ROW) does not affect the topology. The scale-free property is further confirmed below when 'pure' international trade is considered. Although it accounts for roughly 5% of the whole blue VWT, it has most of the features in common with the large-scale network. In what follows, I introduce additional measures to understand whether benefit of trade is counterbalanced by greater systemic risks.

To provide a clear picture of the systemic vulnerability of the network, I compute the $first$- and $second$- order network characteristics. Note that two networks with identical $first-$degree distributions might exhibit considerably different levels of vulnerability, because of the so called 'cascades' effects. Indeed, a country-specific idiosyncratic shock affects not only those countries immediately connected to it, but also those indirectly connected. The $second-$order degree of sector i is defined as the weighted sum of the degrees of the sectors that use sector i's product as inputs, with weights given by the corresponding input shares. In the current context they are derived by the following system of equations:

$$\Psi = \Omega \cdot (\hat{S}_{in})^{-1} \tag{2.10}$$

$$d = \Psi \cdot e \tag{2.11}$$

$$q = \Psi \cdot \hat{d} \cdot e \tag{2.12}$$

where Ψ is the matrix of weights, such that $e' \cdot \Psi = e$, where e is the summation vector. Vector d is the so called weighted *first order-connectivity* (out-) degree which shows a fat-tail distribution (see the left panel of figure 4), which confirms that extreme events are more probable than in the Gaussian distribution. (Acemoglu et al., 2012) show that the distribution of d provides only partial information about the structure of the network, it is thus necessary to compute the weighted *second order-*

connectivity (out-)degree to assess the levels of vulnerability as this also considers the indirect connections between sectors and countries. Figure 4 (right panel) confirms the *heavy tail* (see Table 18 in Appendix A.4 for the statistical tests) behaviour even for q which means that the indirect inter-sectoral links potentially propagates the impact of a shock that hits a node (most notably if it is a 'big' exporter). Because of the scale-free behavior, confirmed by Tables 2 and 3, the same considerations hold in case of international trade only. International input trade transmits shocks across borders in much the same way as domestic input trade transmits shocks across sectors, they are passed downstream through the production chain directly in other countries and may generate remarkable variations in the amount of VW traded. Thus, the network of international input flows, although its tiny fraction, might be a risky channel of water redistribution.

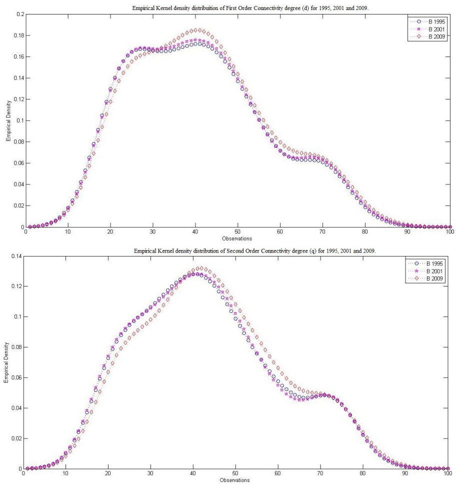


Figure 4: Empirical Density distribution and Countercumulative Function of q in 1995, 2001 and 2009.

The extreme heterogeneity of the connectivity patterns, together with the large fluctuations observed (σ^2_{in} and σ^2_{out}, Table 3), are additional signals that is present a scale-free distributions. Recent literature shows that the heavy-tailed nature of the degree distribution has also important consequences on the network *resilience* in case of removal of vertices or exogenous shocks to vertices. The relevant parameter for these phenomena is the ratio between the first and the second moment of the distribution. In case of directed networks, as those analyzed so far, this heterogeneity parameter has to be defined separately for $in-$ and $out-$ degrees as:

$$\lambda_{S_{in}} = \frac{< S_{in}^2 >}{< S_{in} >} \tag{2.13}$$

$$\lambda_{S_{out}} = \frac{< S_{out}^2 >}{< S_{out} >} \tag{2.14}$$

(2.15)

If $\lambda_{S_{in}} >> 1$ (and/or $\lambda_{S_{out}} >> 1$) the network manifests some properties that are not observed for networks with exponentially decaying degree distributions. Table 3 confirms the heavy-tailed behaviour when comparing the heterogeneity parameters and their high variances. Because most of the analyzed degree distributions are heavy-tailed, fluctuations are extremely large so that the linear correlation coefficient is not well defined for those cases. A full account of the connectivity pattern and of the system vulnerability requires further non-linear indicators of degree correlations. First, I compute the so called *one-point degree correlations* ($k_{in.out}$ and $S_{in.out}$) for individual nodes, in order to understand whether it is present a relation between the number of incoming and outgoing links in single nodes. These are computed as:

$$k_{in.out} = \frac{< \Sigma_i k_{in,i} \cdot k_{out,i} >}{< k_{in} > \cdot < k_{in} >} \tag{2.16}$$

$$S_{in.out} = \frac{< \Sigma_i S_{in,i} \cdot S_{out,i} >}{< S_{in} > \cdot < S_{in} >} \tag{2.17}$$

A significant positive correlation between the in-degrees and the out-degrees of single nodes is found in each year, as summarized in Table 3. This implies that sectors that have a higher number of input-demand relations, i.e. a high in-degree, also tend to supply their output to a relatively higher number of other sectors. This information is crucial to better understand the structure of international trade shown in Figure 2. To best of my knowledge the assessment of these values for environmental variables is novel in the literature.

Table 3: Degree Correlations statistics of BW Networks for 1995, 2001 and 2009.

Ω	BW_{1995}	BW_{2001}	BW_{2009}	BW^{IT}_{1995}	BW^{IT}_{2001}	BW^{IT}_{2009}
$< k_{in} >=< k_{out} >$	71.33	78.66	83.99	64.89	72.15	77.48
$\sigma_{k_{in}}$	50.18	52.05	52.54	48.71	50.54	50.99
$\sigma_{k_{out}}$	191.96	207.72	219.72	182.22	197.80	209.69
$< S_{in} >=< S_{out} > (Km^3)$	0.443	0.468	0.592	0,018	0.023	0.023
$\sigma_{S_{in}}(Km^3)$	2.13	2.25	3.11	0,104	0.109	0.116
$\sigma_{S_{out}}(Km^3)$	4.43	4.63	6.47	0,23	0.28	0.287
$\lambda_{k_{in}}$	106.61	113.08	116.84	101.43	107.52	111.02
$\lambda_{k_{out}}$	587.55	626.83	658.35	576.24	614.019	644.58
$\lambda_{S_{in}}(Km^3)$	10.67	11.32	16.91	0.611	0.54	0.62
$\lambda_{S_{out}}(Km^3)$	44.73	46.21	71.13	2.894	3.394	3.642
$k_{in.out}$	1.62	1.56	1.51	1.68	1.62	1.56
$S_{in.out}$	23.27	23.16	30.39	12.71	8.28	9.69
$r^{\omega}_{i\to j}$	- 0.0235	- 0.0228	- 0.0215	-0.0125	-0.0203	-0.0186

Finally, the assortativity index measures the similarity of connections in the graph with respect to the node strength, hence it is a correlation coefficient between the strengths (weighted degrees) of all nodes on two opposite ends of a link. It is a natural candidate to investigate the correlations of the degrees of neighboring vertices. Through this index, I assess whether relatively high degree nodes have a higher tendency to be connected to other high degree nodes. A positive assortativity coefficient indicates that nodes tend to link to other nodes with the same or similar strength. This property was defined by Newman (2002) for un-weighted networks, while here I introduce the version as explained in Leung and H (2007) as:[15]

[15]The code is a modified version of what is given by MIT Strategic Engineering web site (http://strategic.mit.edu).

$$r^{\omega}_{\delta \to \iota} = \frac{\frac{\sum_j \delta_j \cdot \iota_j}{P} - (\frac{\sum_j \delta j + \iota_j}{2P})^2}{\frac{(\sum_j \delta j^2 + \iota_j^2)}{2P} - (\frac{\sum_j \delta j + \iota_j}{2P})^2} \tag{2.18}$$

where P is the sum of the weighted edges of the Network and δ_j, ι_j represents the $out-$node and $in-$node strength of the two vertices connected by the j^{th} link. For the sake of completeness I computed the assortativity index for each of the 4 possible combinations (out-out, in-in, in-out and out-in), finding very similar findings (Table 3 reports an average value). The values, in contrast with the findings of Konar et al. (2012), are slightly negative in each period, remarking a slight disassortative behaviour even when weights are taken into account (also in case of IT), suggesting that high degree (strength) country-sector pairs tend to have trade relationships with small country-sector pairs more often than expected in a random network, suggesting a potential benefit of redistribution of VWT from big (high endowed) countries toward water scarce regions. In other words, the disassortativity indicates that nations that trade large volumes of water are 'open' to trade with many other nations, so that large volumes of water can be reallocated among several countries, representing a potential water security tool.

The above analysis, together with the disassortative structure of the Network, highlights the duality of VWT. The global network of virtual water might benefit from increasing exchanges, however although international VWT is still a tiny fraction of the whole exchanges, it might be a risky channel because it facilitates the propagation of shocks. The topological properties of the current Blue VWT network bring about some relevant implications that call for policy action aimed at reducing and mitigating the propagation of shocks in the supply of water due to the increasing climatic risks. Action should necessarily involve a coordinated set of measures across countries due to the high degree of dependence on foreign water resources for most countries. Not only 'big' countries but also smaller ones should be included, indeed Figure 2 shows a positive relation between the endowments of Wa and the level of net import of VW (and thus of higher level of external 'dependency' and thus exposure to external shocks). Being part of the VWT network increases a country's vulnerability to crisis that occur in other countries involved in the network, due to the cascade effects; or in other words, there is a potential trade-off between the need to import water-intensive goods (and the associated potential saving in water resources) and the vulnerability to external shocks. Moreover, from the inter-temporal comparison of the $first-$ and $second-$ order connectivity degree and of the indeces of degree correlations (at both a binary and weighted level) it emerges an increasing tendency of the blue water networks to be more vulnerable in time. These are remarkable results about the possibility to incur in imminent crisis.

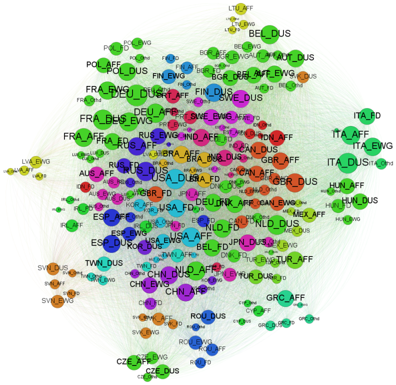
All in all, these results highlight the necessity to start off a serious program of local and global water management strategies to reduce the risks coming from water stress. Therefore, understanding the structure of this production network can inform policy-makers on how to prepare for and recover from adverse shocks that alter the provision and distribution of Blue water.

2.5.1 Community Detection

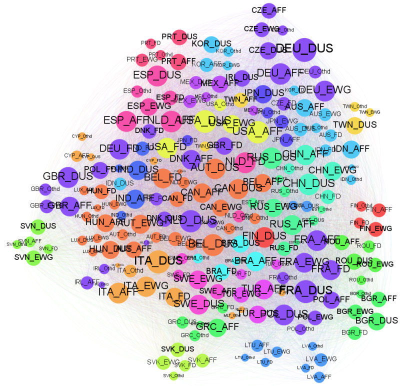
Within the International Trade Network literature it is possible to observe a growing interest in studying how the process of globalization is changing the topology and the spatial distribution of trade, in particular how and which 'communities' of countries are emerging, with many edges connecting nodes in clusters. I applied the modularity optimization[16] introduced by Newman and Girvan (2004), based on the idea that from a comparison between the density of the edges in a sub-graph and that one would expect in a random graph (which would not have any communities), it is possible to detect cluster structures.

Given the big number of edges, I decided to aggregate, without loss of coherence, some sectors of particular interest into 5 macro-sectors in order to have comparable results with the previous IO analysis, in particu-

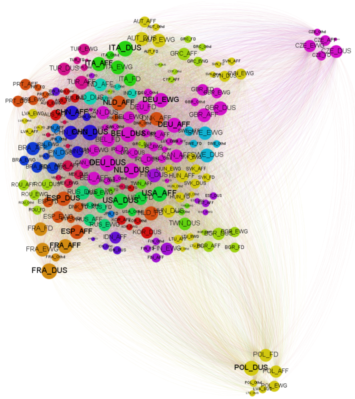
[16] Modularity optimization consists into optimizing the function Q = $\frac{\sum_{ij}(A_{ij}-P_{ij})\delta(C_i,C_j)}{2m}$, where A is the adjacency matrix, P is the random graph with the same degree sequence of A, m is the total number of edges and the δ function returns zero in case if node i and j belonging to the same community.



(a)



(b)



(c)

Figure 5: Community Structure for Blue VWT in 1995 (a), 2001 (b) and 2009 (c).

lar I considered: Agriculture, Hunting, Forestry and Fishing (AFF), Food, Beverages and Tobacco (Fd), Electricity, Gas and Water Supply (EWG), Textile, Chemicals, Metallurgic and Paper industries (DUS) and all the others gathered together (Othd). This simplification allows us to unravel the evolution of the connections among different sectors and their evolution over time. This new graph is composed by 200 nodes that trade both domestically and with foreign partners. In what follows, I discuss the evolution in the emergence of communities by comparing three years of interest: 1995, 2001 and 2009. Note that by allowing intra-national trade, the domestic exchanges result to be the most important component, although the emergence of international communities, whose are not always explained by geographical proximity, is confirmed. Figure 5 describes graphically the various communities for years 1995, 2001 and 2009.

Despite the increasing globalization of value chains, it is observed an increasing tendency of big countries (USA, Japan, China, India and Brazil) to rely more on regional-national VWT than to create international communities. This might be explained by the fact that the domestic amount of virtual water traded is much higher than what they exchange at the international level. Moreover, these countries are also linked to a variety of trading parties without forming any significant cluster. Most communities were based on a single economy. One the other hand, the biggest multi-country community in 1995 was formed by central-eastern European countries (including Germany, Czech Republic, Slovakia, Hungary, Poland, Austria and Slovenia). This big community disappeared in 2001, giving rise to different multi-country communities. The biggest was lead by Germany that also included Austria, the Netherlands, Belgium and Canada. Figure 5 depicts this latter big community in violet. Other important communities grouped together mostly Baltic countries (Latvia, Estonia, Lithuania and, quite surprisingly, the UK in 2009) on the one hand and central-eastern European countries on the other hand.

All in all, European countries tend to create more communities, especially so Central and Eastern European countries, than countries in other continents. A second remarkable result is the fact that many communities are only composed by sectors belonging to one single country: this result highlights the importance of domestic water supply in many countries as opposed to the supply of water coming from other countries. Finally, the composition of the communities sometimes reflect links that go beyond the geographical proximity of countries (e.g. the presence of Canada in an European community) but depend more on comparative advantage of some country in water-intensive products and historically strong trade ties between countries. As seen, the community detection help us to understand the emergence of linkages at international level, providing further information about the effect of technological change. In particular it helps to define the source of variation (given by Θ_{TECH} and Θ_{IE}) unravel through the SDA.

2.6 Discussion

In this Chapter I defined a novel conceptual framework to study the global blue VWT by integrating IO and Network methodologies. It proved to be a fruitful choice because it provides a wider picture of the issues at stake, to wit assessing an efficient allocation of water resources such as to prevent the propagation of local (climatic) risks. The present work contributes to the debate on the potential benefits and risks associated with openness to trade. SDA allowed to unravel the main drivers of VW their evolution over time. There was a substantial contribution to reducing water demand exerted by the composition of final demand and by improvements in the water efficiency of production, while demographic and economic growth and changes in the intermediate input mix has more than compensated such reduction. Interestingly, the role played by changes in trade patterns was rather marginal, contributing only to a moderate increase in virtual water. Besides the aggregate picture, there are some peculiarity in specific countries that seems to be related to their level of affluence and their trajectory of structural change and economic growth.

Network theory extends the information provided by the IO assessment because it captures the non-linear relationships between $in-$ and $out-$ node strength and degree distributions that follow a power law. This finding has important implications for the trade policy of water-scarce countries looking to increase their water availability because, as showed above, the amount of VW increases more than proportionally with the number of commercial partners. The fat-tail behaviour of the $first$– and $second$– order connectivity measures confirms that the system is particularly exposed to the propagation of local (supply-side) shocks due to 'cascade effects' (Acemoglu et al., 2012). The main policy implication of these findings is that a cross-country coordination of water management policies is needed to increase the resilience of the water supply system to negative shocks to some crucial vertix, that would otherwise propagate to a large number of nodes.

When looking at both SDA and Network analysis it turns out that the component 'international trade' is still marginal, while the technological components (H and γ) has ensured to save almost the 30% of water at global level. It means that the impact of a shock can be mitigated by a proportional improvement of water efficiency. This important feature has been captured by the combination of the two methodologies that, in isolation, cannot describe effectively both the systematic risks and the dynamic evolution of the VWT. The *duality* of trade is determined by the apparent minor role played, evidenced by the SDA, coupled with the potential risks related to the propagation of shocks in water supply, evidenced by Network analysis. In other words, there is still large room for reducing the water footprint by reallocating intermediate and final consumption towards more water-efficient countries. Such reallocation, however, would come at the cost of greater exposure to propagation of shocks in the supply of water from specific countries. This duality is particularly challenging for what concerns the negotiation of international trade agreements and of international agreements aimed at promoting water security and an efficient use of water. A reduction of trade barriers may help, in principle, in improving the allocation of production of water-intensive products in water-efficient countries. However, in absence of a pricing mechanism for water, especially in emerging countries, the incentive to promote an overall improvements in water efficiency through trade may be limited. Moreover, as highlighted in this analysis on the topology of the trade network, coordination mechanisms are needed in order to mitigate the risks related to the propagation of shocks to water supply. Finally, Community Detection gives further insights, to be integrated with the results given by SDA, unravelling the evolution of international trade of intermediate goods. Results reveal the presence of different kinds of communities, mostly between European countries or composed by single countries. However, geographical proximity is not enough to explain this phenomenon, as the presence of Canada in the European communities for blue water demonstrates. Current findings call for coordinated actions in favour of a wiser management of water scarcity through the development of transboundary agreements and policies both at global and regional level. The process of globalization should then be matched with a process of international cooperation because countries' actions are not confined to their territorial jurisdiction, but they might interfere, directly or indirectly, with the enjoyment of the right to (virtual) water in other countries. Currently, there is an imbalance between international trade agreements (under the WTO system) and international agreements on sustainable water use, being the former strong, detailed and binding, whereas the latter are weak, unsophisticated, and with low enforcement power. There is the need to widening of WTO rules on trade in virtual water such as allowing export bans on water intensive products on the basis of serious concerns over conservation of their domestic water resources or introducing tariffs that consider the amount of water that has been used to produce imported products. This approach may look similar to the one proposed to tackle the issue of carbon leakage in the context of climate change by means of so-called carbon tariffs. However, it may be difficult to implement it within the WTO rules (Moore, 2011) and it would require specific international negotiations. At European level the EU members have strengthen their relationships over the past decades. The Water Framework Directive (2000/60/EC) sets the objective of achieving the 'good ecological status' of all water bodies in the EU (surface as well as groundwater) by 2015 and the strong recommendation of full cost recovery for water services including environmental and resource costs. Nowadays, this system has changed through 'decoupling' payments to farmers from production and requiring environmentally-friendly nature protection actions from farmers for getting the payments. Moreover, the 2012 Blueprint to Safeguard

Europe's was an important, albeit partial, step towards an integrated and sustainable path of water management.

This Chapter offers a wide framework in which assessing the virtual water content across the life cycle of the products and the potential diffusion of negative shocks. BW is crucial to understand the effects of agricultural subsidies towards a more efficient water resources' management because, with increasing scarcity, the opportunity cost of choosing one use over another increases as well. Given the remarkable results form SDA, that is the high impact of product mix consumption, it might be suggested to implement a 'labelling scheme' to make the consumer aware about the water footprint of different products. It would represent a powerful channel to recompose the consumption bundle from high water intensive products (e.g. meat) toward less water charged (e.g. vegetables). A better understanding of the economic impact and feasibility is postponed to future researches, when more disaggregated data will be available.

This empirical analysis, while interesting on its own right, provides a new point of view in the development of models to forecast resource sustainability and to help the management of resources. Currently, the main hurdle to achieve an efficient use of water consists in reducing the gap between international trade agreements and international agreements on sustainable water use, because the former are strong and the latter weak.

Chapter 3

Are we in deep water? Water scarcity and its limits to economic growth

3.1 Introduction

Freshwater availability in sufficient quality and quantity is one of the major challenges that human societies will face this century. Freshwater, even though it represents only the 2.5% of Earth's water, is a vital resource that is threatened by human (economic) activities and climate change. Many studies have confirmed that the pressure on water resources will increase significantly over the coming decades and this will bring problems for food security and environmental sustainability (Alcamo et al., 2007, Ercin and Hoekstra, 2012, Hoekstra, 2014). Recently there has been growing interest in the use of scenarios for exploring the long-term relationships between complex socio-ecological and economic systems under uncertain conditions. Rosegrant et al. (2003) addressed three global water scenarios for the year 2025 for 69 river basins using three economic activities: Agriculture, Industry and Household consumption. They showed that in many regions poor irrigation management has markedly lowered groundwater tables, damaged soils, and reduced water quality. Alcamo et al. (2007) analyzed the change in blue water (surface and groundwater) withdrawals for two alternative trajectories for population and economic growth, based on the A2 and B2 IPCC scenarios, finding that the principal cause of increasing water stress is growing domestic water use stimulated by income growth. Rockstrom et al. (007a) had its focus on population growth and how to meet the longer-term millennium development goal (MDG) of hunger alleviation in 92 developing countries given projected water availability constraints. De Fraiture (2007) elaborated four possible alternatives scenarios for 115 countries in order to provide alternative strategies for meeting increasing demands of water and food in 2050. Energy production control, local actions and climate change are found to be crucial variables for a safe water management. Rothausen and Conway (2011) highlighted the relation between energy production and water management to understand and describe more effectively their role in greenhouse-gas emissions. Ercin and Hoekstra (2012) developed four water footprint scenarios for 2050 based on population and economic growth, production/trade patterns, consumption patterns and technological development. The main conclusion is that reducing humanity's water footprint to sustainable levels is possible even with increasing populations, provided that consumption patterns change.

The objective of the present study is to identify the main drivers of water pressure under climate change and to assess the social and economic effects, by country and sector, under four alternative narratives. I proceeded by using a multi-regional input-output model (MRIO) extended with water intensity coefficients, to calculate direct and indirect water use. Sectoral production functions and trade data are available for all major OECD countries, their major trading partners and a selection of large emerging economies. Application of input-output analysis to ecological footprints (EFs) is shifting from an ex-post static calculation toward an ex-ante scenario analysis for enhancing the policy relevance of EF analysis Ferng (2009). Previous studies were mostly based on greenhouse emissions, for example, Lutz and Wiebe (2012) estimated a times series of past UK consumption emissions (1993-2010) and future emissions (out to 2050) under five scenarios. They used a global MRIO with data on final demand, carbon intensity and trade balances. They found that under each scenario there were declining UK consumption-based emissions. Scott et al. (2013) applied a MRIO extended with carbon intensity coefficients to build a scenario of the global GINFORS model in line with the Copenhagen pledges for 2020 to calculate the distribution of future consumption-based carbon emissions around the globe using the Global Resource Accounting Model (GRAM). Finally, Dellink (2013) assess the effects of climate change impacts on economic growth through a dynamic global general equilibrium model.

The novelty introduced by the present study is given by the combination of two measures of water scarcity: social (water per capita) and physical (water availability). It goes beyond the previous global water demand scenario studies because I exploited a MRIO database to recover the whole supply-chain, both at national and global level, and to calculate the indirect impacts and feedback effects due to inter-industrial linkages. Departing from Ercin and Hoekstra (2012), I do not impose any relationship between trade variations, intermediate good exchanges and GDP growth; rather the dynamics of each of these factors is endogenously determined through the system of equations described below. I distinguished three categories of water: blue (ground and surface), green (rainfall) and grey (volume of water required to assimilate pollutants). This research is based on the comparison of four alternative economic-climate scenarios developed on the base on the most recent projections of GDP and population growth[1], up to 2100, it explicitly accounts for the variation of total renewable freshwater resources. This Chapter offers the possibility to ground a broad political debate for wise water governance, helping policy makers to understand the long-term consequences of different economic choices. In particular: (i) I take into account the

[1]See 'Supplementary note for the SSP data sets,' Edenhofer (2012) offers a full description of the assumptions and models used by the OECD to project GDP and population growth. Future GDP projections are conducted using an 'Augmented Solow growth model' using two sectors. The OECD model, ENV-Growth, places special emphasis on the drivers of GDP growth over the projection period rather than projecting convergence directly on income levels. The ENV-Growth model features additional input-specific factor productivity for labour and energy. See Appendix B.3 for a description.

heterogenous impact of climate change on precipitation (P), evapotranspiration (PET) and, thus, on renewable fresh-water resources, (ii) I report both social and physical water stress indeces, (iii) I assessed the sustainability, in terms of the virtual water required for production, and compare four GDP and population growth scenarios as provided by the IPCC, (iv) in case of unsustainable scenarios, I derived the technological progress required to meet economic growth projections, (v) I evaluated under which conditions international virtual water trade (VWT) redistributes water resources towards scarce countries, (vi) I disentangled and quantified the impact of social, economic and climate variables, and finally (vii) it is disaggregated the virtual water index into 35 major sectors.

The Chapter proceeds in Section 3.2 with a discussion on data sources, the indicators used and on the framework adopted for implementing the four scenarios. Section 3.3 describes the mathematical models and compares the main results for each scenario. Section 3.4 assesses the technological change required to meet economic growth projections given limited water endowments. The Chapter ends with a discussion on the main outcomes and implications for future water policies.

3.2 Data and Definitions

WIOD[2] contains data on 40 countries (EU, USA and other important developing countries, i.e. India, China and Brazil among others) and 35 sectors for each country. Sectoral water use, reported in WIOD, has been derived from the estimations provided by Mekonnen and Hoekstra (2010), FAOSTAT and EXIOPOL. The International Institute for Applied Systems Analysis (IIASA) and the National Center for Atmospheric Research (NCAR) provide data on the reference scenarios for each Shared Socioeconomic Pathway (SSP). GDP projections are computed by the teams from the Organisation for Economic Co-operation and Development(OECD). Data on future changes in precipitation (P), potential evapotranspiration (PET) and water availability (Wa) are taken from FAO

[2]World Input Output Database, http://www.wiod.org, last November 2013.

GAEZ[3].

Hoekstra et al. (2011) define different types of water based indicators used in this research. This preliminary step is required to frame the sustainability analysis and to determine when environmental water needs are excessively exploited. The *virtual* water (VW) content of a product is the whole amount of freshwater required for production, measured over the full production chain. The water footprint (WF) of a nation is equal to the use of domestic water resources, minus the virtual water export flows, plus the virtual water import flows. Green water (**GN**) indicates the consumptive use of rainwater stored in the topsoil and used for vegetative and agricultural purposes. Blue water (**B**) refers to the consumptive use of ground or surface water, while grey water (**GY**) represents water contamination and is measured as the volume of water required to assimilate pollutants caused by human activity. As a proxy for Water Availability (Wa), following Chapagain and Hoekstra (2007), I used Total Actual Renewable Water Resources[4]. It must be admitted here that the issue of analysing green water scarcity is largely unexplored mostly because there is no consensus on how to measure green availability. For a deeper discussion see Hoekstra et al. (2011), Chapagain and Hoekstra (2007) (pag.34) and Hoekstra and Chapagain (2011), which show the maximum theoretical yearly amount of water available to a country at a given moment. By including Wa in this analysis, I overcame a limitation of Ercin and Hoekstra (2012) who excluded countries' endowments. Due to the lack of consistent data, non-conventional sources of water are not included, although they account for separately to natural renewable water resources as they are considered as non-renewable sources. They include: the production of freshwater by desalination of brackish or saltwater (mostly for domestic purposes); the reuse of urban or industrial waste water (with or without treatment), which increases the overall effi-

[3]http://www.fao.org/nr/gaez/en/

[4]It is the sum of internal renewable water resources (IRWR) and external actual renewable water resources (ERWR), in particular it is computed as the sum of total renewable surface water and total renewable groundwater, less any overlapping. For more information see the FAO AQUASTAT website http://www.fao.org/nr/water/aquastat/main/index.stm.

ciency of fresh water (extracted from primary sources), mostly in agriculture, but increasingly in industrial and domestic sectors, and agricultural drainage water. Finally, groundwater bodies (deep aquifers) have a negligible rate of recharge and are therefore considered as non-renewable for the purposes of this analysis.

The issue of water scarcity (WS), which can be broadly understood as the lack of access to adequate water supply for human and environmental uses, is widely discussed in the literature. However no consensus on how it should be defined or measured has yet been achieved. One of the most commonly used measures of water scarcity is the Falkenmark indicator, that defines water scarcity in terms of the total renewable water resources that are available to the population of a region in any given year. In this context it is simply given as the ratio $\frac{Wa}{POP}$. However, this indicator has been criticised because it does not allow for alternative water uses nor minimising impacts through VWT. A range of alternative indicators for assessing the adequacy of a nation's water resources have been put forward.[5] Due to the complex relation between water resources and social needs, relying on a single indicator may give a misleading impression of water scarcity. For these reasons I ground this analysis over two interrelated dimensions: i) the amount of virtual water necessary to meet social consumption needs (WS^{SOC}), and ii) the physical constraints (WS^{P}) resulting from limited renewable freshwater endowments. In particular, I compute the actual virtual water scarcity per capita as:

$$WS^{SOC} = \frac{WF}{POP} \tag{3.1}$$

where WF is the water footprint of national consumption and POP stands for population size. This index is able to overcome the main shortcomings of the Falkenmark indicator because it accounts for alternative economic uses of water and the exploitation of external water resources through international VWT. WF returns the total footprint, that is the virtual water embedded in domestic consumption minus (plus) the net

[5] For an extensive discussion see Brown and Matlock (2011) and Ridoutt et al. (2009).

virtual water embedded in international exports (imports). The mathematical computation of WF, in a MRIO context, is provided in the next section. Based on the Falkenmark classification, the water conditions in an area can be categorized as: no stress ($WS^{SOC} > 1700$ m^3 per capita per year), stress ($1000 < WS^{SOC} < 1700m^3$), scarcity ($500 < WS^{SOC} < 1000$ m^3), and absolute scarcity ($WS^{SOC} < 500$ m^3). In addition, I calculate the direct pressure on renewable water resources[6] as the ratio between total domestic water consumption (necessary for domestic consumption and exports) and available renewable water.

$$WS^P = \frac{B + GN + GY}{W_a} \tag{3.2}$$

The numerator of Eq. 3.2 returns the sum of total domestic consumption within a country. B is mostly used for Agricultural and food (AFF) production (more than 50%) and Energy (40%), GN is exclusively used in the AFF sector, while GY is distributed among AFF (more than 65%) and other polluting sectors (Chemical, Pulp and Paper, Textile, Basic Metals and Fabricated Metal). Water intensity coefficients for each sector and water use category are kept constant, as given by WIOD, it is therefore not possible to assume that B, GN and GY water are perfectly substitutable. Indeed, GN water cannot be used for alternative purposes; B and GY water can be directed towards alternative uses, the latter once it has been recycled. The thresholds of water stress are provided by Smakhtin et al. (2005): Over-exploitation ($WS^P > 1$), High exploitation ($0.6 < WS^P < 1$), Moderate exploitation ($0.3 < WS^P < 0.6$) and no stress ($WS^P < 0.3$).
In general, projections of freshwater-related impacts caused by climate change are compared to historical conditions (initial conditions of the dynamic system) which, in this Chapter, are grounded on the ex-post analysis of Global Virtual Water distributions Distefano et al. (2014), topology Konar et al. (2012) and evolution Dalin et al. (2012). Table 4 resumes the values of the main variables in 2009 for the environmental factors and

[6]When data for Wa were not available (for Canada, Ireland and Taiwan), I used the percentage of total actual renewable freshwater resources withdrawn, expressed in percentage of the actual total renewable water resources, as provided by FAO AQUASTAT.

Table 4: Socio-ecological 'Initial Conditions' in 2009.

COUNTRY	GDP (Tr)	GDP per capita $	Population (M)	Wa (Km^3)	WS^P	W^{FALK}
BRA	1.97 (2.95%)	10090	195 (2.84%)	8647 (16.17%)	8.46 %	26.58
CAN	1.21 (1.80%)	35330	34 (0.50%)	2902 (5.43%)	9.61 %	51.02
CHN	9.10 (13.61%)	6880	1337 (19.43%)	2840 (5.31%)	59.47 %	1.27
IND	3.60 (5.38%)	2980	1205 (17.51%)	1911 (3.57%)	70.38 %	0.95
JAP	3.93 (5.87%)	30820	127 (1.85%)	430 (0.81%)	11.03 %	2.02
MEX	1.47 (2.19%)	12430	117 (1.71%)	461 (0.86 %)	32.11 %	2.35
RUS	2.01 (3.01%)	14100	142 (2.07%)	4508 (8.43 %)	12.06 %	19.01
TUR	0.90 (1.35%)	12540	72 (1.05%)	211 (0.40%)	59.31 %	1.76
USA	13.04 (19.52%)	42160	309 (4.49%)	3069 (5.74%)	38.46 %	5.95
EU27	13.31 (19.92%)	26500	502 (7.30%)	2055 (3.83%)	33.70 %	2.45

2010 for the socio-economic variables. Brazil, Russia, China, Canada and USA are the biggest countries in terms of Wa, however when economic and demographic factors are taken into account the rank changes drastically. China and India are facing water scarcity as measured by the Falkenmark indicator, confirming that water endowments are unevenly distributed, as well as income per capita. Furthermore China, India and Mexico are approaching over-exploitation of renewable freshwater availability. As it will be shown in the next section, rich arid countries will not suffer from water poverty as their high water supply costs are more than matched by their high ability to pay and/or to import goods and therefore virtual water. This information, neglected by the Falkenmark index, is encoded in the footprint indicator. Finally, I show that increasing water scarcity does impact significantly upon economic growth of both developing and developed, confirming that limited water resources is a global issue.

The simulations are based on the so called Shared Socioeconomic Pathway (SSPs), as described by Edenhofer (2012). Table 5 resumes the assumptions made about the speed of growth (or change) of the key drivers: GDP and population growth, urbanization, technological development, globalization, inequality and environmental sustainability as the main drivers. I run numerical simulations over four pre-defined SSPs. Under the assumptions given for each of the Representative Concentration Pathways (RCP), with respect to preindustrial conditions, global temperatures averaged in the period 2081-2100 are projected to likely exceed 1.5°C for RCP4.5, and are likely to exceed 2° for RCP6.0 and RCP8.5. SRES does not assume any policy to control climate change, unlike the RCP Scenarios. The radiative forcing of RCP2.6, which assumes strong mitigation action, yields a smaller temperature increase than any of the previous SRES scenarios and is not included in the current study. RCP4.5 (RCP8.5) and SRES B1 (A1FI) have similar radiative forcing at 2100, and comparable time evolution. RCP6.0 lies in between SRES B1 and SRES A1B; the radiative forcing of SRES A2 is lower than RCP8.5 throughout the 21st century, mainly due to a faster decline in the radiative effect of aerosols in RCP8.5 than SRES A2, but they converge to within 0.1 W m^{-2} at 2100.

Table 5: Trends of the main variables for each SSP.

SSP	GDP	POP	TECH	SUST	Δ°C	Title	RCP
1	M-H	L	H	H	1.7-3.2	*Sustainability*	4.5
2	M	M	H	M	1.8-3.4	*Middle of the Road*	4.5/6.0
3	L	H	L-M	M	2.4-4.4	*Fragmentation*	6.0/8.5
5	H	M	L-M	L	3.2-5.4	*Conventional*	8.5

The density of population in a given area, including the migration flows, is the basic factor which determines the intensity of water stress/scarcity in a particular region. Economic growth represents a double-edge sword since it might accelerate the development of more efficient technologies but, on the other hand, it likely damages the ecological systems through pollution and over-exploitation of the resources. International Trade influences patterns of (virtual) water use and scarcity, however the reverse does not always hold because water is generally underpriced (Hoekstra, 2010). Water scarcity appears to affect trade patterns only when absolute water shortage force water-scarce countries to import water-intensive products, because they simply cannot be produced domestically, potentially increasing water stress elsewhere Lenzen et al. (2013).

3.3 Simulating Input-Output Scenarios

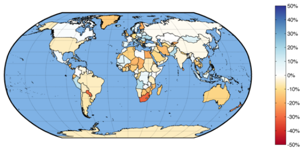
Each Scenario is built upon a different set of assumptions which determines and constrains the evolution of the key variables. IO analysis provides an appropriate and consistent mathematical structure for framing reasonable future scenarios through simple linear algebra computation. It offers a framework in which dealing with both feedback effects and industrial needs, where the latter factor is fundamental in assessing whether consumption patterns are grounded on sustainable industrial (and trade) structure. Because of the lack of data on sectoral growth, the structure of the matrix of technical coefficients (A) is kept fix,[7] while the possibility of its dynamic updating can be the subject of further research.

3.3.1 Model 1 - Population Growth and Climate Change

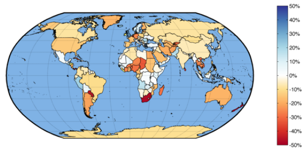
The baseline scenario is grounded on population growth and climate change in order to assess the evolution of the Falkenmark indicator over time (i.e. change in population and Wa). Figure 7 shows the amount of sustainable renewable water resources per capita in each period (5-year length) from 2010 to 2100, for selected countries of interest. The endowment of each country is limited to 60% of Wa in order to ensure, at most, a moderate exploitation of renewable freshwater, whilst leaving sufficient freshwater for environmental and ecosystem purposes. This simple representation neglects any economic effects which will be modelled next. The trend of population greatly differs within each country under different SSPs and between countries (see Table 20). Global warming is expected to modify Wa through changes in precipitation (P) and projected evapotranspiration (PET). Due to the unavailability of data on Wa projections under different RCP scenarios, I compute changes to Wa directly as percentage changes to the ratio of P/PET which are available

[7] Let Z be the square matrix of inter-industrial exchanges of intermediate goods and x the vector of total output, included final consumption, for each sector. I derive the matrix of technical coefficients as $A = Z \cdot \hat{x}^{-1}$, where the hat stands for diagonal matrix. Each entry a_{ij} returns the share of good produced by sector j in the total intermediate input use of firms in sector i, that is the percentage of trade of intermediate goods with the respect of total output of importer's production (per sector).

as RCP model outputs. The P/PET ratio can be treated as an index of aridity/humidity and thus represents changes in precipitation and the evaporation of surface water due to increased temperatures. Therefore the percentage change in Wa follows the same percentage changes in the ratio of precipitation and evapotranspiration over time for any given region or country.



(a)



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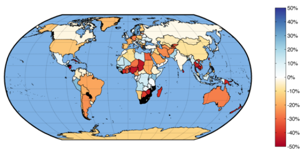
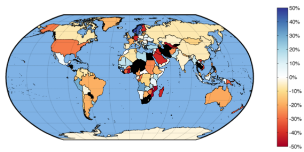


(c)



(d)

Figure 6: Global map of expected Wa variation due to climate change under SSP1 (a), SSP2 (b), SSP3 (c) and SSP5 (d). Red regions are expected to be drier while blue ones would be wetter.

Figure 7 shows the most critical developed (top) and developing (bottom)[8] countries that face water shortages due to population growth and change in Wa. Combining Figure 7 with Tables 20 and 21 is necessary to identify the origin of the projected variation of the Falkenmark indica-

[8]The definition of developing economies follows the International Monetary Fund's World Economic Outlook Report (2014) and World Bank data: High Income per capita (DEV): USA, JPN, ITA, CAN, AUS, GBR and ESP among others; Low-Medium Income per capita (LDC): CHN, IND, RUS, BRA, MEX, TUR and IDN among others.

tor. It sheds a light on how geographical and social conditions shape the amount of water available per capita.

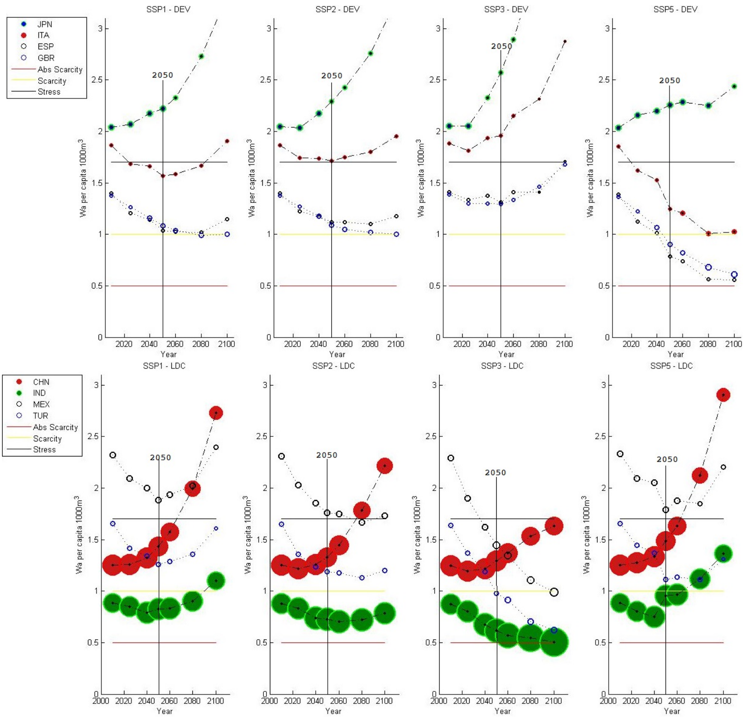


Figure 7: Social Water Scarcity under SSP1-2-3-5 for some of DEV (top) and LDC (bottom) countries, where the bubbles are proportional to the population size.

They report the results for the main critical (with an index close to or below the water stress level) countries, both developed and developing, which show heterogeneous paths. Japan is expected to have an increasing amount of Wa per capita under each scenario because the reduction of population size overwhelms the expected negative impact of climate change on Wa, with a peak of -33% over the period 2050-2080 (SSP3). Italy shows diverging and heterogeneous paths depending on the SSP being considered. Under SSP2 and SSP3 Italy remains above the water stress threshold because the reduction in Wa due to Climate Change is more than compensated by a contraction in the population size, which is particularly evident (-26%) over the period 2020-2050 (SSP3). Under SSP1 Italy is predicted to face a period of vulnerability due to the combined effect of increasing population size and decreasing Wa, waving around the water stress threshold. Spain and Great Britain follow a similar (negative) trend in each scenario, except for SSP3. In Spain the main problem is represented by water shortages (up to -18% over the period 2050-2080), while in UK there is a sharp increase in population (up to +32% over the period 2020-2050). As expected China and India are among the most impacted countries, however only China seems to overcome the WS threshold, over the long term (after the 2070s), due to a large predicted reduction in population size. In both countries the impact of climate change on water resources seems small, with both positive and negative impacts. Under SSP3 China might not be able, before the end of the century, to overcome the threshold of 1700 m^3 per capita because smaller reductions in the number of inhabitants are paired with a corresponding reduction in Wa. India continues to suffer water shortages mostly because the population continues to grow at a faster rate (with a maximum of +39% under SSP3) than Wa which is expected to increase (up to +30% under SSP5). The worst case is represented by SSP3 where the population is expected to grow up to 2.6 billion by 2100, and thus the Falkenmark drops below absolute scarcity levels (500 m^3 per capita). Mexico seems able to provide more than 1700 m^3 to its population under every scenario, except for SSP3 where it drops below the water scarcity threshold (1000 m^3) due to the joint effect of increasing population (up to +36%) and a reduction in Wa (up to -7%). Finally Turkey's social water scarcity index follows a U-shaped path between the water stress and scarcity thresholds under every SSP, with the exception of SSP3 in which it linearly decreases up to 623 m^3 per capita. Here again social dynamics are paired with physical constraints, even though Turkey seems more vulnerable to climate change effects (up to -18% of Wa under SSP5). To summarize, these preliminary results tell us that:

- physical conditions, though important, produce their effect on social water scarcity in the long-run;

- the distribution of water per capita is rather independent from the level of economic development because, in most scenarios, severe conditions would be faced also by advanced economies (e.g. UK and Spain);

- this oversimplified model simply replicates a modern version of the Malthusian problem with water resources. Though interesting because based on physical quantities, it has severe shortcomings in terms of policy relevance because it neglects the economic variables. It does not offer any insight about the kind of good that should be preferred (or avoided) nor what would be the possible saving impact of technological progress or the (re)distributive effects of international trade. These reasons lead me to offer an alternative framework to integrate the information provided by the Falkenmark indicator.

3.3.2 Model 2 - GDP growth and Water efficiency

The first oversimplified model was unable to capture the crucial role of economic factors on water exploitation. Model 2 includes the impact of GDP growth and technological improvement under the assumption of constant economic and trade structure. I assume that the global matrix of technical coefficients is kept constant over the modelling period. Note that structural changes (i.e. sectoral transitions) are not modelled, i.e. more industrialization or services at the expense of agriculture, that developing countries might follow when their incomes rise. By following Ercin and Hoekstra (2012), I assumed that the technological progress occurs directly through water intensity ratios (γ), that is the amount of direct water use per unit of sectoral output. However, this Chapter goes beyond the oversimplified assumption of a single and homogeneous industrial sector, rather, the technical coefficients are endogenously determined through the IO model. In this framework, different rates of technical progress for each country-sector pair and water category (B, GN and

GY) are taken into account.[9] In what follows, I described the system of equations that describes the dynamic evolution of the climate-economic system. Let GDP_t be the level of GDP at time t, the rate of growth from year t to t+1 is given by:

$$g_{t+1} = \frac{GDP_{t+1}}{GDP_t} - 1 \tag{3.3}$$

In a context of no structural change, the Leontief inverse is kept constant.[10] When updating countries' GDP, I used the matrix of final demand F, which includes domestic and international consumption, and matrix Z of IO trade.[11] Let $\text{g}_{i,t}$ be the GDP growth rate of country i from time t-1 to t and $\text{f}_{i,t}$ the vector of total final demand (row sum of F), then:

$$f_{i,t+1} = f_{i,t} \cdot \hat{g}_{i,t+1} \tag{3.5}$$

for i = 1,2,..,N where N is the number of countries. The new level of sectoral output (x_{t+1}) is computed through the Leontief inverse L and the new final demand as:

$$x_{t+1} = L \cdot f_{t+1} \tag{3.6}$$

Note that F is composed of both domestic and international trade in final goods, in particular each row returns the share of exports from each

[9] See the Appendix B.1 for a full description of the values and assumptions made.

[10] In order to be consistent with the data provided by IPCC, I select the table of the year 2010 which is the starting year of the population forecasts. The Leontief inverse is the matrix L which solves the system x = L·f, where it can be shown that L = $(\text{I-A})^{-1}$. See Miller and Blair (2009) for a detailed description of Input-Output Economics.

[11] There are at least two procedures to compute the GDP through IO tables. Let N countries with s sectors, then the first method is to compute the GDP as the sum of the Value added of each sector within the country. In the second method, by abstracting from the time variable t, we have that the GDP of country C as:

$$GDP_i^C = \sum_{i=1}^{s} (f_i^C + Z_{i.}^C - Z_{.i}^C) \tag{3.4}$$

where $\text{Z}_{i.}$ stands for the sum of row i, that is the value of domestic and exported intermediate goods, while $\text{Z}_{.i}$ stands for the sum of column i, that is the amount of domestic and imported intermediate goods. Their subtraction returns the net amount of export of intermediate goods of each sector i in country C. f_i is the vector of total final demand, per each sector i, in country C.

country-sector pair to each other country. This information enables to allocate the variation of final demand (Δf = f_{t+1} - f_t) using the distribution coefficients (φ) of final demand, for each country-sector pair, at the first year (2010). In particular, if one neglects the temporal dimension, in case of sector i:

$$\varphi_i = \frac{F_{i.}}{\sum_j^N F_{ij}} \tag{3.7}$$

where $F_{i.}$ is the vector of final demand (domestic + export) for sector i, and the denominator is the row sum of $F_{i.}$. In this case φ_C of country C is a matrix of 35x41, then for each country C, the new matrix of final demand, including domestic consumption and exports, independently from the population growth, as:

$$F_{C,t+1} = \hat{f}_{C,t+1} \cdot \varphi_C \tag{3.8}$$

The vector of water intensity coefficients γ_t accounts the amount of water per unit of production and it is updated at a constant rate ($\beta \leq 1$) as described in Appendix B.1.1: $\gamma_{t+1} = \gamma_t \cdot \beta$ in the case of no technological change ($\beta = 1$), otherwise one would observe a more efficient use of water if $\beta < 1$. The vector of sectoral water use, in each period, is:

$$w_{t+1} = \gamma_{t+1} \cdot x_{t+1} \tag{3.9}$$

The vector of households water use (WH) is led by the beta coefficient:

$$WH_{t+1} = WH_t \cdot (1 + \rho_{t+1}) \cdot \beta \tag{3.10}$$

where ρ is the rate of population growth. The net balance of virtual water trade which, given by Θ_{BAL} = Θ_{Exp} - Θ_{Imp}[12], is taken into account in order to trace the actual water scarcity of each country. The total water Footprint of national consumption (WF) is given by the sum of domestic use plus the water balance, for instance for country C:

$$WF^C_{t+1} = \gamma^C_{t+1} \cdot L^{CC}_{t+1} \cdot f^{CC}_{t+1} + WH^C_{t+1} - \Theta^C_{BAL} \tag{3.11}$$

[12]For a description see equations from 2.4 to 2.6, Ch. 1, pag. 19.

Note that the first member on the right hand side is driven by the GDP growth and water efficiency change, while WH is determined by the population growth and β. The last term provides the effect due to both heterogeneity in growth rate across countries and the structure of international trade. The aim is to estimate, for each period t, the physical water scarcity index (WS_t^p) which returns the degree of exploitation of renewable freshwater resources.

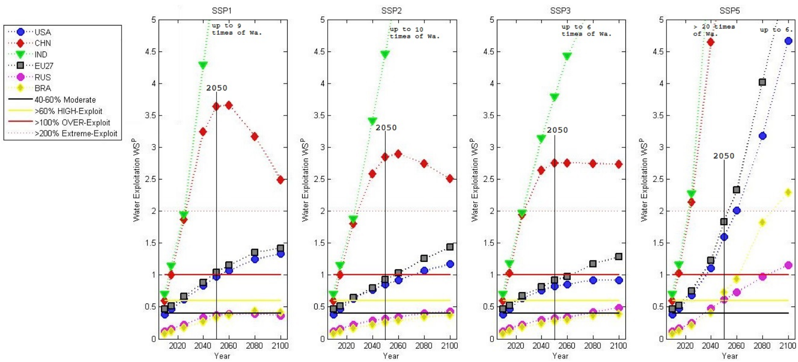


Figure 8: WS^P under different Scenarios, when it overcomes 1 it means that a country is using more than 100% of its Wa.

Figure 8 shows the results, under four different numerical simulations of WS_t^p, while Table 25 to 28 report the percentage changes in total (virtual) water use, for sectoral needs, due to both the technological progress (γ) and the economic growth. This study represents the first attempt isolating the impacts from each of the different socio-economic-ecological factors.[13] This sheds a light on the implications of alternative

[13]From equation 3.9 it is possible to disaggregate the variation of total water use (ΔW) through an additive polar structural decomposition analysis (SDA). For simplicity I compute it by making the difference from the last and the first year of the any sub-period considered (2020-2010, 2050-2020 and 2080-2050). Assuming L constant, it can be showed that:

$$\Delta W = w_{t+1} - w_t = \frac{1}{2} \cdot [\Delta\hat{\gamma} \cdot L \cdot (f_t + f_{t+1}) + (\hat{\gamma_t} + \hat{\gamma_{t+1}}) \cdot L \cdot \Delta f] \tag{3.12}$$

where the the hat stands for diagonal matrix. For a description of the method see Miller and Blair (2009).

water management strategies towards: investments in $R\&D$, economic growth, adjustments to water use per capita either through reductions in demand or reduced population growth rates.

In each scenario India and China overwhelm renewable freshwater resources by the year 2025 which is followed by an increasing, yet unsustainable, rate of economic growth. India will need more than 20 times its Wa by 2100 (SSP5) in order to satisfy its production needs. Overall, any saving on water, though substantial (up to -55% under SSP1), obtained through a reduction in water intensity coefficients (γ) is more than compensated by a growth in GDP. For China there are large variances between each of the different scenarios. Under SSP1 and SSP2 the impact of GDP is significant which peaks during the 2050s where production creates an additional +207% (SSP1) of water use with the respect to present day demand. In SSP3 and SSP5, where technological improvements are assumed smaller, the main difference is given by the rate of GDP growth which is higher under SSP5. In both countries the change in Wa due to climate change is negligible when compared with the impact of economic growth. USA and EU27 attain a very similar path, again, in each Scenario: 2050 represents a crucial year because the USA begins to over-exploit Wa and then it faces worsening environmental conditions. Under SSP5 the USA crosses the 100% threshold before the 2040s exceeding the extreme over-exploitation' threshold, that is 200% of Wa (Vorosmarty et al. (2000)). Finally, Russia and Brazil can cope with agro-industrial needs without crossing any stress threshold (60% of Wa = W^{ST}) due to their considerable Wa endowments. The main exception is SSP5 where, starting from 2050, they overcome W^{ST} up to the 97% and the 118% of Wa, respectively.

When economic variables are included, most countries face an (extreme) over-exploitation of Wa, confirming that water scarcity is an economic problem that both developed and developing countries must deal with in order to avoid considerable economic loss[14] and environmental damage. Before going ahead it is worth to clarify the meaning of over-exploitation in this context. When a country needs more than 100% of its own Wa it

[14]See the Appendix B.3.1 for an assessment of potential GDP losses.

still can afford the production needs through non-renewable water resources. I do not model the impact of over-exploitation, for several periods, on the quality of freshwater resources because there are no available data on the stock of non-renewable resources. What the simulations suggested is that the current (2010) global supply chain is not sustainable when renewable water resources are taken into account. It should be expected, and promoted with adequate policies, a reduction of γ worldwide and a modification in the composition of trade of intermediates (matrix A) and final goods toward less water intensive products. Water abundant countries may play an important role in providing additional resources to water scarce region, and the latter should invest in more R&D and in a redefinition of consumption habits.

Figure 9 confronts the share of virtual water use for B, GN and GY water between 2010 and 2100 for each of the main countries and sectors (see Table 22 and 23 of Appendix B.2). SSP1-2 and SSP3-5 are reported together because they share common assumptions over the pace of technological progress (γ). GN is the dominant category, even though it has a skewed distribution: Indonesia, Australia and Brazil show the highest percentages (more than 80%), while Sweden and Japan (less than 40%) are the smallest (also in absolute terms, 8 and 19 km^3, respectively). At a global level the largest GN water consumers are India, China, USA and Brazil (at least 588 km^3), both at the beginning and at the end of the century, across all scenarios. The highest values of B, both in 2010 and in 2100, are in Sweden (63%) and Japan (44%) mostly due to the Electricity, Gas and Water Supply sectors (EWG) that absorb more than the 87% of B. These values are stable over the whole period for each Scenario. Agriculture, Hunting, Forestry, Fishing with Food, Beverages and Tobacco sectors (AFF) are dominant, in terms of B water, in Spain, India and Turkey (more than 60%), while EWG in Italy covers the 69%. Though these percentages are stable in Japan and Sweden, there are some exceptions depending on the projected economic growth. Brazil, Spain, China, India and Italy, among others, have diverging trajectories and reach higher shares under SSP1, due to the AFF sectors, hence they should experience a structural change, shifting toward more energy-intensive technologies of production for SSP3, SSP4 and SSP5. At the global level most B water users are China, India, USA and Brazil (from 113 km^3 to 314 km^3) both at the beginning and at the end of the century, under each scenario. Finally the most GY water intensive countries over the whole century is China with a share of 32% and an absolute consumption of 537 km^3, confirming that China's rapid industrialization has led to a severe deterioration in water quality in the country's lakes and rivers (Ebenstein, 2012). The main followers at a global level include USA and India (more than 174 km^3); while in terms of the percentage of national water consumption GBR, USA and Italy (at least 14%) are the largest importers.

The sectoral composition is more complex due to the source of production and the level of industrialization, geographical location and natural resource endowments. AFF is dominant, though its quota changes substantially between countries. Spain, Indonesia, GBR and Australia show the highest quotas (more than 97%) for each narrative. However, there are other sectors that are heavy GY water consumers. MET (Basic and Fabricated Metal and Other Non-Metallic Mineral) requires 22% and 18% of total GY water in China and Japan, respectively. CH (Chemicals and Chemical Products) is also an important GY water consumer in Japan, Sweden and China (more than 13%). TXT (Textiles and Textile Products) has a significant impact in Italy (10%) whilst PAP (Pulp, Paper, Printing and Publishing) is significant in Japan, Canada and Russia (around 14%). These percentages are fairly stationary for each scenario over the whole century, but in China and Japan under each SSP there are higher percentages of GY water consumption attributed to MET and CH at the expense of AFF.

The role played by γ and international trade is evaluated in the next section. In this context of severe over-exploitation of Wa, the assessment of social water scarcity is meaningless because it would be grounded on an un-sustainable production. Since that the computation of water footprint is led by the sectoral output growth (x), through the water efficiency coefficient (γ), it would growth indefinitely if the rate of growth of x is higher than the saving of water through both technological progress and international trade. For these reasons, I simulate the social water

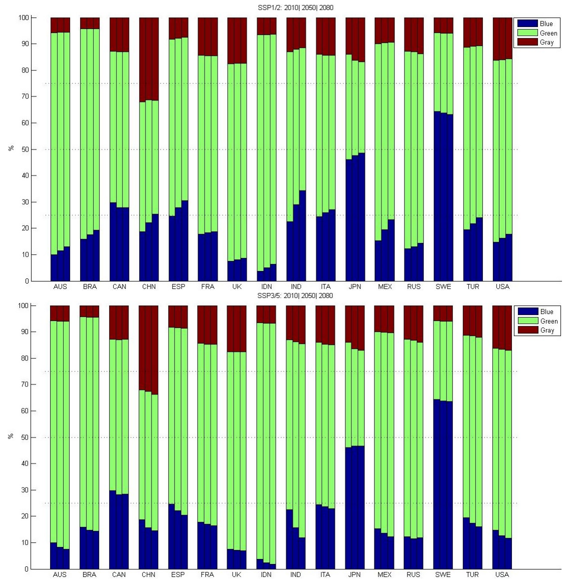


Figure 9: Shares of B, GN and GY virtual water use per country in 2010, 2050 and 2080.

scarcity only under a feasible (in terms of renewable freshwater constrains) industrial production.

In summary, the main results of this model are:

- the scope for productivity improvement and area expansion as assumed in Ercin and Hoekstra (2012) is not sufficient to sustain the energy and food needs given the current structure of intermediate and final goods trade;

- the issue of water scarcity is ubiquitous independently from the level of economic development, sectoral distribution and scenario, with the exception of Russia and Brazil;

- even though the model does not allow for non-renewable resources, the gap from the maximum theoretical value and the expected water industrial needs is so considerable, in particular in

China and India (more than 6 times of Wa), that seems implausible that can be filled by non-conventional sources of water. Even if one admits for this possibility, it would be assessed how long the ecological system can be pumped by its water stocks and how this process could affect the water cycle and then the climate (that might have a feedback effect on water cycle itself);

- economic variables (GDP, efficiency and trade) are able to affect over the short period the exploitation of Wa with the most remarkable effect in India and China expected around the year 2025.

Next Section is dedicated to assess under which conditions the current global supply chain is sustainable with the respect to renewable water resources.

3.4 Sustainability Assessment

Given the great, and increasingly, over-exploitation of available water in each scenario, I computed the technological development that would be necessary to obtain sustainable GDP growth, without having a detrimental impact on the environment, and on freshwater resources in particular. I elaborated a simple algorithm to update β so that technical progress does not remain constant over time. Appendix B.1.1 explains the algorithm applied to smoothly update γ though avoiding unrealistic technological "jumps". In fact it seems implausible that a country, with a fairly unsustainable technology, is able to fill the gap (that is using an amount of water no greater than 60% of its own Wa) in only one period (5 years-length). Gains in efficiency and productivity in water management and use can reduce the economic and environmental risks and enable higher levels of sustainable growth, but how much higher? How far-reaching do those gains have to be? Table 24 of Appendix B.2 compares the cumulative percentage reduction of γ with respect the base year (2010). Column 2 shows the historical change in gamma from 1995 to 2009 as provided by WIOD. Note that this change is a weighted average of the change in B, GN and GY, per unit of production that has occurred in each sector. Spain, GBR and USA experienced an increase of water use per unit of production, that led to a reduction in water efficiency. It might be surprising to see that water productivity has worsened in some countries, since improvements in cultivation and irrigation techniques should have improved efficiency. This reasoning is not readily applicable at the aggregate level, though, because I do not include production factors different from water and the output is measured in monetary terms. For instance, higher water usage could partly compensate lower productivity of other inputs, including non-market factors associated with changing climate conditions. Another possible explanation is that water is not priced effectively resulting in many countries not caring about water as a scarce limited resource, or finally, it might be that the structural change of economic production and trade has shifted some economies towards less water efficient sectors. However, as expected, the majority of large countries have reduced γ, ranging from less than -2% (Italy and Russia) to -5% (Brazil, Canada, GBR and Japan) and even more: India -12% while China, Australia, Mexico and Turkey with more than -20%.

From column 3 to column 6 I report the implied technological change coefficients for the main countries of Model 1. Technological improvements under SSP1 and SSP2 are larger because it is assumed there are water efficiency gains for each water based indicator, with an average variation that goes from -18% in 2050 to -36% in 2100. Notwithstanding similar assumptions, there are heterogeneous variations between countries with minimum values observed in Australia and Spain (less than -15% in 2050 and less than -30% in 2100) and maximum changes in the case of Brazil, China and Mexico (more than -22% in 2050 and more than -41% in 2100). These differences are due to increasing international linkages. In fact the impact of trade of intermediate goods and the structure of economic transactions shape, in a variety of ways, the environmental impact on water resources. The values under SSP3 and SSP5 are obtained under the assumption that only γ_B of the agricultural sector is becoming more efficient. Hence, the change in gamma is rather smaller than before, ranging from a minimum, in 2050, of less than -1% and in 2100 of less than -2% (Brazil and Canada), to a maximum, in 2050, of more than

-5% and in 2100 of more than -9% (Australia, India, Spain and Mexico). However, Figure 8 demonstrates that the pace of water efficiency gains are not sufficient to avoid a rapid over-exploitation of renewable water resources.

Before going ahead it is worth spending few words on an important issue that is strictly tied with technological progress and resource savings, that is the rebound effect. In literature is commonly defined as the combination of the direct effects caused by (energy) efficiency improvements that lower the implicit price of energy and the indirect effects of reducing (energy) costs, often leading to greater consumption. In this context, the assessment of its impact might be ambiguous because in most countries there is not a proper market for water and therefore it might not emerge any impact on price (that does not exist, unless one finds some shadow price). However, this does not mean that the rebound effect is irrelevant for water consumption, indeed it underlines that consumers behaviour is a crucial factor that must be paired with technological progress in order to reach a sustainable path. The elaboration of new database that provides information on the single product, rather than sectoral level, are encouraged in order to establish which bundle of goods would be preferred (or avoided), although the main challenge should be represented by the amount of data required when dealing with global IO systems.

The third section reports the change in γ necessary to follow a sustainable path, i.e. respecting the sustainability constraint water use must be less than 60% of Wa under different Climate Scenarios and precipitation shocks. The entries from column 7 to 14 are greater than before, confirming severe water shortages due to strong growth in GDP. Under SSP5, which represents the highest level of GDP, the change in gamma is particularly high. In each SSP scenario China, India and Turkey show an improvement in water use efficiency of more than 73% (87% in India) by 2050 to 91% by 2100. These values imply a promethean technological progresses in efficiency gains so vast and so rapid that their actual realization seems very improbable, especially when compared against historical trends. The more water abundant countries (Brazil, Russia and Canada) do not need almost any gain in water efficiency to keep the level of water exploitation under the threshold of 60% of Wa, with the exception of the most carbon-intensive Scenario (SSP5), where they need a change in gamma of -50%, -39% and -62% by 2100, for Brazil, Russia and Canada respectively. This means that it is crucial, for a rational and sustainable water management, to make precautionary initiatives as soon as possible (i.e. investment in water efficiency), even in those countries that are currently water abundant, because otherwise they are forced to make larger efforts over a shorter period.

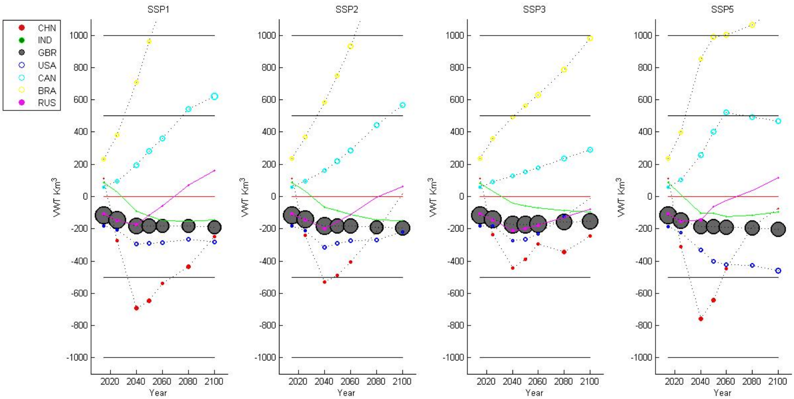


Figure 10: Virtual Water Trade Balance under each SSP for the main countries, where bubble size is proportional to the relative net exports/imports with the respect of domestic water use.

The impact of virtual water trade in the context of sustainable water exploitation will now be discussed. Figure 10 reports the trends, under each SSP, for net exports and imports of virtual water for the largest countries. Brazil and Canada become the main exporters of VW increasing above 1000 km^3 and 500 km^3, respectively, for all scenarios and with lower values for SSP3. More interesting is the paths attained by China, Great Britain and India which suffer social water stress. Each of them becomes a net importer of VW, in this way they can ameliorate the impact of water scarcity through global VWT. Great Britain imports 116 km^3 in 2015 rising to minimum of 154 (SSP3) and a maximum of 203 km^3 (SSP5) in 2100. India starts to be a net importer only after 2030s, reaching at most 148 km^3 (SSP2) in 2100, whilst China peaks in 2040 in each scenario and thereafter reduces the amount of VW imported keeping it at around 300 km^3 in 2100.

Surprisingly Russia, though it is a water abundant country with a modest level of water exploitation, appears to be a net importer in each scenario with a peak in the 2040s. Only after the 2070s it becomes a net exporter, with the exception of SSP3, but with total exports always remaining below 200 km^3 representing less than 5% of its own endowment. Results corroborate those observed in the literature that water endowment is not an explicative variable of VW. Finally the size of the bubbles (Figure 10) are proportional to net exports of VW and domestic water use, i.e. they represent the degree of water dependency on other countries, a large bubble shows it is highly dependent on VW while a small bubble shows it is relatively independent. GBR shows the biggest circles meaning that the role played by VW is crucial to ensure a sufficient amount of virtual water to its population. The possibility to save domestic water resources through virtual-water imports neglects that many water-scarce countries lack the ability to export energy, services or water-extensive industrial commodities in order to afford the import of water-intensive agricultural commodities. Moreover, import of food carries the risk of moving away from food self-sufficiency towards more urbanization Ercin and Hoekstra (2012). In addition, developing countries with large water endowments may not have the industrial capacity to export water-intensive products.

Table 6 reports the implied (virtual) water per capita under sustainable growth, led by a fast technological improvement. Technological progress and trade that allows all countries to overwhelm the WS^{SS} threshold by 2025 providing more than 2000 m^3 per capita per year, with increasing trends through the whole of the century. Only India seems able to escape from social water stress after the 2080s, notwithstanding a huge technological progress and increasing imports of VW, while under SSP3 the index decreases by 830 m^3 under social water scarcity threshold. In all the other cases the index fluctuates between WS^{SS} and WS^{SC}

with values ranging from a minimum of 1200 m^3 on 2025 to a maximum of 1992 m^3 per capita in 2100, slightly above the water stress index.

Table 6: Water Footprint per capita (1000 m^3), as a proxy of actual water scarcity, including the impact of Virtual Water Trade (net balance).

	SSP1			SSP2			SSP3			SSP5		
COUNTRY	**2025**	**2050**	**2080**	**2025**	**2050**	**2080**	**2025**	**2050**	**2080**	**2025**	**2050**	**2080**
CHN	2.19	2.80	2.53	2.10	2.49	3.23	2.05	2.33	1.70	2.24	2.88	2.62
IND	1.32	1.41	1.91	1.29	1.22	1.36	1.24	1.02	0.68	1.26	1.61	2.28
ESP	2.74	2.90	3.35	2.74	2.98	3.37	2.85	3.36	4.57	2.67	2.65	2.32
UK	2.65	3.13	3.06	2.63	3.10	3.11	2.67	3.38	4.10	2.65	2.88	2.11
ITA	2.59	2.88	3.37	2.58	3.01	3.38	2.60	3.29	4.38	2.60	2.77	2.66
JPN	2.67	3.50	4.90	2.64	3.40	4.87	2.67	3.61	5.96	2.71	3.51	4.23
MEX	2.28	2.35	3.21	2.21	2.16	2.51	2.12	1.81	1.45	2.28	2.74	3.84
TUR	3.25	3.48	4.37	3.13	3.23	3.47	3.10	2.73	1.93	3.32	3.27	3.84

3.4.1 Uncertainties and Limitations

This study, as any other attempt to assess the ecologic-economic sustainability through mathematical models, has uncertainties related to input data (WIOD, IPCC, FAO, OECD) and limitations due to the assumptions of the Leontief model used for numerical simulations. First of all, this Chapter deals with aggregate annual averages, therefore it is not possible to trace the variation in water supply within a single year (inter-annual variability) that determines the quality[15] of the water at disposal. As pointed out by Vorosmarty et al. (2000), blue water shortage is more appropriately expressed at pixel level rather than at country level, the former gives a more realistic relationship between the water resource and the actual accessible water for people. There are no data in Wa that identify the volume of water that is able to sustain ecosystems, nor does it account for the volumes of water that are potentially available from non-conventional sources (reuse, desalination, non-renewable groundwater). Currently blue water availability estimation neglects the spatial

[15]For instance if the total amount of GN is kept unchanged for two years but the concentration of the rainfall passes from a balanced distribution, toward a skewed distribution, then the latter may be an index of extreme events which may harm the economy, the environment and people

inaccessibility of blue water concentrated in a certain part of a country, this means that the current analysis exaggerates the Wa in two respects: that all blue water is available for use at its source and is spatially accessible from anywhere within the country. Future research should consider changes in infrastructure, installed water-storage capacity, cultivated land use, and irrigated area to include those adaptive measures that might play an important role in avoiding future risks. As noted by Alcamo et al. (2007), increasing water availability is a double-edge sword: it could have a positive influence by reducing river basin water stress, however an increase in water availability in one season may not be beneficial during that season, nor transferable to another season. Some impacts and risks from climate change have not been quantified in this study, including extreme weather events, damaging runoff events (due to an increase of the P/PET ratio) and large-scale disruptions. From the economic point of view, WIOD does not provide any information about African countries that are among the most critical regions in which an intensification of physical and social water scarcity is expected, therefore future research shall include those critical countries. Additionally, this study do not provide any insight about the consumer responsibility due to the higher level of aggregation of the IO tables adopted, so it is encouraged an effort towards the elaboration of consistent databases able to fill this gap.

From a methodological point of view in the literature there are several attempts to overcome the rigidity of the technical coefficients (A) either through the development of dynamic models (see Miller and Blair (2009)) or by the introduction of alternative techniques (i.e. RAS and Field of Influence). This step is crucial to provide an accurate description of the possible evolution of the economic structure conceived as the share of production of each sector. Lack of data and the complexity of the model involved forced us to keep constant the structure of matrix A. Finally any (very) long-term study comes with a set of difficulties which consist of intrinsic unpredictable events (e.g. historical or political), the introduction of new technologies or the discovery of new resources and the change in the preferences and consumption behaviour. Combining all these elements in a consistent and integrated modeling framework presents a substantial computational challenge but will ultimately result in persuasive and actionable insights for water (and ecological) risk management in the face of unescapable global change.

3.5 Conclusions

In this Chapter, I developed numerical simulations, for four different climate Scenarios (SSP), based on a dynamic MRIO model in order to assess the feasibility of OECD GDP growth forecasts, the social repercussions of limited fresh-water resources and the effects of climate change. This research shows that the factors that determine the sign and magnitude of water-stress response vary between major economic and developing regions, however, it shows that water scarcity is a global issue with serious potential to cause economic harm. It has been demonstrated that climate change alone seems to have a smaller impact than socio-economic drivers for most countries, except Turkey, Mexico and Brazil. Geographically, a number of salient results were found. In line with the latest report from MIT on global water stress (Schlosser, 2014), countries that are already experiencing water stress will be the most impacted in the future under the combined effects of socio-economic shifts and climate change. This is particularly true for India. The Falkenmark indicator can tell nothing about a countries ability to alleviate social water stress through virtual water trade. The use of I-O data allow us to trace different sources of virtual water consumption for each water category (B, GN and GY), economic sector and country.

Similar to Ercin and Hoekstra (2012) the impact of economic growth combined with technological progress is now simulated to assess the conditions under which a country should be concerned about physical water scarcity. China and India must deal with severe and imminent water shortage problems, as they are not able to pursue economic growth without over-exploiting natural water resources. The same holds for the most advanced economies, although this occurs later in time (around 2050), while only Russia, Japan and Brazil seem to be the less vulnerable. However, under the most carbon-intensive Scenario (SSP5) also these regions are impacted by environmental constraints. Hence, water constraints represent a physical limit to economic growth. A possible alternative to these pessimistic scenarios is to boost technological progress via investment in water efficiency (γ). India, China, USA and EU27 are expected to require promethean technological improvements, far greater than what historical trends suggest in order to avoid GDP losses. Another way to prevent this negative trend is to reduce overall demand by diminishing the amount of water that is wasted, modifying the consumption bundle towards less water-intensive products or slowing the rate of population growth. In accordance with the current literature, many water-stressed countries are mostly affected by socio-economic variables rather than directly from climate change. From the point of view of social water scarcity, it appears that trade is one of the more prominent ways of escaping water stress, with the only exception of India.

This Chapter represents the first study where the impact of each factor contributing to water stress is quantified through a structural decomposition analysis. I isolate and quantify the impact of each driver, showing that the most important driver of water scarcity is GDP growth which greatly overcomes any expected water saving due to technological progress. Population dynamics and variations in Wa, due to climate change, play a minor role in most of the countries under assessment, with the exception of India. Uncertain regional climate change can play a secondary role to either exacerbate or dampen the increase in water stress due to socio-economic growth. The strongest climate impacts on relative changes in water stress are seen in Brazil and Turkey, but strong impacts also occur over Europe. This information is crucial for the comparison of alternative policies which are used for investments in water efficiency, international trade agreements, population control measures and the promotion of economic growth. Another novelty introduced in this study is given by the computation of the sectoral impact. Due to heterogeneous production functions, there is no one best solution that can be applied universally; a global agreement on VWT should be paired with local initiatives. Depending on the context, some countries will find it more convenient to be more energy-intensive and to import food (Japan and Sweden) while other countries are already heavily dependent on foreign food (China and India among others) and thus they need to find the best combination from alternative virtual water uses. In particular, China and India need to clean up production processes, due to fast industrialization, to avoid the subtraction of a growing amount of water for food production. In those countries policies based on GY recycling and green technologies are fundamental to avoid extreme water exploitation and to ensure a better quality of water. This Chapter sheds light over the complex evolution of water-climate-economic systems, in particularly under severe water constraints. Though based on simple linear algebra, the IO model is able to ascertain non-linear trends in the main variables (VWT, social and physical water scarcity) suggesting that it is a useful tool to frame future environmental policies in order to manage scarce water resources in a complex and uncertain world. The outcomes of this study should be interpreted in an holistic general manner, considering the limitations and uncertainties associated with modelling future climate change trajectories.

Chapter 4

An Evolutionary approach to International Environmental Agreements

4.1 Introduction

Anthropogenic climate change is the biggest challenge that humans are facing, in order to avoid, or at least to restrain, the possible disasters that might occur in case of an increase of global temperature higher than 2 degrees, as described in the last Intergovernmental Panel on Climate Change report (see Edenhofer (2012)). The most important problem is related to transboundary pollution of greenhouse gas emissions. The formation and development of International Environmental Agreements (IEA) has been the subject of a fast growing branch of the economic literature over the past decade, in particular non-cooperative games go back to Hoel (1992), Carraro and Siniscalco (1993) and Barrett (1994). There are several important design issues that self-enforcing IEA have to address: despite the global benefits of reducing green-house gas discharges, no agent has any incentive to reduce her own burden, there is not any supranational force able to enforce any agreement, there is a temptation to free ride and a high level of asymmetry in historical responsibilities and in the (future and uncertain) benefits-costs distribution. At least this is the classical framework in which completely informed rational agents should operate. Yet the number of signatories of IEA is increasing and, at local level, many people are making efforts to reduce emissions and putting pressure on businesses and governments to do the same. Contrary to what observed historically, Barret (1994) shows, with a game with identical agents, that only a small number of coalitions are stable and that in general the number of signatories size is small (around three) when the difference in net benefits between the noncooperative and full cooperative outcomes is high. Actually, it seems that the size of the IEA coalition is a minor problem, since that the number of signatories has grown substantially in time (from 113 in Stockholm 1992 to 195 countries in the recent IEA held in Lima on December 2014). Other authors tried to explain this dichotomy by including asymmetries (Pavlova and de Zeeuw (2013) and McGinty (2005)), transfers (Colmer (2011) and Carraro et al. (2006)), moral concerns (Jeppesen and Andersen (Jeppesen and Andersen)), uncertainty (Kolstad (2007) and Heal and Kristrom (2002)) or by framing a dynamic (de Zeeuw (2008), Rubio and Ulph (2007) and Calvo and Rubio (2012)) or an evolutionary game (Courtois et al. (2004), McGinty (2010) and Vasconcelos et al. (2013)). The consensus is that any case of failure of the compliance of the IEA is due to a voluntary action to free ride. Though often almost all parties agree that something should be done to protect the global environment, a progressive increase in the yearly air pollution is observed, at global level, measured by the concentration of CO_2. However there is a great heterogeneity between countries in terms of the difference between international agreements and actual level of emissions, for instance some Kyoto participants are well above their target while others are well below.[1]

There is a general consensus that "no one country" can solve the global climate change problem Meserve (2008), neither waiting for a "single worldwide solution" appears less problematic. In addition to the prob-

[1] In particular, paired with the bad performances of USA, Canada and Australia, there are some successful examples of emission reductions with the respect to the Kyoto standards: Japan, France, Italy, Germany and UK among others (see Oliver et al. (2014)).

lem of waiting too much, "global solutions" negotiated at a global level, if not backed up by a variety of efforts at national, regional, and local levels, however, are not guaranteed to work well Ostrom (2009). That is, the first step of each country is to pursue domestic climate policies consistent with domestic pressures (Bodansky et al. (2004)), reinforced by an international agreement in line with the economic structure. The people most hurt by impacts may not have adequate representation at higher levels and may be unable to articulate clear solutions to reduce greenhouse gas emissions and help them adapt to the variety of threats they face Agrawal (2008). "Think Globally but Act Locally" hits right at a major dilemma facing all inhabitants of our globe.

This study aims to explain and simulate: i) under which economic conditions a country *fails* to respect the IEA or when it attains better results than expected, ii) the role played by consumers' *environmental awareness*, iii) under which conditions there is space for a country to implement *voluntary* actions. As the empirical evidence suggests, even those countries which did not sign past agreements (USA) or which were exonerate from emitting controls (developing countries), are implementing different kind of local policies to regulate and limit pollution. One of the most successful efforts made by many local governments across the United States has been to reduce the level of fine-particulate air pollution (which in some cases has reduced greenhouse gas emissions as well). Berkeley, California, has adopted a general policy to reduce emissions substantially over time. One of the programs is called Berkeley FIRST (Financing Initiative for Renewable and Solar Technology) and is designed to reduce the barrier of up-front costs. Other local-level efforts to overtly increase the level of alternative energy production or reduce the level of automobile use have been reported for many cities around the world including Sorsogon, Philippines; Esmeraldas, Ecuador; Maputo, Mozambique; and Kampala, Uganda, where efforts are supported by the Cities in Climate Change Initiative, funded by the government of Norway and the UN Development Account. Moreover also China and India, which were the most claimer against the proposal of the EU in the last meeting of Copenhagen on December 2013, have implemented serious national policy to

protect the environment. For instance India set up the National Solar Plan through which partially substitute the fossil energy with a cleaner one. Also China in the last five-year national plan has decided to allocate 800 billion of dollar to counteract the high level of pollution of some regions, such as Hebei, Shanxi and Shandong.
This Chapter follows the tradition of the literature that considers *uniform* emission reduction quotas. It differs from the previous literature in three respects. First, the analysis is not based on a stylized model where parties are modeled 'as if' they were individual rational agents, but I ground their action on their economic structure. Second, I offer a micro-foundation of the economic system with an Evolutionary Game where consumers and firms interact, determining the level of emissions for any given level of environmental standards fixed by the IEA. Finally, the complexity of the model limits the possibility to analytically derive every results, therefore the analysis is integrated with (parameterised) simulations, using a handy Maple algorithm, to determine the alternative evolutionary equilibria that each country reaches when IEA is enforced.
The Chapter is structured as follow: Section 4.2 shows the results from the evolutionary interaction between household and firms and the different regimes, in terms of equilibria, that characterize each country. Section 4.3 describes the 2x2 one-shot IEA game and the conditions under which countries find out convenient to coordinate their actions, while Section 4.4 presents the results from numerical simulations. Finally, Section 4.5 draws the conclusions and indicates the main policy implications.

4.2 GAME 1 - Evolutionary Micro-foundation

I assessed the evolutionary dynamics of production convection in a two-step procedure which integrates the results from two games (Γ_1 and Γ_2), the former at national-scale level and the latter at the global level (IEA). Γ_1 shows what it can be considered the dynamics of isolated economies in which, due to interior conditions, it is established a certain percentage (in terms of investment or as a quota of GDP) of "green" production. Let consider a normal-form (strategic) game with a player set composed by individuals that comprise $\Omega = \{\mathcal{H}, \mathcal{F}\}$ finite populations, namely households ($\mathcal{H}$) and firms ($\mathcal{F}$). Each population splits in clubs depending on the strategy $s = \{E, P\}$ agents play or the behavior that agents follow, that stand for *ecologic* (E) and *polluting* (P), respectively. The normal form representation of the Game is given by the next matrix payoff:

Table 7:
Normal form game Γ_1.

Players	$\mathcal{F}_E$	$\mathcal{F}_p$
$\mathcal{H}_E$	h_E , f_E	0 , 0
$\mathcal{H}_P$	0 , 0	h_P , f_P

The dynamic evolution of the fraction of each club i.e., given the complementarity of the two strategies {E, P}, is simply derivable from the evolution of the proportion of ecological households and firms, namely of α and β, according to the following replicators dynamics:

$$\dot{\alpha} = \alpha \cdot (1 - \alpha) \cdot [H_E - H_P] \tag{4.1}$$

$$\dot{\beta} = \beta \cdot (1 - \beta) \cdot [F_E - F_P] \tag{4.2}$$

where H_s and F_s are the expected fitness of choosing the $\mathcal{H}_s$ and $\mathcal{F}_s$ strategies respectively. In both cases the percentage of green players increases if the fit given by the green strategy is higher than what expected when the polluting strategy is played.[2] Let introduce the payoff structure for both players and strategies, the expected values and the evolutionary dynamics which characterize Game 1.

4.2.1 Households

The utility of a household h depends on his material payoff (h_s). Let assume that the consumption of the two goods gives the same level of

[2]Note that the payoffs out of the diagonal are always zeros because I assume that when people with different strategies are matched they do not sign any contract. To wit, the green consumers do not want to buy polluting goods and viceversa.

utility[3], yet the relationship between the environmental standards (θ), required to avoid health and social damages from polluting processes of production, and the share of firms operating under green production (β) shape the total payoff. In particular, the payoff of the green household is a piece-wise function defined as:

$$h_E = \begin{cases} u - c(\theta - \beta), & \text{if } \beta < \theta. \\ u, & \text{otherwise.} \end{cases} \tag{4.3}$$

where $u > 0$ is the constant level of utility from consumption. Households who decide to play the green strategy carry a monetary cost ($c > 0$) proportional to the difference between the environmental standard ($1 \geq \theta \geq 0$) and the share of the green firm ($1 \geq \beta \geq 0$). This additional cost represents the willingness to finance the ecological friendly production. I assume that in case of no environmental concerns – i.e. $\beta > \theta$ – the green household simply receives utility from consumption because it is expected no environmental concerns. There is a double interpretation of c: the first stands on the assumption that green consumers pay more because the good carries an extra-cost, imposed by the Government, in order to finance the green start-up, yet the model do not take into account the process of formation of prices nor the mechanism of redistribution of this extra payment. Secondly, from a broader perspective, I report, among the several real-case initiatives, that many green startups got off the ground using *crowd-funding* sites, such as 'FoodCycle', which recycles food waste into nutritious meals for those in need. However the potential gains from this kind of investments are not modelled. On the other hand, the polluter household plays the polluting strategy h_P and obtains the following payoff:

$$h_P = \begin{cases} u - \delta(\theta - \beta), & \text{if } \beta < \theta. \\ u, & \text{otherwise.} \end{cases} \tag{4.4}$$

where δ represents how much the consumer (and public opinion) perceives the possible damages from a polluting consumption, thus repre-

[3]In other words, green and polluted goods are perfect substitutes because both goods are able, through their material characteristics, to satisfy in the same manner the needs of consumers.

senting a (kind of) moral cost. Here $0 < \delta \leq 1$ is a parameter used as a proxy of the level of *environmental consciousness* prompt by public opinion and media. Given δ, the utility of h_P decreases inasmuch the environmental standards are not respected, i.e. when $\theta - \beta$ is high. Since that the utility from consumption is the same in both cases, households simply compare the monetary cost of being environmental friendly (c) with the moral cost (δ) of consuming polluting goods. It is simple to recover the fit of each strategy and assess whether households prefer the green or the polluting strategy. The expected payoff of choosing the green and the polluting strategy are $H_E = E(\mathcal{H}_E) = \beta h_E$ and $H_P = E(\mathcal{H}_P) = (1-\beta)h_P$ respectively. Households choose the green (polluting) strategy if and only if $H_E > H_P$ ($H_E < H_P$). Note that if $\beta = 0$ then $H_E > H_P$ if and only if $\theta > \theta_0 \equiv \frac{u}{\delta}$; while if $\beta = 1$, it always holds $H_E > H_P$. Therefore, in case $0 < \theta \leq \theta_0$ there is only one interception between H_E and H_P, given either by:

$$\beta_0^* \equiv \frac{1}{2}, \text{ if } 0 < \theta < \min\{\theta_0, \frac{1}{2}\} \tag{4.5}$$

or by

$$\beta_1^* \equiv \frac{\theta(c+\delta) + \delta + \sqrt{\Delta_\beta}}{2(c+\delta)} \text{ if } \frac{1}{2} < \theta < \theta_0, \tag{4.6}$$

where $\Delta_\beta = [\theta(c+\delta) + \delta - 2u]^2 - 4(c+\delta)(\delta\theta - u)$.[4] Note that if the environmental awareness is 'sufficiently low' (i.e. $\delta < u$), then there is a single interception between H_E and H_P for any value of $\theta \in [0,1]$. In case $\beta < \beta^*_{0,1}$, the expected payoff of the polluting strategy is greater than that of the green one, while if $\beta > \beta^*$ the reverse holds (see Figure 4.11(a)). When $\theta > \theta_0$, the two curves – H_E and H_P – can be either secant ($\Delta_\beta > 0$), tangent ($\Delta_\beta = 0$) or without any point in common ($\Delta_\beta < 0$) when the expected payoff of the green strategy is always greater than the polluting one. It holds that if $\delta \leq \frac{c^2+4u^2}{4u}$ the determinant is always positive, otherwise

$$\Delta_\beta \geq 0 \Longleftrightarrow \theta \leq \theta_1 \equiv \frac{\delta + 2u - 2\sqrt{(\delta - c)u}}{c+\delta}.$$

[4]From the last term of Δ_β, it is straightforward that $\theta < \theta_0$ is a sufficient condition for $\Delta_\beta > 0$.

When $\theta_0 < \theta \leq \theta_1$, H_E and H_P have two intersections: the first one is either β_0 or β_1, described above, while the second is given by:[5]

$$\beta_2^* = \frac{\theta(c+\delta) + \delta - \sqrt{\Delta_\beta}}{2(c+\delta)}. \tag{4.7}$$

In this case, for $0 \leq \beta < \beta_2^*$ and for $\beta_{0,1}^* < \beta \leq 1$ the expected payoff of the green strategy is greater than that of the polluting one, while for $\beta_2^* < \beta < \beta_{0,1}^*$ the reverse holds (see Figure 4.11(b)). Figure 4.11(c) shows a case in which there is no interception between the two expected payoff, i.e. $\theta > \theta_1$. In this case the green strategy is always preferred for any value of β.

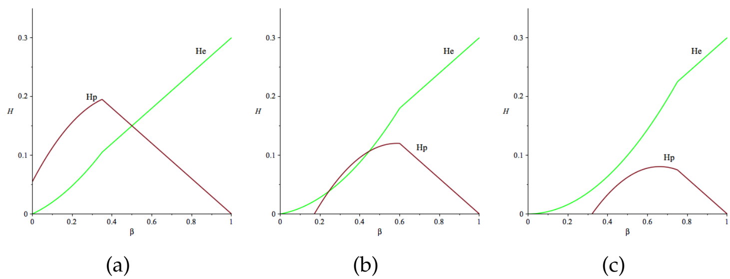


Figure 11: Examples of households equilibrium. Values of parameters: $\delta = 0.7$, $c = 0.4$, $u = 0.3$. (a) A single interception ($\theta = 0.35$), (b) Two interceptions ($\theta = 0.6$), (c) No interception ($\theta = 0.75$).

4.2.2 Firms

From the firm's side I assume that the green firms are characterized by the following payoff:

$$f_E = \begin{cases} \pi_E + \frac{c(\theta-\beta)\alpha}{\beta}, & \text{if } \beta < \theta, \\ \pi_E, & \text{otherwise.} \end{cases} \tag{4.8}$$

[5]More precisely, if $\theta_0 < \theta < \min\{1/2, \theta_1\}$, the solutions are β_1 and β_0, while if $\max\{\theta_0, 1/2\} < \theta < \min\{1, \theta_1\}$, the solutions are β_1 and β_2. This difference does not affect the qualitative dynamics.

where $\pi_E > 0$ is the profit from the green selling. Each green firm receives a subsidy which is equal to the total amount of extra-cost paid by each green household multiplied by the share of green consumers (α). This amount decreases as the share of green firms β approaches the environmental standards (θ). This is justified by the fact that the green technology is not yet developed to be as efficient as the polluting one and its impact is still marginal. An instructive example is provided by the last OECD report (2014) that confirms the tiny share (1%), by 2011, of renewable resources in the production of primary energy, while oil, gas and coal together cover more than four-fifths of the total amount (30.7%, 29.2% and 21.5%, respectively). Therefore, the public subsidy should help to boost the investment in new green startups to stimulate investments in green sectors. On the other side, the polluting firms are characterized by the following payoff:

$$f_P = \begin{cases} \pi_P - \frac{\gamma(\theta-\beta)}{1-\beta}, & \text{if } \beta < \theta, \\ \pi_P, & \text{otherwise.} \end{cases} \tag{4.9}$$

where $\pi_P > 0$ is the net profit that, in line with what stated above, is assumed to be greater than that of the non-polluting firms ($\pi_P > \pi_E$). They can be interpreted as an average profit proportional to the market share of the belonging sector. Moreover, $\frac{\gamma(\theta-\beta)}{1-\beta}$ is a *tax* function which depends on the relation between the actual level of green production (β), the ecological standards fixed by the government (θ) and a multiplicative factor (γ) which measures the monetary cost of the difference $\theta - \beta$. The total cost afforded by the F_P depends on the stringency of environmental policies and on the number of polluting firms. Since the polluting firms must jointly cover the cost of environmental damages, the total amount is determined by the percentage of polluting firms. Given the share of households which choose the green or the polluting strategy, firms find it convenient to choose the green (polluting) production if and only if the expected payoff of $\mathcal{F}_E$ is greater (lower) than the expected payoff of choosing $\mathcal{F}_P$. As before, let us define $F_E = E(\mathcal{F}_E) = \alpha f_E$ and $F_P = E(\mathcal{F}_P) = (1-\alpha) f_P$ the expected payoff of the green and the polluting production respectively.

The expected payoffs of firms depend on both α and β. Note that F_E is an increasing function of α, such that $F_E = 0$ when $\alpha = 0$ and $F_E > 0$ when[6] $\alpha = 1$. On the other hand, the expected payoff of the polluting strategy is linear in α, and it is decreasing in α if $\beta > \theta$. Instead, when $\beta < \theta$ the slope of the function F_P depends on the sign of $\pi_P - \frac{\gamma(\theta-\beta)}{1-\beta}$ which expresses the difference between the whole profits of polluting industries and the (monetary evaluation) of the environmental damages. Obviously when this last expression is negative, that is when $\beta < \bar{\beta} \equiv \frac{\gamma\theta-\pi_P}{\gamma-\pi_P}$, F_E is greater than F_P for any value of α.

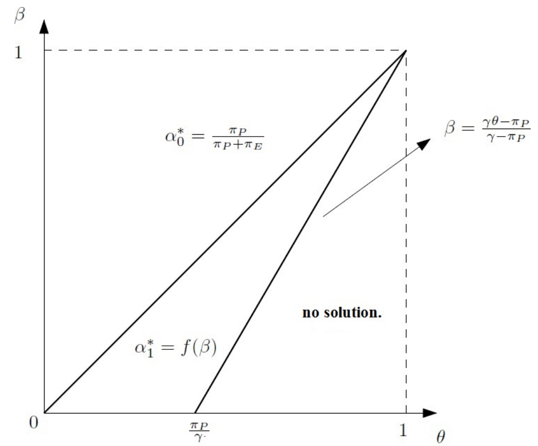


Figure 12: The interception between the expected payoff of green and polluting strategies in the plane $\{\theta, \beta\}$.

Figure 12 shows the resulting interceptions between F_E and F_P in the plane $\{\theta, \beta\}$. When $\beta > \theta$ there is an internal value of α (α_0^*), such that firms are indifferent between the two strategies, which does not depend on β. When instead $\bar{\beta} < \beta < \theta$, there is an internal value of α (α_1^*), such that $F_E = F_P$, but this value is an increasing function of β. Note that $\theta > \frac{\pi_P}{\gamma}$ is a necessary condition to induce at least one firm to deviate from the polluting convention – i.e. when $\alpha = 0$ and $\beta = 0$. More precisely the

[6] The value of F_E at $\alpha = 1$ depends on the relation between θ and β. If $\beta < \theta$ then $F_E = \pi_E + \frac{c(\theta-\beta)}{\beta}$, otherwise $F_E = \pi_E$.

two alternative solutions are:

$$\alpha_0^* = \frac{\pi_P}{\pi_P + \pi_E}, \tag{4.10}$$

$$\alpha_1^* = \frac{\beta[\gamma(\theta - \beta) - (\pi_P + \pi_E)(1 - \beta)] + \sqrt{\Delta_\alpha}}{2c[(\theta - \beta)(1 - \beta)]}. \tag{4.11}$$

where Δ_α is always positive.[7] These results, combined with those of the previous subsection, determine analytically the equilibria of the evolutionary game. In what follows I establish the conditions under which (*Regimes*) the dynamic system converges to an interior equilibrium and when it is (locally) stable.

4.2.3 Regimes

Households and firms change their behavior according to the replicator dynamics described by equations 4.1. Given the results above, depending on the value of θ I derive five *Regimes* (R_i) that qualitatively change the dynamic properties of the system.[8] For the sake of clearness, let assume that the economy is, as a starting point, in the polluting convention where $\beta = \alpha = 0$ and that the government establishes a certain level of environmental standard ($\theta > 0$).

R_1: When $0 \leq \theta < \min\{\frac{u}{\delta}, \frac{\pi_P}{\gamma}\}$, the isoclines and the phase diagram of the system are shown in Figure 4.13(a). In this case there is no interior (locally) stable equilibrium. The introduction of an environmental law ($\theta > 0$) is not sufficient to induce the system to detach from the polluting productive convention. The possible explanations of the failure of the policy (θ) could be: that consumers are not enough aware of the potential environmental damages they may suffer from contaminant goods and they thus weigh more the utility from consumption, or that the gain from dirty production are so high to more than compensate the covering of the

[7]Note that the other solution in α of $F_E = F_P$ is always negative. Moreover $\Delta_\alpha = \beta^2\{(1-\beta)[2\gamma(\pi_P + \pi_E)((\beta - \theta) + (\pi_P + \pi_E)(1-\beta)] + 4c(\pi_P - \gamma)(2\theta + \beta^2) + \gamma^2(\theta - \beta)^2\} + 4c\{\beta\pi_P(\beta^2(2+\theta) - (\theta + \beta)) + \gamma(\beta^2\theta^2 - \beta - 2\theta) - \theta^2\}$

[8]Figure 3 shows the phase diagram for each Regime. Note that the black circles indicate the (locally) stable equilibria and the dotted line the level of stringency of the environmental law (θ).

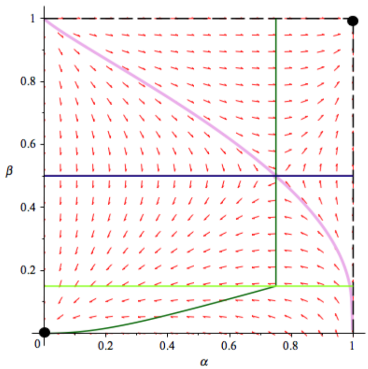
environmental costs. Note that given θ an increase in δ or γ may induce the system to depart from R_1 and to follow one of the other regimes.

R_2: When $\frac{\pi_P}{\gamma} < \theta < \frac{u}{\delta}$, the polluting convention becomes unstable because the environmental law is 'sufficiently high' to induce the start-up of new green firms, or the shift towards clean processes, as long as $\beta < \bar{\beta}$, that is the condition for which $F_E > F_P$. If $\bar{\beta} < \beta^*_{0,1}$, then all the trajectories departing from the polluting convention converge to the point with coordinate ($\alpha^* = 0$, $\beta^* = \bar{\beta}$). This is a corner solution (Figure 4.13(b)), where, in order to avoid the cost of polluting strategy, some firms find it convenient to choose the green technology even without any consumer. This result is odd, but it signals the imbalance between the high cost for polluting firms and the low awareness of households to environmental concerns. Given that $\beta^*_{0,1} \leq 1/2$, when $\gamma < \pi_P$ this case disappears because $\bar{\beta} > 1/2$. On the other hand if $\bar{\beta} > \beta^*_{0,1}$, as long as β increases, households find it convenient to choose the green production. This process ends up when $\alpha = \beta = 1$. Thus the only globally stable equilibrium is the green convention (see Figure 4.13(c)).

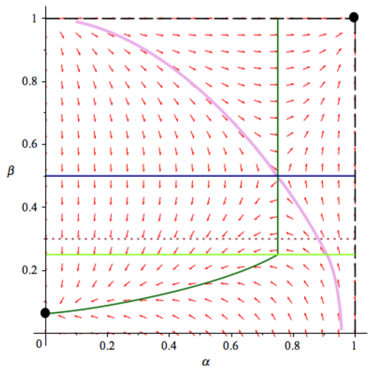
R_3: When $\frac{u}{\delta} < \theta < \frac{\pi_P}{\gamma}$, households find it convenient to choose the green strategy so that they induce the firms to supply more green goods and services. The dynamical system is characterized by two locally stable equilibria, an interior point ($\alpha^* > 0$, $\beta^* > 0$) and the clean convention ($\alpha^* = 1$, $\beta^* = 1$). In this case all the trajectories departing from the polluting convention join the interior equilibrium where $\beta^* \leq \theta$ (see Figure 4.13(d)), therefore the policy has only a partial effect and it is not wholly efficacious because θ is not strict enough to induce the expected share of firms to shift their production from the polluting convention. Its impact is indirect and simply stands on the stimulus from the demand side.

R_4: When $\max\{\frac{u}{\delta}, \frac{\pi_P}{\gamma}\} \leq \theta < \min\{\theta_1, 1\}$, households and firms find it convenient to choose the green strategy. The dynamical system is characterized by two locally stable equilibria, the interior and the green convention. In this regime all the trajectories departing from the polluting convention end up to the interior equilibrium where $\beta^* \leq \theta$ (see Figure 4.13(e)), accordingly the same considerations of the previous regime holds true here.

R_5: When $\theta_1 < \theta < 1$ the only globally stable equilibrium is the green convention (see Figure 4.13(f)) because the environmental law is sufficiently high to induce any agent to prefer the ecological strategy. Note that in this case the environmental standards have not to be necessarily strict to obtain the green transition, rather its success is strictly tied with the economic structure of the country. As it will be clear with the numerical simulation (Section 4.4) the role of firms and consumers is crucial. When the environmental consciousness is highly spread in the society and the industrial profits are close to those coming from clean production, then it is sufficient a (relatively) little stimulus from the Government. This result shows that the country should not simply impose an environmental law, rather it should put an effort to stimulate the citizens' responsibility because it might be a channel to save resource otherwise spent to recover the environmental damages.[9]



(a)



(b)

[9]Value of parameters of Figure 13 are: (a) $\delta = 0.7, c = 0.3, u = 0.35, \gamma = 1.1, \pi_E = 0.1, \pi_P = 0.3, \theta = 0.15$; (b) $\delta = 0.5, c = 0.5, u = 0.35, \gamma = 1.5, \pi_E = 0.1, \pi_P = 0.3, \theta = 0.6$; (c) $\delta = 0.5, c = 0.1, u = 0.15, \gamma = 1.5, \pi_E = 0.1, \pi_P = 0.3, \theta = 0.25$; d) $\delta = 0.5, c = 0.1, u = 0.15, \gamma = 1.5, \pi_E = 0.1, \pi_P = 0.6, \theta = 0.35$; (e) $\delta = 0.5, c = 0.1, u = 0.15, \gamma = 1.5, \pi_E = 0.1, \pi_P = 0.6, \theta = 0.45$; (f) $\delta = 0.5, c = 0.1, u = 0.15, \gamma = 1.5, \pi_E = 0.1, \pi_P = 0.6, \theta = 0.55$.

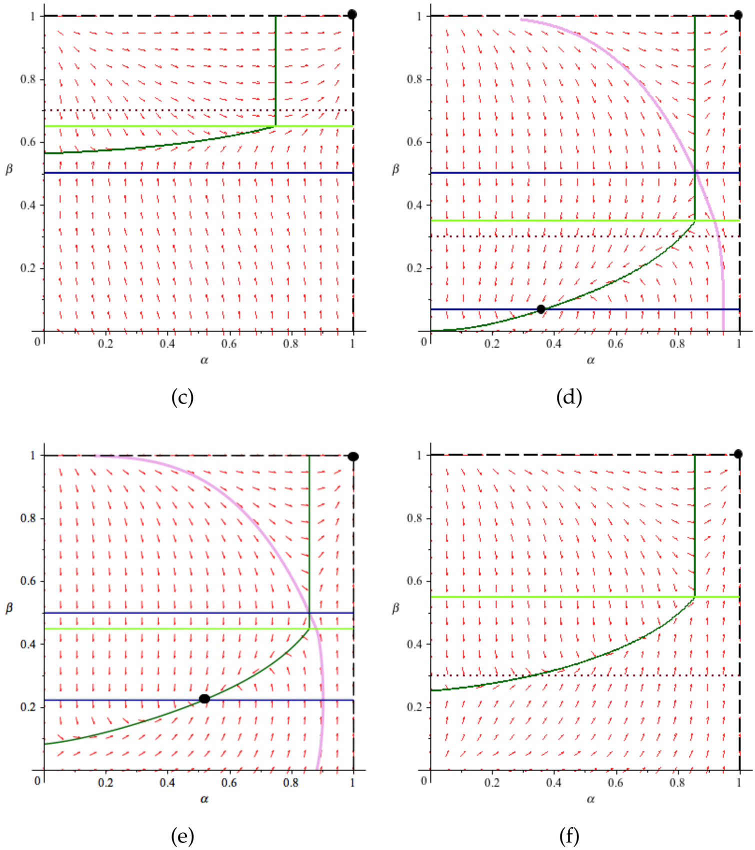


Figure 13: Phase diagram of the dynamical system in case of Regimes: R_1 (a), R_2 (b-c), R_3 (d), R_4 (e) and R_5 (f).

The red arrows show the directions of the trajectory. The isocline of the share of green firms (β) is given by the dark green curve. The isocline of the share of green households (α) is given by the horizontal dark blue line(s). The value of θ is the light green horizontal line. The dot horizontal line is the value of u/δ. The magenta curve shows the basin of attraction of the two convention if applicable.

4.3 *GAME 2 - IEA*

In designing the IEA game I follow the model of Endres and Finus (1999) with the needed extensions given the results of Γ_1. Assume two countries $i = \{N, S\}$ with a welfare objective function $W_i(\theta_i)$,[10] dependent on national θ_i, defined as the difference between the industrial profits $(\pi_{E,i} + \pi_{P,i})$, proxy for the benefits $\Pi_i(\theta_i)$, and the costs or damages due to the global pollution $D_i(\theta_i, \theta_{-i})$. The asymmetric nature of IEA implies that N and S must be two different groups, where N stands for Northern and richer countries, whilst S means Southern and poorer countries. For simplicity I model only the case with two countries, each one the leader or the representative of its group in order to define a bilateral treatise, as for instance the last agreement between USA and China held in November 2014. Let assume, as in Pavlova and de Zeeuw (2013), a one-to-one relationship between production and emission given by $\pi_{P,i}$ and quadratic profit and damage functions. Notice that in this model, given the evolutionary foundation of country's economic structure, it is not assumed that a country behaves as if it were an individual (given that it is not an homogeneous entity), in fact it may even fail to engage the treatise due to the economic structure rather than a deliberatively choice to free-ride. For these reasons each country, when involved in an IEA, bargains in order to define an uniform θ^*_{global}. Let us assume:

- 2 countries which decide *simultaneously*;
- *Single agreement* on θ^*_{global} based on the smallest common denominator (SCD)-rule which ensures *external stability*;[11]
- *"Good-faith"* commitment which ensures *internal stability*.

Each party agrees and decides simultaneously over a uniform international environmental standard (θ^*_{global}). Among the different bar-

[10] Note that, in line with the current literature, I do not include the households payoffs in the welfare function. From a mathematical point of view its exclusion simplifies the calculations without any significant loss in the meaning of the results. In fact, in equilibrium, the total welfare of the households does not depend on θ, therefore its value simply cancels out when I compute the first derivative.

[11] See Endres and Finus (1998) for the mathematical proof.

gaining process, the focus is on uniform solutions, it is assumed that governments already recognize the externality before negotiations start. Though often almost all parties agree that something should be done to protect the global environment, they disagree about the degree of emission reduction therefore negotiators claim for different clean production standards. Frequently, since international agreements are voluntary and governments do not have the same interests, a compromise is sought which only reflects the *Smallest Common Denominator* (SCD).[12] The SCD-decision rule implies that if $\theta_i < \theta_j$, then $\theta^*_{global} = \theta_i$. In an international bargaining context, one would expect that proposals are strategically motivated, however, as demonstrated in Endres and Finus (1998), the SCD-decision rule is immune to strategic offers. Furthermore, it is assumed that each country behaves "as if" it believes that it is actually able to respect the international treatise (*good-faith commitment*). This ensures the internal stability and, in this context, it is fundamental because the aim is to show a different source of IEA failure rather than free-riding. As noted by Chayes and Chayes (1991, p. 311):

> "International lawyers and others familiar with the operations of international treaties take for granted that most states comply with most of their treaty obligations most of the time. [...] Although there are some obvious exceptions where states have signed treaties without a serious intention to comply, ordinarily the decision is made in good faith, presumably after a process, however imperfect, that weighs the costs and benefits of compliance. [What this implies is that] states' behavior in entering into treaties suggests that they believe they are accepting significant constraints on future freedom of action to which they expect to adhere over a broad range of circumstances."

Where states do not comply with an agreement, the reason is often that states do not have the means to comply rather than that they do not have

[12] See Hoel (1992), Endres (1995), Endres and Finus (1998) and Finus (2001) for a theoretical explanation and empirical assessments.

the desire to comply. This reasoning is utterly consistent with the model developed below.
When the international environmental treatise is embodied in Γ_1, each country reaches an evolutionary equilibrium (α^*, β^*) dependent on both parameters' value and initial conditions, that are assumed unknown to the governments. This implies that it would be no more necessary to assume free-riding in order to have different performances ($\beta^* \neq \theta^*_{global}$) than what ratified during the IEA. Each country *i*={*N*,*S*} is characterized by the following welfare function:

$$W_i = \Pi_i - a_i \cdot D \tag{4.12}$$

and, in particular, the profit and damage function are defined as:

$$\Pi_i = b_i[d_i(\theta_i \cdot \pi_{E,i} + (1-\theta_i) \cdot \pi_{P,i}) - \frac{((1-\theta_i) \cdot \pi_{P,i})^2}{2}] \tag{4.13}$$

$$D = (\sum_{k=\{i,j\}} (1-\theta_k) \cdot \pi_k)^2 \tag{4.14}$$

where a, b, d ϵ (0,1) $\forall i, j \epsilon \{N, S\}$, with $i \neq j$, and $D(\theta_i, \theta_{-i})$ is a quadratic function of the global emissions, representing a proxy of the potential damages caused by extreme climate events. Π_i is composed by two components: the first one is the benefit deriving from production, which is reflected by an higher level of profit, and a second member which stands for the *local* environmental deterioration and health problems due to industrial discharges of polluting firms. In case a_i is null, each nation chooses the business-as-usual (BAU) solution given by θ_i^{BAU} that maximizes Π_i. Pavlova and Zeeuw (2013) interpret $0 \leq a_i \leq 1$ as the vulnerability to environmental damages, to wit the probability to incur in negative climate events with the consequent economic losses. In this model it is exogenous and might be interpreted as the result coming from a social debate in which are taken into account the opinion of the scientific community, the environmental consciousness of citizens (δ) and the pressure of public opinion.[13] It is shown that the success of the environ-

[13]This interpretation recalls the concept of extended-peer-community introduced by Futowicz and Ravetz in their core paper on Post-Normal Science. The interested reader is referred to Futowicz and Ravetz (1994).

mental policy depends on the preferences of consumers, the efficiency of green technology and on the level of environmental awareness spread in the society. The optimum share of emissions under the business-as-usual hypothesis is:

$$\theta_i^{BAU} = 1 - d_i \frac{(\pi_{P,i} - \pi_{E,i})}{\pi_{P,i}^2} \tag{4.15}$$

Notice that θ^{BAU} is always ϵ (0,1)[14] and that, given d and $\pi_{E,i}$, it increases with the respect of π_P because the government must fix more stringent environmental standards in order to compensate the local ecological damages. On the other hand, a rich country with $\pi_{P,i}$ high might still find convenient to fix stringent environmental standards if it has an advanced green technology, and then when $\pi_{E,i}$ is high as well. In fact in this case it would be an advantage to speed up the green transaction because it can yield high profits without hurting the environment, avoiding public expenditure to recover any possible environmental damage.

In contrast, if the global externality is recognized by each state ($a_i > 0$), then each country is affected by emissions emanating from its own and the foreign industry and there is the necessity to bargain in order to reach an agreement. The **uncoordinated** equilibrium is given by the max of equation 4.13 with the respect to θ_i (for each country), while the social optimum (SO) is computed over the sum of all the Welfare functions involved. Thus there is a difference between the non-cooperative (uncoordinated) equilibrium and the cooperative (coordinated) equilibrium. I am interested in an *endogenous* determination of abatement under different economic conditions, showing the importance of local actions and environmental consciousness. The chances that local actions and environmental organisations will have a major role in future IEAs seem to have improved recently. For instance several international environmental organizations, such as GreenPeace and WWF, have put pressure to governments in order to actively protect and preserve the ecological systems, and they also help public opinion to become more sensitive to the care of nature. Even a recent report of the World Bank (2015) explicitly recognizes the role played by local communities in the management of

[14] Obviously in case of negative values, the country opts for no environmental laws.

natural resources. The numerical simulations of Section 4.4 explain the role of local environmental consciousness for the success of IEA policies. If the global externality is recognized by both governments, each country maximise W_i, and it will propose:

$$\begin{aligned} \theta_i^{NC} &= K_i^{NC}\{\pi_{P,j}(b_j b_i + a_j b_i)[\pi_{P,i}^2 - d_i(\pi_{P,i} - \pi_{E,i})] + \\ &+ \pi_{P,i} a_i b_j [\pi_{P,i}\pi_{P,j} + d_j(\pi_{P,j} - \pi_{E,j})]\} \end{aligned} \tag{4.16}$$

where

$$K_i^{NC} = [\pi_{P,i}^2 \pi_{P,j} \cdot (b_j b_i + a_j b_i + a_i b_j)]^{-1} \tag{4.17}$$

with (j, i) = {N,S} and $j \neq i$. Given the high non linearity of the functions involved, it is not possible to establish a simple relationship between the optimal level of environmental standards and the parameters and variables involved. Section 4.4 shows the results from different numerical simulations which give fruitful insights, here the exposition is limited to two extreme cases which make the equation more tractable. I derived the conditions under which a country behaves as the bottleneck of the international agreement, to wit the country that defines the smallest common denominator. I compared the results under the hypothesis that countries differ only either in the marginal industrial benefits ($b_i \neq b_j$) or in the risk to suffer economic losses from climate change and global pollution ($a_i \neq a_j$). Let assume that both green and polluted profits of the former country follow the same proportion with respect to those of the second country, that is $\pi_{P,N} = m\pi_{P,S}$ and $\pi_{E,N} = m\pi_{E,S}$, with $m > 1$, and that the green profits are $\pi_E = n\pi_P$, with $n \in (0,1)$, in both country. Obviously N is reacher than S because $m > 1$, which is a measure of income and technological inequality. Furthermore, let assume that both countries have the same marginal benefits, $b_N = b_S = b$ and $d_N = d_S = d$, but **different climatic risks**: $a_N = \tilde{z} \cdot a_S$, with $\tilde{z} > 0$. Differences in a might be due to either different weights put to the environment, which can be related to the economic development of a region, or to the geographical location (e.g. Italy may suffer more from sea level rise than Russia). Country i will be the bottleneck (i.e. let $i = S$ and $\theta_N > \theta_S$, it results that $\theta^*_{global} = \theta_S$)

of the IEA game inasmuch as:

$$\tilde{z} > \bar{z}^{NC} \equiv 1 + \frac{b}{a_S}\frac{(1-m)}{(1+m)} \tag{4.18}$$

$$\lim_{m \to +\infty} \bar{z}^{NC} = 1 - \lambda_S \tag{4.19}$$

$$\tag{4.20}$$

where $\frac{b}{a_S} = \lambda_S > 0$ is the *benefit-risk ratio* of country *S* given by the benefit of local production and potential losses from global emissions. The threshold $\bar{z}^{NC}$ depends on both the income (and historical) inequality (*m*) and λ_S. Given that *N* is reacher than *S* then, independently from λ_S, if country *N* is more risky ($\tilde{z} > 1$) it would like to see a higher joint emission reduction, however the convention will be dictated by country *S* (i.e. $\theta^*_{global} = \theta_S$). The same result holds even when $\tilde{z} < 1$ under the assumption that $\lambda_S > 1$ and that the level of inequality is sufficiently high (*m* >>1). A typical example is given by China that is likely to suffer from extreme climate events (e.g. desertification) but is finding more convenient to develop further the industrial production and it is thus less concerned about emission reductions.

Let now consider the opposite case of equal climate damage, $a_N = a_S = a$ but **different opportunity costs** of abatement: $b_N = \hat{z} b_S$. In this case country *S* will determine the stringency of the IEA game inasmuch as:

$$\hat{z} < \bar{\bar{z}}^{NC} \equiv \frac{a \cdot (1+m)}{a(1+m) + b_S \cdot (1-m)} \tag{4.21}$$

$$\lim_{m \to +\infty} \bar{\bar{z}}^{NC} = \frac{1}{1 - \lambda_S} \tag{4.22}$$

where in this case $\lambda_S = \frac{b_S}{a}$. A richer country proposes an higher environmental convention inasmuch as it faces lower opportunity costs and the poorer country expects low benefit-risk ratio. Let assume that *N* has low opportunity costs ($\hat{z} < 1$) and that $\lambda_S < 1$, then $\theta_N > \theta_S$ always because the threshold is greater than 1, while in case $\lambda_S > 1$, and *m* 'sufficiently high', then $\bar{\bar{z}}^{NC} < 0$ and thus country *N* dictates the IEA because *S*, though poorer, faces a greater opportunity cost with respect to the same climate risk. Results confirm an inverse relation between opportunity costs and damage costs, furthermore I show that the level of inequality can lead to counterintuitive results where, for instance, a riskier country prefers a lower level of emission abatement.

The **coordinated** equilibrium, denoted by the superscript C, is based on the extended welfare function the social optimum that is obtained by maximising the sum of the welfare functions of the two countries:

$$\theta_i^C = K_i^C \cdot [\pi_{P,j}[(b_j b_i + a_j b_i + a_i b_i) \cdot (\pi_{P,i}^2 - d_i(\pi_{P,i} - \pi_{E,i})]+ \\ + \pi_{P,i}[(a_i b_j + a_j b_j)(\pi_{P,i}\pi_{P,j} + d_j(\pi_{P,j} - \pi_{E,j})]] \tag{4.23}$$

where

$$K_i^C = [\pi_{P,i} \cdot \pi_{P,j}(b_j b_i + a_j b_i + a_i b_j + a_i b_i + a_j b_j)]^{-1} \tag{4.24}$$

which follows the same structure of the uncoordinated equilibrium, but it includes the interaction effect of cost opportunity and climate risk within each country. Given the non-linearity of this solution, I apply the same comparative analysis, explained above, in order to establish under which conditions $\theta_N^C > \theta_S^C$ and when $\theta_i^C > \theta_i^{NC}$ for all $i = \{N, S\}$. Let assume again that both countries have the same marginal benefits, $b_N = b_S = b$ and $d_N = d_S = d$, but **different climatic risks**: $a_N = \tilde{z} a_S$, with $\tilde{z} > 0$. In this case country S will always be the bottleneck of the IEA game because $m > 1$. It means that, independently from the level of climate risk, the poorest country always dictates the IEA. A possible explanation is that, in a context of coordinated maximization, S knows that, even when it is more risky ($\tilde{z} < 1$), the same percentage of emission reduction after the IEA has the same opportunity cost in both countries, however in absolute values N will reduce more, since that the amount of its polluted production is greater. More interesting is the comparison between uncoordinated and coordinated values, which returns two thresholds ($0 < \zeta_i^C < 1 < \zeta_j^C$) which define the space where coordinated environmental standards are higher in both countries, that is:

$$\theta_i^C > \theta_i^{NC} \qquad if \qquad \tilde{z} > \zeta_i^C \tag{4.25}$$

$$\theta_j^C > \theta_j^{NC} \qquad if \qquad \tilde{z} < \zeta_j^C \tag{4.26}$$

$$\zeta_i^C \equiv \frac{1}{2}\frac{\sqrt{b^2 + 4a_i^2} - b}{a_i} \qquad < 1 \qquad always \tag{4.27}$$

$$\zeta_j^C \equiv \frac{\sqrt{a_i^2 + a_i b}}{a_i} \qquad > 1 \qquad always \tag{4.28}$$

Hence for $\tilde{z} \,\epsilon\, (\zeta_i^C, \zeta_j^C)$ both N and S find optimal to fix more stringent emission reductions under a coordination regime. Differently from the great bulk of literature, here coordinated actions are not necessary more environmental friendly, but their success depends on the level of inequality, in terms of potential economic losses due to climate change. Notice that the space for which coordination leads to curb more emissions increases with respect to λ_i, in fact $\frac{\partial \zeta_i^C}{\partial a_i} > 0$ and $\frac{\partial \zeta_i^C}{\partial b} < 0$, furthermore $\frac{\partial \zeta_j^C}{\partial a_i} < 0$ and $\frac{\partial \zeta_j^C}{\partial b} > 0$. On the other hand, in case of **different opportunity costs** of abatement ($b_N = \hat{z} \cdot b_S$) country S will be the bottleneck if:

$$\hat{z} < \frac{2a(1+m)}{2a(1+m) + b_i(1-m)} = \bar{\bar{z}}^C \tag{4.29}$$

$$\lim_{m \to +\infty} \bar{\bar{z}}_C = \frac{2}{2 - \lambda_S} \tag{4.30}$$

thus the same reasoning for uncoordinated equilibrium holds here, with the only exception is represented by the fact that now the benefit-risk ratio is halved because the aggregate welfare function is considered. Moreover, in this case, the coordinated equilibrium is always higher than the uncoordinated, in both countries, for each $\hat{z} > 0$.

In summary I have shown that when the economic framework, to wit consumers and firms's choices, is taken into account the structure of IEA becomes less trivial than what exposed in the great bulk of literature. In particular the relation between BAU, non-cooperative and coordinated action is determined by the degree of international (income and technological) inequality, by level of polluting profits and by the benefit-risk ratio. Their combination could lead to (apparently) counterintuitive results, that actually are able to grasp several real case phenomena. First of all, this Chapter established the conditions for which a poor and risky country is less concerned about environmental issues (e.g. China) because it focuses more on economic growth. Secondly, the coordination of action does not automatically imply more stringent international environmental standards, rather when the inequality is large and the expected loss from climate change is not too high in the bottleneck country, the bargaining process could lead to ratify a smaller θ_{global}. This is a possible explanation of the fact that, in the case of the Kyoto Protocol, for many developing countries (non-Annex I Parties) the compliance of the treatise was not mandatory.

4.4 Numerical Simulations with 2 asymmetric countries

For sake of simplicity I identify different kind of countries structured along two axes, representing two key dimensions: environmental consciousness (δ) and economic performance (π), which can be either high or low. Their combination reflects the North-South dichotomy between rich and poor countries but it adds the possibility to be green also in low-income regions (see Figure 14). In particular, I compare three different regimes of environmental consciousness depending on the level of δ (high, medium or low). Section 4.3 gives some insights in very simplified worlds where only one parameter was allowed to change, i.e. under a ceteris paribus framework it is showed the impact from climate change and the opportunity costs ought to the green transaction. Numerical simulations allow to elaborate several alternatives, with many parameters that vary at the same time, giving a range of possibilities which clarifies the relation between the stringency of IEA standards (θ^*) and the actual result (β^*) that each country should attain given its own economic structure.[15] For simplicity, let assume that γ = 1 always, that the Rich country

[15] I run numerical simulations with Maple, the codes are disposable under request.

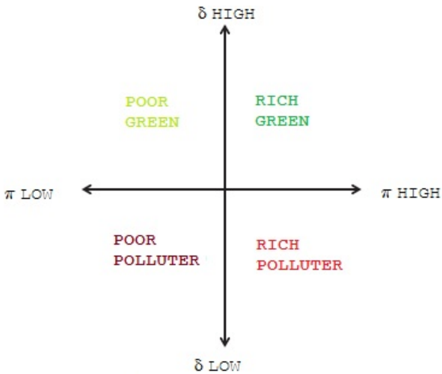


Figure 14: The four categories of countries in this study.

N is characterized by $\pi_{P,N}$ = 0.60 and $\pi_{E,N}$ = 0.20 and that the level of inequality is m = 2 such that industries of country S generate the half of the profits: $\pi_{P,S}$ = 0.30 and $\pi_{E,S}$ = 0.10. Moreover, the cost that each green household faces are kept constant, that is c = 0.50 (medium level) and the utility from consumption at u = 0.10. This framework allows a simple assessment of the relative impact of the environmental consciousness by setting the level of δ to: high (0.90), medium (0.50) or low (0.3). The other parameters, $\{a, b, d\}_i$ for each country i, vary in order to define four alternative scenarios:

1. *High Cost-Risk in Southern country (HS)*: $a_S > a_N$, $b_S > b_N$ and $d_S = d_N$ so that $\{0.40, 0.80, 0.45\}_S$ and $\{0.20, 0.40, 0.45\}_N$;
2. *High Cost-Risk in Northern country (HN)*: $a_S < a_N$, $b_S < b_N$ and $d_S = d_N$ so that $\{0.20, 0.60, 0.45\}_S$ and $\{0.45, 0.90, 0.45\}_N$;
3. *Asymmetric Cost-Risk distribution (AS)*: $a_S > a_N$, $b_S < b_N$ and $d_S < d_N$ so that $\{0.60, 0.20, 0.45\}_S$ and $\{0.20, 0.60, 0.75\}_N$;
4. *Extreme Asymmetry (EX)*: $a_S >> a_N$, $b_S << b_N$ and $d_S < d_N$ so that $\{0.90, 0.10, 0.45\}_S$ and $\{0.10, 0.90, 0.75\}_N$.

Each scenario returns the level of expected welfare $W_i^*(\theta^*_{global})$, under the 'good-faith' commitment assumption (as if each country is able to attain the IEA standards θ^*_{global}) and following the SCD-rule in which, in case of different proposals, countries agree to ratify the less stringent environmental standard. Moreover, I computed the actual welfare $\hat{W}_i(\beta^*_i)$[16] which depends on the actual quota of green firms (β^*_i), the expected (G^*_i = (1 - θ^*_{global})$\cdot\pi_P$) and actual level (determined by the fraction of polluting firms, i.e. $\hat{G}_i$ = (1 - β^*)$\cdot\pi_P$) of greenhouse gas emissions and the interior equilibrium in each country (α^*_i, β^*_i). Finally, I compared the result from an hypothetical 2x2 static game (Tables 8- 9) in which both countries have dichotomic strategies: polluting (θ = 0) or being environmental friendly (θ = 1). There are four different outcomes: $W^{00}_i = b_i(d_i\pi_{P,i} - \frac{\pi^2_{P,i}}{2}) - \frac{a_i(\pi_{P,i}+\pi_{P,j})^2}{2}$ in case both countries neglect environmental issues, $W^{11}_i = b_i d_i \pi_{E,i}$ when they decide to get rid of any polluting production process, $W^{10}_i = b_i d_i \pi_{E,i} - \frac{a_i\pi^2_{P,j}}{2}$ when country j pollutes and i acts unilaterally to green up the production while the reverse holds for $W^{01}_i = b_i(d_i\pi_{P,i} - \frac{\pi^2_{P,i}}{2}) - \frac{a_i(\pi_{P,i})^2}{2}$. The results from the following normal form game give further insights on which country has more convenience in being the bottleneck of the IEA.

Table 8:
Case 1 (left) and Case 2 (right).

Players	S^{HS}_E	S^{HS}_P	S^{HP}_E	S^{HP}_P
N_E	(0.036, 0.036)	**(0.027, 0.054)**	(0.081, 0.027)	**(0.06, 0.045)**
N_P	(0.00, -0.036)	(-0.045, -0.09)	(0.00, -0.009)	(-0.101, -0.27)

Case 1 and 2 have only one Nash Equilibrium (bolded) in pure strategy in which S it finds convenient to pollute while N acts *unilaterally* to abolish fossil fuels and any other polluting source. Case 3 and 4 present the specular equilibrium where N opts for dirty productions while S is environmental friendly. In any case, who finds optimal to choose the strategy θ = 1 receives the greatest payoff. These simple games are worth because, depending on the Nash equilibrium, they predict who will be the

[16] In order to compute the actual welfare it is assumed that even when country i does not attain the IEA ($\beta^*_i \neq \theta^*_{global}$), the other one does.

Table 9:
Case 3 (left) and Case 4 (right).

Players	S_E^{AS}	S_P^{AS}	S_E^{EX}	S_P^{EX}
N_E	(0.09, 0.009)	(0.081, -0.009)	(0.135, 0.005)	(0.13, -0.031)
N_P	**(0.126, -0.099)**	(0.081, -0.225)	**(0.225, -0.157)**	(0.202, -0.355)

Note: The subscript E stands for ecological strategy ($\theta = 1$), while P stands for polluting actions ($\theta = 0$).

bottleneck of the IEA game when θ is allowed to get any value in the continuum $\Re$ within the interval [0,1], in fact the polluter in any of the above Nash Equilibria is who dictates the IEA. However, when the decision is not discrete both countries find convenient, in the examples below, to set up green environmental standards, such that θ^*_{global} >0.

4.4.1 Case 1

In the first scenario S faces a medium risk, higher than that of N, to incur in damages due to global pollution and even higher opportunity cost. Under the BAU hypothesis, given this structure, S finds convenient to not impose any environmental restrictions while N would have an incentive to halved its polluting production. When environmental externality is recognized, both countries are involved in international agreement and, differently from what expected, they agree for more stringent policies under the NC framework. Given the SCD-rule the bottleneck (bolded) is the poor country that, notwithstanding the peril of environmental damages, does not want to curb excessively its economic growth. Under coordinated actions S is again the bottleneck, thought it fixes a slightly lower percentage of green production ($\theta_S^{*NC} > \theta_S^{*C}$). Note that here, and in the subsequent examples, the expected payoff is always greater under the most stringent environmental standard. When θ^*_{global} is embodied in Γ_1 it becomes evident the crucial role played by the level of *environmental consciousness* (δ): only when it is *high*, keeping constant the other parameters, both countries are able to precisely respect the treatise under the non-cooperative framework, while if they had coordinated their action they would attain a quota of green firms slightly below what ratified. In each Case I obtain that $\beta^*_N = \beta^*_S$ and that $\alpha^*_N \geq \alpha^*_S$. The reason is rather simple: the fraction of green firms is the same because in each (sub-)scenario, dependent on δ, the value of the parameters (c, u, δ, θ), which determine β^*, are the same in both country.

Table 10:
High Cost-Risk in Southern country.

		BAU (*a* = 0)		NON-COOP		COORD	
Scenario	*Outcome*	**N**	**S**	**N**	**S**	**N**	**S**
	θ^*	*0.50*	*0.00*	*0.75*	**<u>0.50</u>**	*0.96*	**<u>0.46</u>**
'Good-Faith'	W*	0.054	0.072	<u>0.034</u>	<u>0.023</u>	0.030	0.017
	G*	0.30	0.30	0.30	0.15	0.320	0.161
	α^*	0.75	0.00	0.75	0.75	0.67	0.59
δ HIGH	β^*	**0.50**	*0.00*	**0.50**	**0.50**	*0.404*	*0.404*
	$\hat{W}$	*0.054*	0.072	<u>0.034</u>	<u>0.023</u>	0.026	0.016
	$\hat{G}$	0.30	0.30	0.30	0.15	0.36	0.18
	α^*	0.47	0.00	0.47	0.10	0.47	0.15
δ MEDIUM	β^*	*0.30*	*0.00*	*0.30*	*0.30*	*0.26*	*0.26*
	$\hat{W}$	0.051	0.072	<u>0.019</u>	<u>0.017</u>	0.013	0.015
	$\hat{G}$	0.42	0.30	0.42	0.21	0.44	0.22
	α^*	0.23	0.00	0.23	0.00	0.24	0.00
δ LOW	β^*	*0.125*	*0.00*	*0.125*	*0.125*	*0.098*	*0.098*
	$\hat{W}$	0.044	0.072	<u>0.001</u>	<u>0.008</u>	-0.007	0.001
	$\hat{G}$	0.52	0.30	0.52	0.26	0.54	0.27

On the other hand, the fraction of green consumers, that makes the firms indifferent, is bigger in the richer country because, even thought the ratio (n) between polluting and green profits is the same in both countries, the absolute difference $\pi_P - \pi_E$ is greater in this region. More green consumers is thus required to make the polluted firms, in the rich region, indifferent.

4.4.2 Case 2

$\forall i$={N,S}, the parameters d_i, $\pi_{P,i}$ and $\pi_{E,i}$ are the same as in Case 1 then, based on equation 4.15, under the BAU hypothesis the results of Case 1 hold here, where S is again the bottleneck in the NC framework. Case 2 is in line with the great bulk of literature since that the Social Optimum requires more stringent environmental standards ($\theta_N^{*C} > \theta_S^{*NC}$), that yield lower emissions and higher welfare. If both countries have ratified θ_N^{*C} they would attain a complete green transaction with only green firms and consumers, to wit they obtain environmental performances better than what ratified independently from the level of environmental consciousness.

Table 11:
High Cost-Risk in Northern country.

Scenario	*Outcome*	BAU (*a* = 0) N	BAU (*a* = 0) S	NON-COOP N	NON-COOP S	COORD N	COORD S
	θ^*	*0.50*	*0.00*	*0.77*	**0.36**	**0.75**	*0.77*
'Good-Faith'	W*	0.121	0.072	0.044	0.017	0.10	0.033
	G*	0.30	0.30	0.382	0.19	0.146	0.072
	α^*	0.75	0.00	0.62	0.50	1.00	1.00
δ HIGH	β^*	**0.50**	*0.00*	*0.275*	*0.275*	**1.00**	**1.00**
	$\hat{W}$	0.121	0.054	0.025	0.016	0.079	0.024
	$\hat{G}$	0.30	0.30	0.38	0.19	0.00	0.00
	α^*	0.47	0.00	0.43	0.21	1.00	1.00
δ MEDIUM	β^*	*0.30*	*0.00*	*0.163*	*0.163*	**1.00**	**1.00**
	$\hat{W}$	0.115	0.054	-0.005	0.013	0.079	0.024
	$\hat{G}$	0.42	0.30	0.50	0.25	0.00	0.00
	α^*	0.23	0.00	0.01	0.00	1.00	1.00
δ LOW	β^*	*0.125*	*0.00*	*0.023*	*0.023*	**1.00**	**1.00**
	$\hat{W}$	0.099	0.054	0.05	0.008	0.079	0.024
	$\hat{G}$	0.52	0.30	0.59	0.295	0.00	0.00

The latter does not play any role because, in this Case, $\theta_N^{*C} > \theta_1$ which is the threshold upon which the system converges to the 'green-green' equilibrium (see Regime 4.13(f)). Notice that in column 5-6 the welfare associated with $\alpha_i^* = \beta_i^*$ = 1 is lower than that of Table 11 because each country assumes that the other fits the IEA standard (that is lower than 1). δ plays a crucial role only under the NC framework, in fact when it is *low* both countries reaches an interior equilibrium close to (0,0) where the emissions are maximum. Inasmuch as inequality increases the level of emissions increases as well showing that a more equal distribution of environmental risks and industrial profits would lead to better environmental status.

Table 12:
Asymmetric Cost-Risk distribution.

		BAU ($a = 0$)		NON-COOP		COORD	
Scenario	*Outcome*	**N**	**S**	**N**	**S**	**N**	**S**
	θ^*	*0.17*	*0.00*	**0.27**	*1.00*	**0.45**	*1.00*
'Good-Faith'	W*	0.165	0.018	0.120	-0.112	0.132	-0.06
	G*	0.50	0.30	0.438	0.219	0.332	0.17
	α^*	0.47	0.00	0.57	0.44	0.66	0.57
δ HIGH	β^*	*0.07*	*0.00*	*0.17*	*0.17*	*0.38*	*0.38*
	$\hat{W}$	0.163	0.018	0.113	-0.012	0.131	-0.06
	$\hat{G}$	0.558	0.30	0.50	0.25	0.372	0.186
	α^*	0.00	0.00	0.353	0.187	0.463	0.17
δ MEDIUM	β^*	*0.00*	*0.00*	*0.07*	*0.07*	*0.247*	*0.25*
	$\hat{W}$	0.162	0.018	0.107	-0.136	0.126	-0.07
	$\hat{G}$	0.60	0.30	0.558	0.28	0.452	0.226
	α^*	0.00	0.00	0.00	0.00	0.233	0.00
δ LOW	β^*	*0.00*	*0.00*	**0.00**	**0.00**	*0.08*	*0.08*
	W*	0.162	0.018	0.09	-0.145	0.113	-0.11
	G*	0.60	0.30	0.60	0.30	0.552	0.28

4.4.3 Case 3 and Case 4

Case 3 defines a more realistic scenario where richer country is less risky but faces higher opportunity cost since it has to convert advanced, and profitable, polluting production process through high technological and infrastructural investments. Case 4 proposes an extreme version of Case 3 to underline the impact of unequal distribution of risks and profits between countries. Obviously, in both cases, N dictates the IEA because has less convenience in reducing the emissions since it faces high cost-risk ratios ($\lambda_N^{(3)}$ = 3 and $\lambda_N^{(4)}$ = 9).

Under the BAU hypothesis both countries have low incentive in promoting environmental laws, therefore the quota of green firm is (almost) null independently from δ which plays a marginal role when it is not supported by governmental policies. The SO requires more stringent standards and returns higher level of welfare. Under a NC regime they converge to low green production convention when the environmental consciousness is not 'sufficiently' high.

Finally a cross comparison between different scenarios allows to clarify the importance of local environmental consciousness in attaining higher level of clean production. Notice that in Case 1 with θ^{*NC} = 0.50 both countries converge to β^* = 0.125 when δ is *low*, while in Case 3 with θ^{*NC} = 0.26 both countries converge to β^* = 0.17 if δ is *high*. This clearly shows that local participation can have the positive impact to fasten the process of cleaning production and to save resources for alternative use, because they allow governments to fix less stringent standards and to avoid additional expenditures to recover environmental damages.

Table 13:
Extreme Asymmetry.

		BAU ($a = 0$)		NON-COOP		COORD	
Scenario	*Outcome*	**N**	**S**	**N**	**S**	**N**	**S**
	θ^*	*0.17*	*0.00*	**0.17**	*1.00*	**0.29**	*1.00*
'Good-Faith'	W*	0.247	0.009	0.22	-0.23	0.224	-0.17
	G*	0.50	0.30	0.50	0.25	0.427	0.213
	α^*	0.47	0.00	0.47	0.34	0.58	0.45
δ HIGH	β^*	*0.07*	*0.00*	*0.07*	*0.07*	*0.192*	*0.192*
	$\hat{W}$	0.246	0.009	0.21	-0.257	0.223	-0.19
	$\hat{G}$	0.558	0.30	0.558	0.279	0.484	0.242
	α^*	0.00	0.00	0.00	0.00	0.38	0.199
δ MEDIUM	β^*	*0.00*	*0.00*	**0.00**	**0.00**	*0.09*	*0.09*
	$\hat{W}$	0.243	0.009	0.20	-0.273	0.217	-0.21
	$\hat{G}$	0.60	0.30	0.60	0.30	0.546	0.273
	α^*	0.00	0.00	0.00	0.00	0.00	0.00
δ LOW	β^*	*0.00*	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**
	$\hat{W}$	0.243	0.009	0.20	-0.273	0.21	-0.22
	$\hat{G}$	0.60	0.30	0.60	0.30	0.60	0.60

4.4.4 Uncertainties and Limitations

Madani (2013) and Kolstad (2011) have stressed that prescribing policy actions on the sole base of oversimplified game models can results in biased actions with potential harm for the well-being of billions of people around the globe. While simplifications are essential to modeling complex systems, the effects of simplifying assumptions on the theoretical outcomes should not be ignored when interpreting the results. For these reasons I have to spend few words on the limitations and the interpretations that come out from the current study.

One of the caveats, which must be mentioned when interpreting this model, is that it uses rather specific functions and parameter values to derive the bargaining outcomes and the evolutionary paths. I assumed quadratic profit and damage function in line with the great bulk of literature because I aimed to show a different source, from free-riding, of the heterogenous environmental performances. However a promising extension of this model would be to assess the outcomes when more realistic damage and profit functions are involved. This would open the door towards an empirical assessment of the factors that hamper or facilitate the green transition. Secondly, climate change is strictly tied with other factors, not included in this model, such as population and economic growth, technological progress and spillover, heterogeneous impact of different pollutants, stock of emitted GHGs remaining in the atmosphere, creation of new green jobs, trade and international transfers and the time and cost of conversion from a fossil-based economy towards a new one fed by renewable energies. Obviously, taking into account all these features in an unique, simple and tractable mathematical model is unattainable. From a theoretical point of view it is offered an innovative perspective where grounding a multi-scale analysis. However, Game 2 is based on one-shot game, while in reality parties do have a chance of switching strategies, players can make multiple moves and counter-moves during the course of the bargaining process and there is a time lag between proposals and the final ratification of the IEA. Finally, to conclude, in accordance with the observation of Kolstad (2011), I have shown the importance of income inequality which is often neglected in classical IEA games.

4.5 Discussion and concluding remarks

This Chapter considered two countries, with different economic structures, negotiating emission reductions (defining an unique global environmental standard) and it compared the outcomes from several combinations of abatement costs, environmental consciousness and consumers' preferences, both analytically and with numerical simulations. This mathematical framework confirmed that 'global solutions', if not backed up by a variety of efforts at national, regional, and local levels to prompt environmental consciousness, are not guaranteed to work well. To best of my knowledge this study is the first combining two different games in a consistent framework, which is a methodological novelty. I showed that the different evolutionary paths at micro level, determined by the interactions between firms and consumers, are essential to explain different environmental performances and the heterogenous capacity of each country to precisely attain, to fail or to overcome the international environmental standards.

From the *micro* point of view, the model was able to identify five different 'Regimes', under which each economy reaches different equilibria, that define the range of 'success' of global standards bargained between countries. It results that IEA alone are 'weak' policies if not backed up by local initiatives and a sufficient level of ecological awareness. Indeed, from the numerical simulations, it emerged that the very same international standards might lead to very different results. This is an important finding, in particular in sight of the next Conference of Paris on next December, because it suggests that national governments should focus not only in acquiring bargaining power with the respect to other countries, but in prompting their own citizenship to care about environment. If public opinion is particularly 'biased' toward environmental preservation, then the government could impose lower standards and thus saving resources for other public investments.

From the *macro* point of view it was assessed the impact of inequality, asymmetric risks and opportunity costs distribution. Firstly, there is an inverse relation between opportunity costs and damage costs: given a certain level of inequality, a country will establish more environmental friendly standards inasmuch the benefit-cost ratio is high. Secondly, historical inequality, in terms of different level of profits generated by the industries and different technological development of both green and polluting firms, and heterogenous risks play a key role. Case 4 confirms that, in case of extreme inequality, the environmental standards are low, which determines higher level of emissions and a lower welfare for the poorest country. This might explain why the Kyoto protocols were not mandatory for the developing countries. Even though I treat the case with two countries, this Chapter provides a possible insight for the emergence of multiple coalitions composed by (almost) homogeneous countries.

The main contribution, with the respect to the current literature on

IEA, stands on the modelisation of the economic structure which gives further insights to explain the gap between the promises of the agreements and the actual results. The notion of free-riding might be misleading when dealing with collective entities, like countries, which do not behave as (rational) individual. Rather, what one observes, in terms of national performances, is the outcome of a complex system where agents interact to fulfil their needs and desires. In this respect, the model highlights the role of environmental consciousness and citizen's responsibility thought as a key feature for the possible transition towards a fossil-free economy. Another remarkable extension of the current study is to explicitly model the formation of δ, its influence on both government decisions and international agreements. As seen above, many ONGs, local communities or simply groups of people have put pressure towards a definitions of serious and ambitious environmental standards. Moreover, this variable stands behind the consumer's choices and its contribution is crucial to boost a kind of 'innovation' from the demand-side aimed at change the consumption bundle and to force markets to shift towards the supply of sustainable goods and services.

Finally, from the numerical simulations and from subsection 4.2.3 and Section 4.3, it emerged that the results are robust and have clear economic explanations. The combination of two games seems a reasonable compromise between the complexity of the problem at hands and the elaboration of a theoretical model able to grasp the most important relations, with a tractable system of equations (in fact most of the results are derived analytically). Another promising extension of the current research could be to define a more general framework in which combine the micro and macro levels in line with a multi-scale perspective. This seems to be suggestive because it opens the debate around the coordination between international agreements and the active role of citizenship. Combining all these elements in a consistent and integrated theoretical model presents a substantial challenge. This study wants to pave the way towards more comprehensive game where real and relevant factors are seriously taken into account in a reasonably simple and tractable model.

Appendix A

Supplementary Materials: Chapter 1.

A.1 Structural Decomposition Analysis

IO allows to identify and quantify the main drivers of change through the so called *structural decomposition analysis (SDA)* which allows to disentangle the technological change from a shift in the final demand (see Miller and Blair (2009), Ch. 13). Let assume to have the total output (x) of two consecutive periods, t and $t + 1$, expressed in a common base-year price,[1] then it is possible to decompose the variation as:

$$\Delta x = x_t - x_{t-1} = \frac{1}{2}[\Delta L \cdot (f_t + f_{t-1}) + \Delta f \cdot (L_t + L_{t-1})] \tag{A.1}$$

where the first term, on the right hand side, expresses the change of the IO structure (technology and trade) and the latter the effect from a variation of the final demand. It has long been recognized, in the literature on SDA, that there is not a unique criteria to do a decomposition. The results may differ significantly across the alternative procedures (see Dietzenbacher and Los (1999); Su and Ang (2012) for comparisons). To overcome the non-uniqueness problem, Dietzenbacher and Los (1999) have

[1] In order to transform each matrix in a common base-year price, I must divide each element by $(1 + r)$ where r is the rate of inflation from year t to $t + 1$.

proposed to use the average of all possible decomposition forms. In case of n determinants (or variables), the number of alternative decompositions is $n!$. They also showed that the average of all decompositions can be adequately approximated by the average of the two so-called **polar decomposition** forms. The first polar form is derived by starting the decomposition with changing the first variable first, followed by changing the second variable, changing the third variable, and so forth. The second polar form is derived exactly the other way around, i.e. changing the last variable first, followed by changing the second-last variable, and so on.

By following Su and Ang (2012), I present the additive decomposition of equation 2.2 to describe the increase from year t - 1 to year t of the total water use:

$$\Delta w = w_t - w_{t-1} = \Theta_{IE} + \Theta_{TECH} + \Theta_{CONS} \tag{A.2}$$

where Θ_{IE} represents the *intensity effect*, that is the variation of water use for any unit of output (γ), computed as:

$$\Theta_{IE} = \frac{1}{2}[\Delta\hat{\gamma} \cdot L_t \cdot f_t + \Delta\hat{\gamma} \cdot L_{t-1} \cdot f_{t-1}] \tag{A.3}$$

Afterwards I calculate Θ_{LEON} that captures the variation of Leontief coefficients, from which it is possible to recover the impact from the change in the technological composition (H) and in the trade structure (T) of intermediate goods exchanges. Static comparative analysis allows to quantify the variation in water requirements given a change of matrix L, by keeping all the other variables unchanged, as:

$$\Theta_{LEON} = \frac{1}{2}[\hat{\gamma}_{t-1} \cdot \Delta L \cdot f_t + \hat{\gamma}_t \cdot \Delta L \cdot f_{t-1}] \tag{A.4}$$

Finally, Θ_{CONS} represents the variation of virtual water due to a shift in the volume of final demand, both at domestic and international level:

$$\Theta_{CONS} = \frac{1}{2}[\hat{\gamma}_{t-1} \cdot L_{t-1} \cdot \Delta f + \hat{\gamma}_t \cdot L_t \cdot \Delta f] \tag{A.5}$$

The additive chaining technique Su and Ang (2012) allows to recover the whole variation, from the first and the last year of interest, simply by summing consecutive one-year decompositions:

$$\Delta w_{(T,0)} = w_T - w_0 = \sum_{\tau=1}^{T} \Delta w_{(\tau,\tau-1)} \tag{A.6}$$

I start by computing the matrix $H_{(35x1435)}$ which gives the sum of technical coefficients of A, for each sector, by including all the intermediate imports of each country. The component H should be interpreted as the contribution to water footprint of changes in the mix of intermediate inputs with no consideration of the geographical origin of intermediate inputs. For country C I have H_C of size 35x35:

$$H_C = \sum_{j=1}^{R} A_{j1} \tag{A.7}$$

Matrix $\mathrm{T}_{(1435x1435)}$, which entries are the ratio between regional technical coefficient with respect of total technical coefficient (H), captures the impact of different a different trade composition of intermediate goods. For country C I compute T_{jC} $\forall j \epsilon R$, e.g. in case of country 1:

$$T_{j1} = A_{j1} \odot H_1 \tag{A.8}$$

where $\odot$ indicates the Hadamard product, which, in this case, is the element-wise ratio for two matrices of the same dimensions. Recall that matrix A includes both T and H, it is possible to rewrite ΔL with the respect to H and T through matrix A. In particular, I apply the multiplicative decomposition of the Leontief inverse:

$$\Delta L_{POLAR} = \frac{1}{2}[L_{t-1} \cdot \Delta A_{POLAR} \cdot L_t + L_t \cdot \Delta A_{POLAR} \cdot L_{t-1}] \tag{A.9}$$

hence:

$$\Delta A_{POLAR} = \frac{1}{2}[(\Delta T \circ H_t + \Delta T \circ H_{t-1}) + (T_t \circ \Delta H + T_{t-1} \circ \Delta H)] \tag{A.10}$$

where $\circ$ is the Hadamard product, which is the element-wise product for two matrices of the same dimensions. At this point it is worth to decompose the matrix of final demand ΔF in order to find the trade structure and the impact of product mix distribution over time. It is possible to assess the impact of population size and in per capita consumption. This is possibly extendible by comparing it with water per capita, trying to find some relations between this two dimensions. Let define $\tilde{F}$ as a RSxR matrix where each column accounts the national distribution of final demand by considering both domestic consumption and imports, for each sector. Let q be the overall level of the final demand, then for country C we have:

$$q_C = \sum_{j=1}^{R} \tilde{F}_{jC} \tag{A.11}$$

which is a column vector with the distribution of domestic demand plus imports of country C over all the 35 sectors. Let $\tilde{D}$ be the trade structure for final products, then for each country C I must compute $\tilde{D}_{1C}$, $\tilde{D}_{2C}$, ..., $\tilde{D}_{RC}$, or in general for each $j \epsilon R$:

$$\tilde{D}_{jC} = \tilde{F}_{jC} \odot q_C \tag{A.12}$$

Afterwards, let decompose q by taking into account the population size. Let Q be the vector of total demand in each country and $\Phi = \sum_{c=1}^{N} q_C$ be the product of population and consumption per capita, that is also given by $\Phi = q_{POP} \cdot q_{CAP}$. Moreover, let $\tilde{q}$ be the percentage distribution of total final demand for each sector, i.e for country C we have that Φ_C is a scalar, then:

$$\tilde{q}_C = q_C / \Phi_C \tag{A.13}$$

The final demand vector $\tilde{F}_{kC}$ of country C, for any j = 1,2,...,R, is given by:

$$\tilde{F}_{kC} = \tilde{D}_{kC} \circ (\tilde{q}_C \cdot q_{CAP,C} \cdot q_{POP,C}) \tag{A.14}$$

Polar decomposition technique reduces the computation at only two equations, the first one in which the static comparative analysis starts from the component (D), while the second equation beginning from the last element (POP). As showed by Dietzenbacher and Los (1998) the polar decomposition is a good approximation of the average of all the possible decompositions, which number increases almost exponentially with the number of variables. In this case $\tilde{F}$ depends on 4 variables, this would imply the computation of 4! = 24 equations. In this case the polar decomposition for the final demand is given by:

$$\Theta_{CONS} = D_{POLAR} + Q_C + Q_{CAP} + POP \tag{A.15}$$

where D_{POLAR} is the polar decomposition of the final demand trade structure, which is the counterpart for final demand of the component T:

$$D_{POLAR} = \frac{1}{2}[\Delta D \circ q_t + \Delta D \circ q_{t-1}] \tag{A.16}$$

Q_C represents the variation of in the distribution of the demand among sectors, it quantifies the role played by changes in the product mix of final demand for a given level of final demand and for a given 'geographical' composition of final demand.:

$$Q_C = \frac{1}{2}[(D_{t-1} \circ (\tilde{\Delta(q)} \cdot Q_t) + (D_t \circ (\tilde{\Delta(q)} \cdot Q_{t-1})] \tag{A.17}$$

Finally, POP and Q_{CAP} indicate the impact of population and consumption per capita growth, respectively:

$$Q_{CAP} = \frac{1}{2}[(D_{t-1} \circ (\tilde{q_{t-1}} \cdot \Delta q_{CAP} \cdot POP_t) + (D_t \circ (\tilde{q}_t \cdot \Delta q_{CAP} \cdot POP_{t-1})] \tag{A.18}$$

$$POP = \frac{1}{2}[(D_{t-1} \circ (\tilde{q_{t-1}} \cdot q_{CAP,t-1} \cdot \Delta POP) + (D_t \circ (\tilde{q}_t \cdot q_{CAP,t} \cdot \Delta POP)] \tag{A.19}$$

Therefore, equation (2.2) can be rewritten as:

$$w = \hat{v} \cdot (I - T \circ H)^{-1} \cdot (D \circ (\tilde{q} \cdot q_{CAP} \cdot POP)) \tag{A.20}$$

A.2 Tables

Table 14: Global Water Trade Balance (km^3) by sector for a selection of countries: 1995, 2001 and 2009.

		BLUE WATER		
COUNTRY	SECT	**1995**	**2001**	**2009**
AUS	AFF	3.75	5.94	0.65
	EWG	-0.75	-0.88	-2.39
	DUS	-0.10	-0.13	-0.35
	Other	0.00	0.00	-0.01
BRA	AFF	-0.59	1.14	1.57
	EWG	2.20	4.56	5.67
	DUS	-0.05	-0.06	-0.25
	Other	-0.01	0.02	0.02
CAN	AFF	-2.44	-3.51	-5.04
	EWG	20.77	24.77	17.55
	DUS	0.48	0.63	0.31
	Other	-0.02	-0.01	-0.04
CHN	AFF	12.68	6.13	13.13
	EWG	7.48	8.46	36.14
	DUS	0.70	1.06	6.18
	Other	0.02	0.02	0.13
IND	AFF	15.64	19.88	15.92
	EWG	1.30	0.54	-0.61
	DUS	0.16	0.22	0.16
	Other	0.00	0.01	0.00
ITA	AFF	-4.11	-4.31	-4.50
	EWG	-3.60	-4.48	-3.84
	DUS	-0.11	-0.22	-0.38
	Other	-0.01	-0.01	-0.02
JPN	AFF	-22.21	-16.77	-14.55
	EWG	-8.71	-7.73	-7.54
	DUS	-0.60	-0.59	-0.82
	Other	-0.15	-0.12	-0.12
RUS	AFF	-2.48	-2.03	-10.29
	EWG	9.09	14.96	8.86
	DUS	0.28	0.47	0.06
	Other	-0.03	-0.01	-0.01
USA	AFF	-4.80	-15.81	-8.34
	EWG	-22.61	-39.50	-29.95
	DUS	-0.05	-1.39	-1.89
	Other	0.19	0.09	0.13

Table 15: Global Water Trade Balance in 1995, 2001 and 2009 for a selection of countries.

	Blue water		
	1995	2001	2009
AUS	2.89	4.94	-2.11
AUT	-0.03	0.21	1.04
BEL	-2.88	-4.13	-4.96
BGR	0.16	0.09	0.05
BRA	1.55	5.65	7.01
CAN	18.80	21.88	12.78
CHN	20.87	15.67	55.58
CZE	-0.74	-1.06	-1.29
DEU	-19.42	-19.43	-21.55
DNK	-1.47	-1.36	-1.48
ESP	-2.78	-0.68	-2.46
FIN	-0.24	-0.50	-0.74
FRA	-6.33	-6.67	-9.07
GBR	-10.68	-14.07	-15.46
GRC	-0.61	-1.17	-1.66
HUN	-0.54	-0.89	-0.79
IDN	-0.66	-0.88	-2.16
IND	17.09	20.64	15.47
IRL	-0.31	-0.61	-1.29
ITA	-7.84	-9.02	-8.74
JPN	-31.66	-25.21	-23.
KOR	-6.86	-6.44	-7.42
MEX	0.48	-3.46	-3.21
NLD	-4.95	-5.45	-5.93
POL	-0.88	-1.97	-2.27
PRT	-0.79	-1.14	-1.16
ROU	0.64	0.39	-0.08
RUS	6.86	13.39	-1.37
SWE	1.37	1.94	1.21
TUR	0.92	0.80	-0.47
TWN	-2.66	-2.75	-1.77
USA	-27.27	-56.60	-40.05
ROW	58.66	79.01	69.18

Table 16: Additive SDA from 1995 to 2009 for a selection of countries.

	△ Blue (2009-1995)				
	IE %	TECH %	SIZE %	△ %	△ (Km3)
AUS	-46.4	-9.3	41.9	-13.8	-2.2
AUT	-84.6	59.3	34.0	8.7	0.8
BEL	-1.9	-15.5	19.9	2.5	0.0
BRA	3.1	9.4	38.5	51.0	38.0
CAN	-14.2	-12.1	35.3	8.9	7.7
CHN	-61.0	22.9	116.5	78.4	138.4
DEU	-36.1	7.5	19.7	-8.8	-0.7
DNK	-9.0	1.1	14.8	6.9	0.0
ESP	-11.7	15.5	47.1	50.9	7.4
EST	-10.8	-10.3	37.2	16.2	0.0
FRA	10.3	-22.3	-1.4	-13.5	-3.0
GBR	-3.5	-22.6	21.4	-4.8	-0.1
GRC	-12.7	-42.7	45.6	-9.8	-0.5
IDN	-35.2	13.3	49.6	27.6	3.8
IND	-14.5	-19.0	59.5	26.1	63.0
IRL	-34.7	5.1	58.4	28.9	0.1
ITA	7.8	-2.3	12.4	17.9	2.6
JPN	-12.5	-3.0	5.4	-10.0	-2.4
KOR	-43.4	28.3	29.3	14.3	0.3
MEX	-31.7	-2.6	44.2	9.9	2.0
NLD	-17.3	-9.3	27.1	0.4	0.0
POL	-10.5	-11.6	73.6	51.4	0.7
PRT	-66.2	25.1	27.8	-13.3	-0.6
RUS	-7.9	-18.3	35.3	9.2	5.1
SWE	-11.9	-10.2	18.7	-3.3	-0.6
TUR	-63.6	17.4	54.4	8.2	1.9
USA	-5.7	-15.0	24.8	4.1	7.1
ROW	-79.1	41.2	70.2	32.3	156.7

Table 17: Sectoral classification in WIOD (based on Nace rev 1.1).

ID	Description	Nace codes
AFF	Agriculture, Hunting, Forestry and Fishing	01, 02, 05
C	Mining and Quarrying	10, 11, 12, 13, 14
Fd	Food, Beverages and Tobacco	15, 16
Tx	Textiles and Textile Products	17, 18
19	Leather, Leather and Footwear	19
20	Wood and Products of Wood and Cork	20
Pp	Pulp, Paper, Paper , Printing and Publishing	21, 22
23	Coke, Refined Petroleum and Nuclear Fuel	23
CH	Chemicals and Chemical Products	24
25	Rubber and Plastics	25
OMet	Other Non-Metallic Mineral	26
Met	Basic Metals and Fabricated Metal	27, 28
29	Machinery, Nec	29
30t33	Electrical and Optical Equipment	30, 31, 32, 33
34t35	Transport Equipment	34, 35
36t37	Manufacturing, Nec; Recycling	36, 37
EWG	Electricity, Gas and Water Supply	40, 41
F	Construction	45
50	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles	50
51	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles	51
52	Retail Trade, Repair of Household Goods	52
H	Hotels and Restaurants	55
60	Other Inland Transport	60
61	Other Water Transport	61
62	Other Air Transport	62
63	Other Supporting and Auxiliary Transport Activities	63
64	Post and Telecommunications	64
J	Financial Intermediation	65, 66, 67
70	Real Estate Activities	70
71t74	Renting of Machinery and Equipment and Other Business Activities	71, 72, 73, 74
L	Public Admin and Defence; Compulsory Social Security	75
M	Education	80
N	Health and Social Work	85
O	Other Community, Social and Personal Services	90, 91, 92, 93
P	Private Households with Employed Persons	95
HH	Households	HH

A.3 SDA Plot

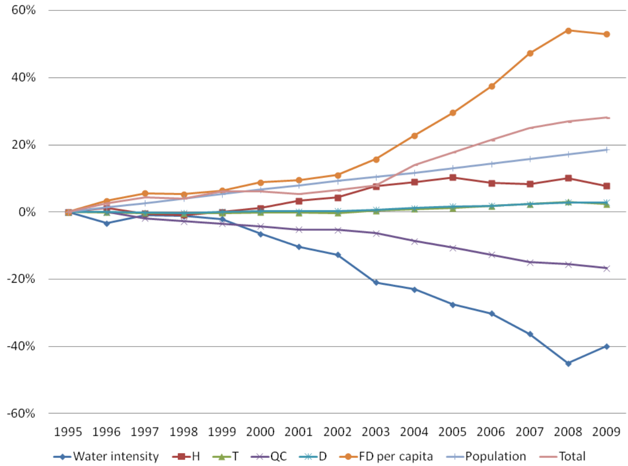


Figure 15: SDA- World summary

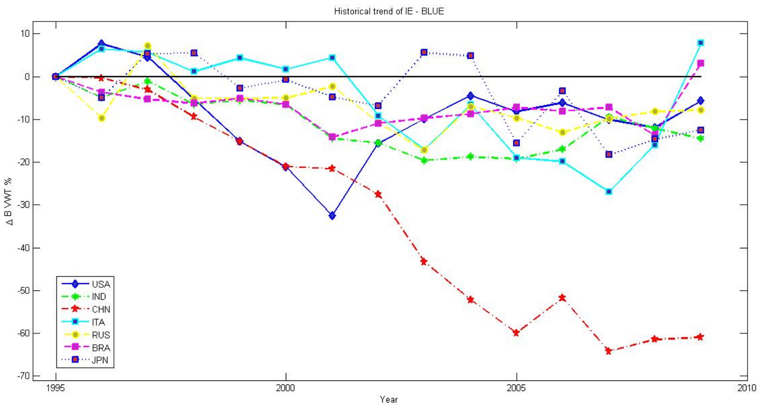


Figure 16: SDA: W component - water intensity (selected countries)

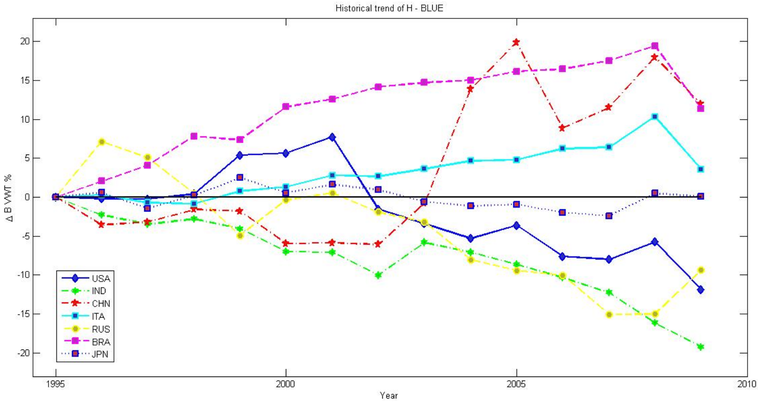


Figure 17: SDA: H component - production technology (selected countries)

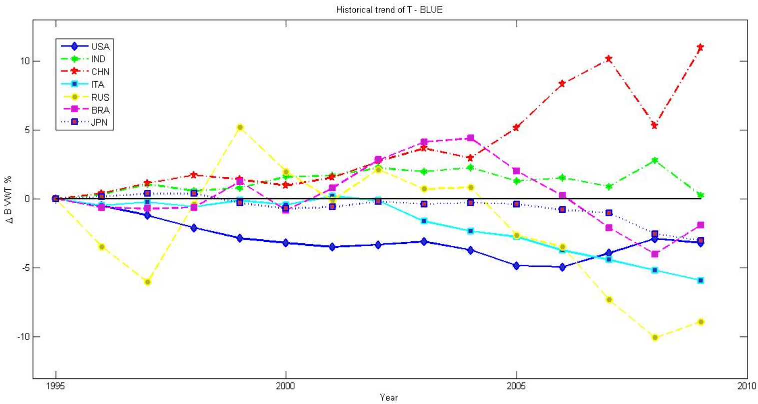


Figure 18: SDA: T component - trade structure of intermediate inputs (selected countries)

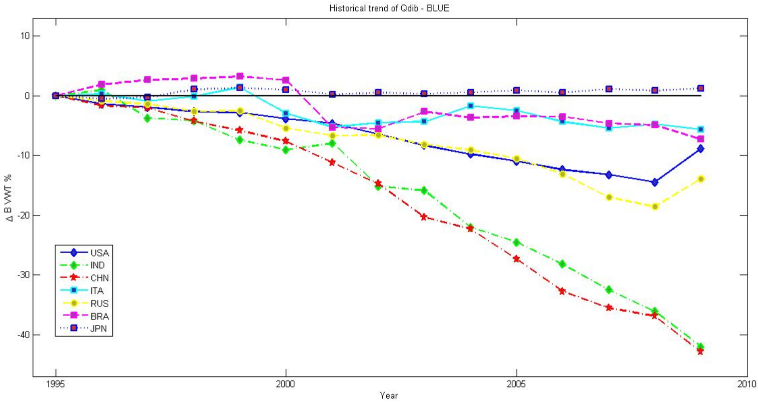


Figure 19: SDA: Q_C component - change in the product structure of final demand (selected countries

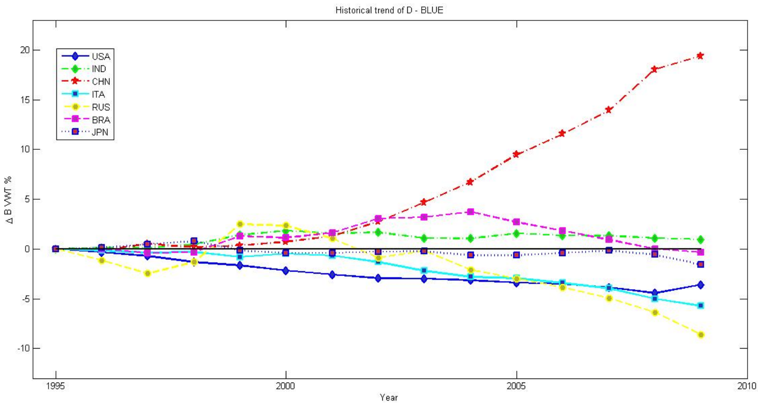


Figure 20: SDA: D component - change in the trade structure of final demand (selected countries)

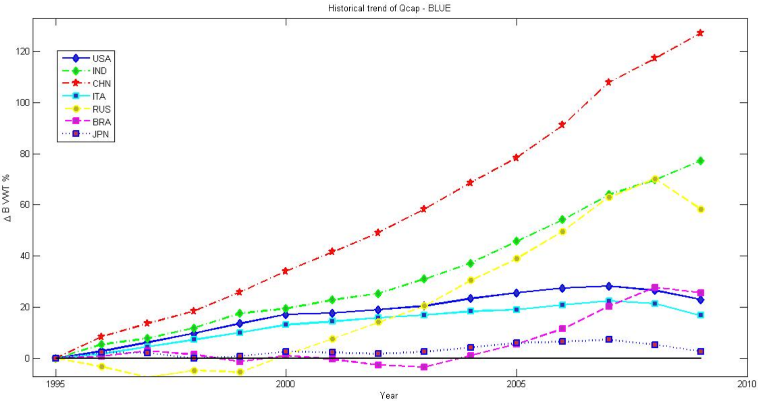


Figure 21: SDA: Per capita total final demand component (selected countries)

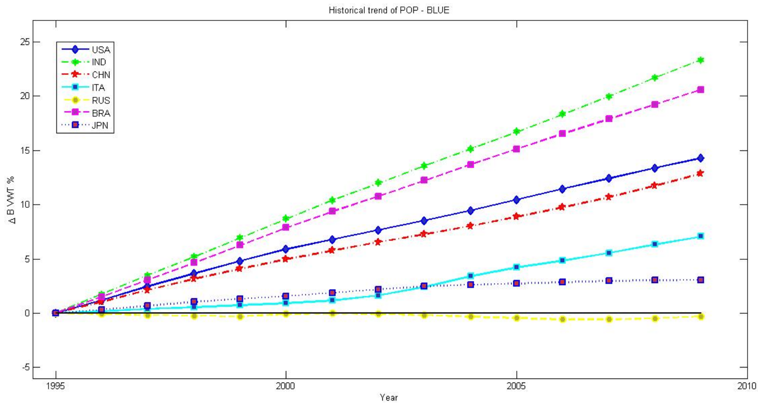


Figure 22: SDA: Population component (selected countries)

A.4 Network and Community Detection Plots

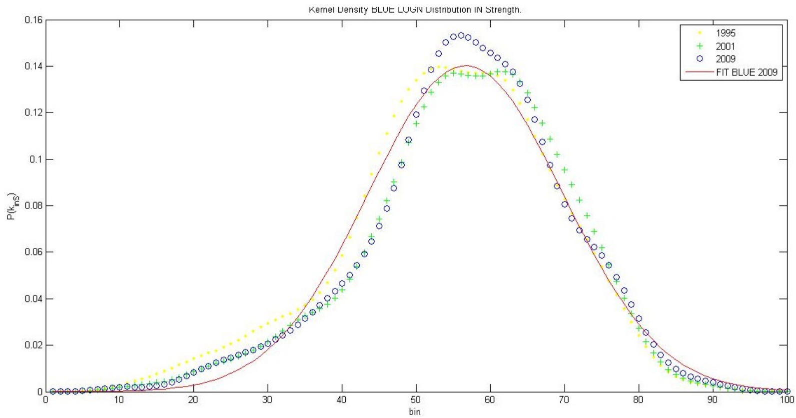


Figure 23: Kernel Density distribution of K^{inS}.

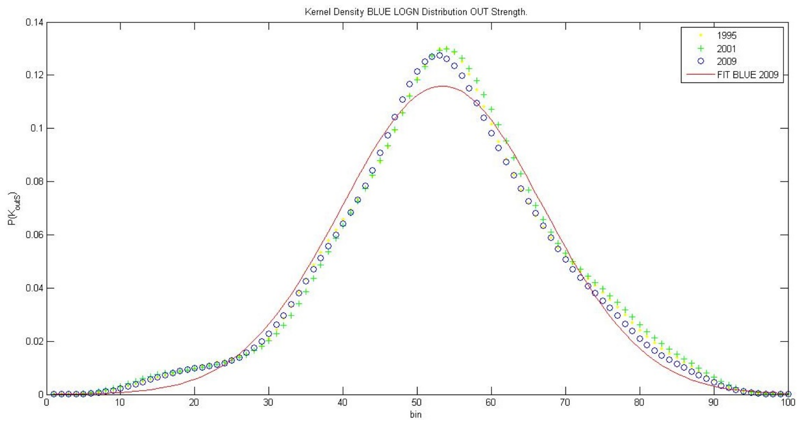


Figure 24: Kernel Density distribution of K_{outS}.

Following Roson and Sartori (2015), to better capture the trend of the distribution over time, I compute some descriptive statistics (kurtosis, skewness and standard deviation), for both the **d** and **q** degree distributions, which are summarized in Table 18. These values are positive and far greater than what expected in case of Gaussian distribution, confirming the fat-tail behavior of both **d** and **q**. Moreover the Lilliefors test always rejects the hypothesis of normal distribution of the samples.

Table 18: Statistical test of fat tail behavior.

	First Order Degree (**d**)			Second Order Degree (**q**)		
Year	**Kurtosis**	**Skewness**	**St. Dev**	**Kurtosis**	**Skewness**	**St. Dev**
1995	45.69	5.39	11.33	80.79	7.42	14.95
2001	41.24	5.27	11.45	77.74	7.36	15.22
2009	32.55	4.77	11.02	51.92	6.23	14.71

Appendix B

Supplementary Materials: Chapter 2.

B.1 Technological assumptions

The effect of technological development is considered in terms of changes in water productivity in each sector and water category. It is assigned a percentage decrease to green and blue water coefficients for each scenario based on the scope for improvements in productivity as given by De Fraiture (2007), who show levels of potential improvement per region in a qualitative sense. I bring from Ercin and Hoekstra (2012) the estimates of technological progress, even though they are adapted to fit the IO nature of the model applied. For scenario SSP3 and SSP5 it is assumed that γ_B (blue water) of the AFF sector has a different rate depending on five macro-area (Tab 19, column B), as a result of improvements in irrigation technology. For scenario SSP1 it imposed that γ_B and γ_{GY} of both DUS and EWG sectors gradually diminish up to -20% from 2010 to 2050. It is also applied a reduction of both γ_{GN} (as a result of improvements in rainfed agriculture) and γ_{GY} (to reflect improvements in waste-water treatment levels) of AFF sector in each macro-area (Tab 19, column A). Note that it is followed a gradual technological improvement, to wit γ diminishes every period in order to obtain a total reduction equal to the percentages showed in the table below. A simple example might clarify the point. Let assume that sector i needs 100m^3 of water per unit of production (γ) and that one wants a whole reduction of -20% from 2010 to 2050 (40-years length) in order to obtain 80m^3 per unit at the end of the time span considered. Given a compound rate law, with a constant coefficient β, it must hold in each period t (5-year length) that $\beta = 0.9725$. Considering that $\gamma_{t+1} = \gamma_t \cdot \beta$, then the sequence of technological progress can be rewritten as $\{\gamma_t\}$ = $\{$100; 97.25; ....; 80$\}$ for $t = \{0, 1, ..., 8\}$. Note that the same coefficient of technological speed (β) is kept constant till 2100.

Table 19: Technological improvements (β factor reduction) for the main macro-areas from 2010 to 2050.

Region	A	B
OECD	- 20%	- 20%
EST-EU	- 20%	- 30%
LAM	- 30%	- 20%
ASIA	- 30%	- 40%
ROW	- 30%	- 30%

B.1.1 Sustainable Technological change

The procedure is described as follow:

- Step 1: computing WS$_t^p$ $= \frac{\gamma_{t-1} \cdot x_t}{Wa_t}$, for each country i, that is the theoretical water exploitation given the technology of the previous period (γ_{t-1}).
- Step 2a: if for a country i happens that WS$_{i,t}^p > 1$, then find β_t^* such that the new γ_t^* (= $\gamma_{t-1} \cdot \beta_t^*$) provides an amount of water equal to Wa$_{i,t}$, to wit having WS$_{i,t}^{p*} = 1$;
- Step 2b: if for a country i happens that WS$_{i,t}^p \epsilon$ (0.8, 1), then find β_t^* such that the new γ_t^* (= $\gamma_{t-1} \cdot \beta_t^*$) provides an amount of water equal to the 80% of Wa$_{i,t}$, to wit having WS$_{i,t}^{p*} = 0.8$;

- Step 2b: if for a country i happens that $\text{WS}^{p}_{i,t} \epsilon$ (0.6, 0.8), then find β^*_t such that the new γ^*_t (= $\gamma_{t-1} \cdot \beta^*_t$) provides an amount of water equal to the 60% of $\text{Wa}_{i,t}$, to wit having $\text{WS}^{p*}_{i,t} = 0.6$;

- Step 3: computing the average technological improvement as $\pi_t = \frac{\gamma^*_t}{\gamma_{t-1}}$-1.

I decided to split Step 2 in three alternatives to avoid big 'technological jumps', in fact it seems implausible that a country, with a fairly not sustainable technology, would be able to recover the gap (that is using an amount of water no greater than the 60% of its own availability) in only one period (5 years-length).

B.2 Tables

In what follows I provide the tables with the quantification of the expected change of population growth and climate change and the impact of the main drivers (GDP, technology and climate) through the Structural Decomposition Analysis. Given the complexity of these tables I provide a brief resume of the key points per each table (when needed):

- Table 20 : Each column shows, for each SSPs, the percentage change of population size within each subperiod, that is the first column shows the growth from 2010 to 2020, the second from 2020 to 2050 and the last from 2050 to 2080. A comparison with the change in Wa (see Table 21), allows to disentangle the main factor that drives the variation of the projected Falkenmark indicator.

- Table 21 : Each column shows, for each SSPs, the percentage change of population size within each subperiod, that is the first column shows the growth from 2010 to 2020, the second from 2020 to 2050 and the last from 2050 to 2080.

- Table 22 and 23: I report only the entries for B and GY since that GN is exclusively used in the Agricultural sector. In particular I compare the percentages, with the respect to the total of each water base indicator, between 2010 and 2100. For simplicity I show the values under SSP1 and an average of the shares under SSP3. This is due to the common assumption of SSP1-2 and of SSP3-5 scenarios which generates almost the same results (less than 1% in the absolute difference). The sectors are: AFF stands for Agriculture, Hunting, Forestry, Fishing with Food, Beverages and Tobacco; E is Electricity, Gas and Water Supply; CH is Chemicals and Chemical Products; MET is obtained by Basic and Fabricated Metal; PAP is Pulp, Paper, Printing and Publishing. Sums lower than 100% are due to the use from other sectors that are not reported given their marginal impact.

- Table 24 : Comparison between historical values (column2), technological change as provided in Ercin and Hoekstra, sustainable path with and without dam capacity.

Table 20: Projected population growth under different scenarios.

$\Delta POP\%$	**SSP1**			**SSP2**			**SSP3**			**SSP5**		
ISO	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**
AUS	16.96	40.50	17.35	16.70	38.66	18.03	12.90	13.21	-6.68	20.55	64.73	38.39
BRA	6.83	3.18	-16.43	8.10	10.02	-8.75	9.39	18.95	5.19	6.69	2.45	-16.93
CAN	11.41	29.21	14.71	11.02	26.01	14.16	7.80	2.15	-12.05	14.28	51.29	36.58
CHN	2.22	-10.70	-28.10	2.83	-8.42	-24.65	3.31	-5.65	-16.32	2.21	-10.68	-28.05
ESP	6.22	10.97	-3.02	5.84	8.18	-3.40	3.52	-7.20	-23.05	8.19	23.99	13.76
GBR	7.07	17.94	9.52	6.73	15.68	8.67	4.61	-0.80	-12.27	8.81	32.51	28.58
IND	11.16	13.89	-10.30	13.35	24.91	0.81	15.31	39.55	21.42	11.11	13.69	-10.41
ITA	2.40	2.44	-8.53	1.90	-0.37	-8.32	0.01	-13.78	-25.97	3.87	12.91	6.27
JAP	-0.83	-9.38	-17.65	-1.36	-12.98	-18.34	-2.63	-22.49	-33.44	-0.09	-3.26	-6.76
MEX	9.53	7.48	-11.43	11.25	17.86	-0.20	13.56	35.99	21.46	8.64	1.92	-15.52
RUS	-1.20	-7.40	-14.89	-0.69	-3.70	-4.45	-0.82	-5.27	4.25	-0.67	-2.75	-11.83
TUR	9.70	9.45	-11.11	11.35	18.35	-0.89	13.56	32.21	20.61	9.66	9.34	-10.93
USA	8.49	22.08	13.19	8.17	19.82	11.74	5.92	1.66	-10.07	10.49	38.72	32.95

Table 21: Expected Wa variation, due to climate change, under different scenarios.

$\Delta Wa\%$	**SSP1**			**SSP2**			**SSP3**			**SSP5**		
ISO	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**
AUS	-4.06	-6.60	-1.31	-3.73	-3.34	-4.02	-2.40	-3.74	-3.32	-8.78	-3.77	-12.26
BRA	-7.81	-3.87	-6.76	-4.66	-6.29	-6.57	-3.47	-9.28	-8.15	-10.88	-21.92	-26.06
CAN	-0.20	0.20	-1.70	-2.88	-0.69	-1.78	-1.91	-1.03	-3.03	-0.40	-2.57	-1.24
CHN	1.41	1.62	0.06	-0.87	-0.55	1.10	-2.22	1.36	-0.84	2.43	4.42	2.62
ESP	-10.06	-6.59	-4.42	-9.55	-2.60	-4.87	-5.10	-8.79	-17.00	-13.16	-16.32	-18.51
FRA	-4.43	-6.23	-3.10	-6.75	-5.06	-1.63	-7.23	-6.01	-11.81	-10.96	-12.09	-13.38
GBR	-1.95	-1.96	0.11	-1.88	-3.65	1.86	-3.39	-2.35	-0.79	-1.96	-6.57	-3.51
IDN	2.28	1.25	-0.02	-0.54	0.66	-1.57	-1.28	-2.40	0.20	0.99	-0.22	-5.31
IND	4.93	6.40	-1.98	5.99	3.37	0.44	5.21	0.89	7.76	-0.86	29.97	4.67
ITA	-8.40	-5.30	-2.78	-6.10	-2.28	-3.77	-5.77	-5.41	-12.51	-9.45	-14.86	-14.13
JAP	-0.31	-1.68	1.00	-3.23	-0.41	-1.57	-4.66	-0.16	-3.65	5.37	1.63	-7.06
MEX	-3.25	-6.35	-4.72	-3.60	-1.85	-5.62	-5.82	-2.85	-7.03	-4.72	-14.77	-12.96
RUS	-1.93	0.48	-0.34	-2.25	-0.54	-1.09	-0.77	-1.80	-1.51	-1.12	-2.17	-3.00
SWE	-1.46	1.49	-1.39	1.78	-3.05	1.39	-1.26	1.13	1.55	-1.03	-2.64	-4.77
TUR	-8.22	-5.49	-4.19	-9.60	-0.72	-5.63	-5.44	-11.03	-13.30	-6.22	-18.46	-11.12
USA	-2.71	-3.83	-1.11	-6.36	-1.40	-1.86	-5.13	-1.46	-3.99	-1.23	-10.26	-2.42

Table 22: Sectoral decomposition of Blue water use under SSP1/2 and SSP3/5.

% Shares	$\mathbf{B}_{AFF}$			$\mathbf{B}_{E}$		
ISO	**2010**	**SSP1**	**SSP3**	**2010**	**SSP1**	**SSP3**
AUS	77.53	88.29	72.79	21.87	11.38	26.46
BRA	14.58	23.00	7.61	85.04	76.62	91.93
CAN	2.49	5.28	1.98	95.55	92.21	95.55
CHN	46.21	57.18	26.98	47.89	38.04	64.92
ESP	69.39	78.44	57.35	29.24	20.33	40.29
FRA	20.93	31.12	14.94	72.51	62.51	77.41
GBR	31.10	41.86	22.39	59.70	49.82	66.65
IDN	84.00	90.48	72.12	15.86	9.44	27.66
IND	90.44	94.47	82.22	8.59	4.98	15.98
ITA	27.93	38.12	18.77	68.92	58.48	76.86
JPN	10.43	12.78	5.21	86.61	83.08	90.34
MEX	70.20	78.88	50.46	28.93	20.49	48.09
RUS	27.66	30.60	15.84	69.69	66.55	80.84
SWE	0.62	01.06	0.39	98.91	98.42	99.10
TUR	63.11	74.35	51.91	35.54	24.54	46.10
USA	59.24	75.49	52.96	37.01	21.63	41.64

Table 23: Sectoral decomposition of Grey water use.

% Shares	GY_{AFF}			GY_{PAP}		
ISO	**2010**	**SSP1**	**SSP3**	**2010**	**SSP1**	**SSP3**
AUS	97.37	97.87	97.87	0.99	0.74	0.76
BRA	80.48	74.92	80.16	3.03	3.73	2.97
CAN	70.62	70.85	71.03	13.54	12.67	12.81
CHN	55.64	46.23	54.15	6.59	7.80	6.70
ESP	100.00	100.00	100.00	0.00	0.00	0.00
FRA	69.35	67.53	67.98	7.04	7.19	7.13
GBR	98.15	97.95	97.97	0.32	0.35	0.35
IDN	98.58	98.42	98.80	0.21	0.23	0.18
IND	67.78	63.12	69.71	6.06	7.40	6.05
ITA	67.18	60.79	61.35	6.42	7.05	6.95
JPN	38.88	25.34	25.89	13.79	12.90	12.93
MEX	83.28	77.62	82.80	0.23	0.30	0.23
RUS	52.65	40.68	44.87	13.51	16.01	14.90
TUR	86.49	85.48	85.82	3.85	4.51	4.33
SWE	73.61	70.72	72.06	2.40	2.43	2.42
USA	80.77	80.66	80.79	4.14	3.78	3.80

% Shares	GY_{CH}			GY_{MET}		
ISO	**2010**	**SSP1**	**SSP3**	**2010**	**SSP1**	**SSP3**
AUS	0.43	0.35	0.35	1.00	0.89	0.87
BRA	5.71	7.22	5.70	8.09	10.85	8.60
CAN	6.23	6.59	6.49	9.17	9.49	9.25
CHN	13.41	16.47	13.99	22.36	27.00	23.04
ESP	0.00	0.00	0.00	0.00	0.00	0.00
FRA	13.53	14.72	14.43	6.58	7.30	7.17
GBR	0.68	0.65	0.65	0.79	1.00	0.98
IDN	0.51	0.58	0.44	0.23	0.22	0.17
IND	12.51	13.05	10.73	12.46	14.94	12.28
ITA	8.59	11.71	11.36	7.45	10.53	10.22
JPN	27.96	33.89	33.91	18.26	26.58	26.00
MEX	0.68	0.87	0.67	10.89	15.07	11.47
RUS	14.78	22.24	19.64	13.19	15.59	14.85
TUR	6.56	6.17	6.13	3.10	3.83	3.72
SWE	0.97	1.01	0.99	19.90	22.90	21.54
USA	5.29	5.48	5.40	8.73	8.97	8.89

Table 24: Expected Technological change under different scenario and assumptions.

	WIOD	**Ericn-Hoekstra (2014)**				**Sustainable Technology**							
	$\Delta\gamma\%$	**2050** $\Delta\gamma\%$		**2100** $\Delta\gamma\%$		**2050** $\Delta\gamma\%$				**2100** $\Delta\gamma\%$			
COUNTRY	**2009-1995**	**SSP1/2**	**SSP3/5**	**SSP1/2**	**SSP3/5**	**SSP1**	**SSP2**	**SSP3**	**SSP5**	**SSP1**	**SSP2**	**SSP3**	**SSP5**
AUS	-25.64	-14.94	-5.05	-29.48	-9.97	-61.81	-81.59	-52.92	-79.14	-35.90	-51.89	-72.29	-92.79
BRA	-6.25	-24.81	-0.94	-46.78	-1.73	0.00	-30.73	0.00	-22.64	0.00	0.00	-18.11	-65.48
CAN	-5.10	-19.89	-0.10	-39.26	-0.20	0.00	-8.58	0.00	-8.86	0.00	0.00	0.00	-63.04
CHN	-27.45	-22.79	-3.24	-42.98	-5.97	-79.47	-88.49	-73.81	-78.72	-65.22	-79.45	-82.88	-91.58
ESP	14.02	-14.86	-5.13	-29.33	-10.12	-56.97	-78.33	-49.44	-76.17	-33.42	-51.85	-64.37	-91.23
GBR	4.96	-16.62	-3.15	-32.81	-6.22	0.00	-43.18	0.00	-39.14	0.00	0.00	-15.92	-76.95
IND	-12.24	-19.79	-6.90	-37.29	-12.68	-86.93	-94.55	-82.91	-94.18	-76.08	-89.37	-88.03	-95.96
ITA	-1.95	-17.29	-2.67	-34.12	-5.27	-29.49	-60.72	-15.78	-56.89	0.00	-13.37	-34.81	-76.45
JPN	-5.12	-18.77	-1.22	-37.04	-2.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-17.31
MEX	-21.43	-21.96	-5.67	-41.02	-10.43	-59.38	-79.63	-52.24	-81.63	-46.42	-71.82	-58.32	-81.67
RUS	-1.50	-18.22	-1.69	-35.95	-3.34	0.00	0.00	0.00	-14.19	0.00	0.00	-3.73	-48.93
TUR	-24.60	-17.00	-3.00	-33.55	-5.92	-69.72	-82.42	-65.46	-84.90	-60.63	-80.69	-77.57	-91.14
USA	3.36	-15.92	-4.03	-31.43	-7.95	-50.53	-71.42	-43.42	-67.44	-29.63	-37.80	-63.62	-87.69

Table 25: Water change, under SSP1, due to technological progress (γ) and economic growth (GDP).

	SSP1								
	Δ **W**$_\gamma$**%**			Δ **W**$_{GDP}$ **%**			Δ **Wa%**		
COUNTRY	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**
AUS	-6.12	-24.49	-18.68	44.06	136.67	64.01	-4.06	-6.60	-1.31
BRA	-9.68	-39.99	-27.53	43.61	149.54	49.95	-7.81	-3.87	-6.76
CAN	-6.23	-22.52	-19.93	30.69	87.80	56.94	-0.20	0.20	-1.70
CHN	-11.19	-41.57	-19.38	113.43	207.64	6.57	1.41	1.62	0.06
ESP	-4.82	-17.07	-15.76	13.99	65.51	53.86	-10.06	-6.59	-4.42
FRA	-5.73	-22.23	-19.48	18.92	92.83	60.15	-4.43	-6.23	-3.10
GBR	-5.95	-22.26	-19.53	24.00	88.88	56.40	-1.95	-1.96	0.11
IDN	-11.75	-68.00	-31.64	81.57	355.84	73.44	2.28	1.25	-0.02
IND	-9.45	-55.31	-25.17	84.03	383.44	93.38	4.93	6.40	-1.98
ITA	-5.37	-19.61	-17.78	11.92	68.65	47.80	-8.40	-5.30	-2.78
JAP	-5.59	-19.44	-16.94	15.05	59.31	29.15	-0.31	-1.68	1.00
MEX	-8.82	-35.65	-25.94	36.39	136.88	59.35	-3.25	-6.35	-4.72
RUS	-6.49	-24.65	-16.66	45.34	120.72	22.72	-1.93	0.48	-0.34
SWE	-6.28	-23.42	-20.35	31.39	97.15	60.42	-1.46	1.49	-1.39
TUR	-6.00	-23.91	-16.32	51.67	146.71	46.26	-8.22	-5.49	-4.19
USA	-5.79	-20.86	-16.78	34.12	93.04	42.47	-2.71	-3.83	-1.11

Table 26: Water change, under SSP2, due to technological progress (γ) and economic growth (GDP).

	SSP2								
	Δ **W**$_\gamma$**%**			Δ**W**$_{GDP}$**%**			Δ **Wa%**		
COUNTRY	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**
AUS	-6.11	-21.79	-18.57	43.59	101.04	62.46	-3.73	-3.34	-4.02
BRA	-9.71	-33.57	-27.70	44.26	96.91	51.21	-4.66	-6.29	-6.57
CAN	-6.21	-21.53	-19.76	30.22	75.84	54.79	-2.88	-0.69	-1.78
CHN	-11.13	-33.73	-20.56	111.78	134.53	18.09	-0.87	-0.55	1.10
ESP	-4.81	-15.93	-15.74	13.63	48.71	53.51	-9.55	-2.60	-4.87
FRA	-5.72	-20.58	-19.36	18.52	72.23	58.64	-6.75	-5.06	-1.63
GBR	-5.94	-20.69	-19.59	23.36	69.53	57.09	-1.88	-3.65	1.86
IDN	-11.75	-51.19	-31.92	81.48	223.99	75.64	-0.54	0.66	-1.57
IND	-9.50	-43.36	-26.39	85.45	261.22	106.69	5.99	3.37	0.44
ITA	-5.35	-18.20	-17.83	11.44	50.34	48.48	-6.10	-2.28	-3.77
JAP	-5.57	-17.34	-16.62	14.31	32.95	25.04	-3.23	-0.41	-1.57
MEX	-8.88	-32.41	-27.47	37.85	108.08	73.54	-3.60	-1.85	-5.62
RUS	-6.47	-22.13	-18.20	44.87	89.48	41.98	-2.25	-0.54	-1.09
SWE	-6.26	-22.09	-20.68	30.81	81.16	64.36	1.78	-3.05	1.39
TUR	-6.04	-22.13	-17.61	53.03	121.97	64.85	-9.60	-0.72	-5.63
USA	-5.77	-19.01	-16.52	33.32	68.23	38.98	-6.36	-1.40	-1.86

Table 27: Water change, under SSP3, due to technological progress (γ) and economic growth (GDP).

	SSP3								
	Δ W$_\gamma$%			**Δ W$_{GDP}$ %**			**Δ Wa%**		
COUNTRY	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**
AUS	-0.52	-1.51	-1.10	40.87	58.54	18.78	-2.40	-3.74	-3.32
BRA	-0.15	-0.43	-0.30	46.64	60.52	17.03	-3.47	-9.28	-8.15
CAN	-0.05	-0.16	-0.12	27.98	56.33	21.50	-1.91	-1.03	-3.03
CHN	-1.63	-3.53	-1.71	114.58	87.64	0.64	-2.22	1.36	-0.84
ESP	-0.98	-2.72	-2.28	11.47	15.60	8.75	-5.10	-8.79	-17.00
FRA	-0.22	-0.65	-0.50	16.93	42.13	17.21	-7.23	-6.01	-11.81
GBR	-0.14	-0.40	-0.30	21.32	37.10	12.55	-3.39	-2.35	-0.79
IDN	-0.53	-1.55	-0.70	85.29	152.18	32.60	-1.28	-2.40	0.20
IND	-3.57	-10.79	-5.51	88.55	159.83	55.86	5.21	0.89	7.76
ITA	-0.39	-1.09	-0.86	9.66	19.97	6.41	-5.77	-5.41	-12.51
JAP	-0.26	-0.65	-0.47	13.21	8.34	-9.82	-4.66	-0.16	-3.65
MEX	-0.70	-2.24	-1.66	41.02	84.87	45.63	-5.82	-2.85	-7.03
RUS	-0.32	-0.86	-0.57	45.14	63.72	27.29	-0.77	-1.80	-1.51
SWE	-0.04	-0.10	-0.07	28.70	46.17	19.43	-1.26	1.13	1.55
TUR	-0.87	-2.63	-1.94	55.88	86.03	44.16	-5.44	-11.03	-13.30
USA	-0.58	-1.65	-1.22	31.46	43.64	8.70	-5.13	-1.46	-3.99

Table 28: Water change, under SSP5, due to technological progress (γ) and economic growth (GDP).

	SSP5								
	Δ **W**$_\gamma$%			Δ **W**$_{GDP}$ %			Δ **Wa**%		
COUNTRY	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**	**2020**	**2050**	**2080**
AUS	-0.54	-2.48	-1.63	48.91	223.78	124.85	-8.78	-3.77	-12.26
BRA	-0.15	-0.71	-0.40	45.88	230.08	85.27	-10.88	-21.92	-26.06
CAN	-0.06	-0.24	-0.17	34.39	177.91	117.97	-0.40	-2.57	-1.24
CHN	-1.65	-6.20	-1.90	119.35	302.77	23.40	2.43	4.42	2.62
ESP	-1.01	-4.01	-3.47	16.23	116.88	116.65	-13.16	-16.32	-18.51
FRA	-0.22	-0.95	-0.74	21.01	152.06	123.24	-10.96	-12.09	-13.38
GBR	-0.14	-0.59	-0.46	26.89	149.11	121.99	-1.96	-6.57	-3.51
IDN	-0.54	-3.21	-0.94	85.78	529.44	110.14	0.99	-0.22	-5.31
IND	-3.55	-22.30	-7.23	86.76	536.93	134.19	-0.86	29.97	4.67
ITA	-0.39	-1.58	-1.29	13.74	120.10	106.55	-9.45	-14.86	-14.13
JAP	-0.26	-0.94	-0.69	16.61	105.47	73.46	5.37	1.63	-7.06
MEX	-0.69	-3.10	-1.95	37.23	194.56	90.13	-4.72	-14.77	-12.96
RUS	-0.32	-1.32	-0.63	47.97	201.86	53.72	-1.12	-2.17	-3.00
SWE	-0.04	-0.15	-0.11	34.85	162.83	125.47	-1.03	-2.64	-4.77
TUR	-0.86	-3.72	-2.20	53.13	203.86	78.57	-6.22	-18.46	-11.12
USA	-0.60	-2.40	-1.72	37.43	152.09	95.71	-1.23	-10.26	-2.42

B.3 OECD Projections

Starting from 2030 China should face a continuous declining trend, in each SSP, of the population size that goes from 1337 million (MM) in 2010 to 1028 MM under SSP3, while it decreases to less than 665 MM under SSP1-5. India shows the same inverted U-shape path under SSP1-5 with a peak of 1600 MM in 2050 and a minimum of 1170 MM in 2100; whilst under SSP3 it is expected a linear growth up to 2608 MM in 2100. For Japan it is projected, under each SSP, a reduction of population size that reaches at most 105 MM (SSP5) and at least 46 m (SSP3). USA and EU27 are converging to the same size, in 2100, under each SSP from a minimum of 260 MM (SSP3) to a maximum of 731 MM (SSP5). Population dynamics of Brazil and Russia are expected to be particularly similar under each SSP, except SSP3 in which Brazil should face a population sizing up to 276 MM, in 2100, while Russia should keep the level of 2010 of 149 MM. In the other cases they both show a declining path toward minimum levels, in 2100 under SSP4, of 135 MM for Brazil and of 88 MM for Russia.

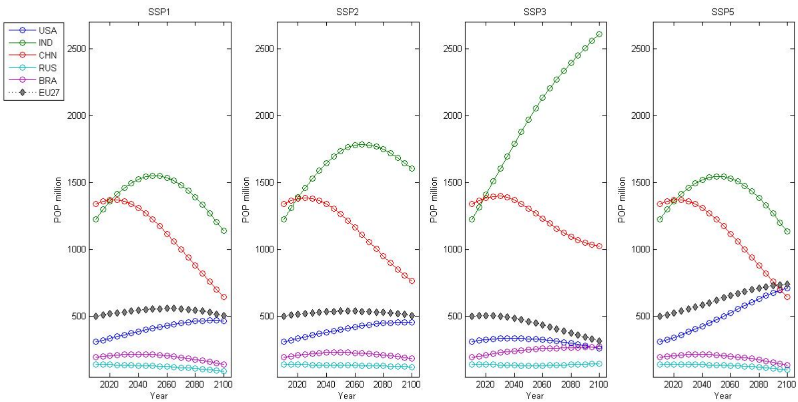


Figure 25: Population trends under four SSP scenarios.

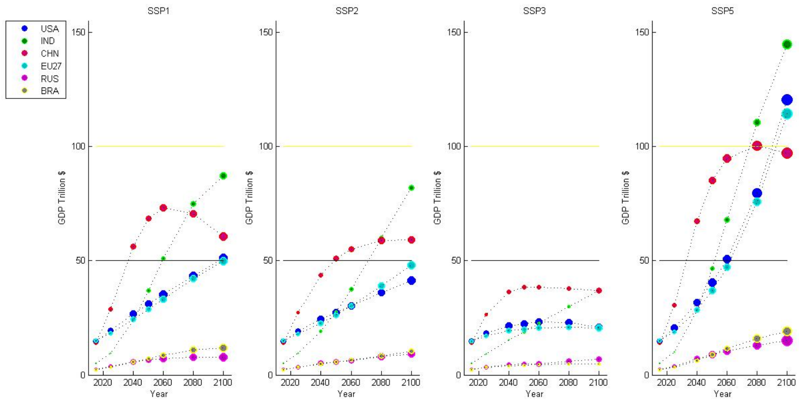


Figure 26: GDP growth under SSP1-2-3-5, where the size of the bubbles are proportional to the income per capita.

Figure 26 shows the patterns of economic growth for each scenario: India is projected to be the first economy at the end of the century, in terms of GDP, with China, USA and European Union as followers. Each scenario indicates substantial differences both in terms of speed of growth and levels of GDP. SSP4 presents a convergence around 50 Trillions of $ in those countries, while under SSP1 India overcomes 87 Trillions (Tr) and China reaches more than 60 Tr, after a peak of 73 in 2050. SSP3 sees a rapid growth of China and India which, after overcoming the level of USA and EU27 (China in the year 2025 while India in 2075), converges to 37 Tr of $, far below any previous case. Under the Business as Usual case (SSP5) India grows exponentially, reaching 144 Tr of $, followed by USA (120 Tr), EU27 (110 Tr) and China (97 Tr). In each scenario Russia and Brazil attain a very similar path converging to a minimum of around 5 Tr of $ (SSP3) to a maximum of around 17 Tr of $ (SSP5).

In terms of income per capita there are more inequalities and variations under different SSPs. India is the poorest in each SSP, ranging from a minimum of 9590 (14160) $ per capita per year in 2050 (2100) under SSP3 to a maximum of 30060 (127520) under SSP5. USA and EU27 are keeping the first and second rank, respectively, in each SSP, ranging from a minimum of 67240 (79870) $ per capita per year in the United States and from 43390 (64680) $ per capita per year in the European Union (SSP3) to a maximum of 84740 (168990) $ and 59490 (154530) $ per capita per year, respectively, under SSP5. Finally Russia and Brazil, though close in absolute values, should diverge in terms of income per capita with Russia ranging from a minimum of 35140 (46640) $ per capita per year on 2050 (2100) under SSP3 to a maximum of 63790 (147750) $ under SSP5; whilst Brazil should go from a minimum of 17080 (17680) $ per capita per year on 2050 (2100) under SSP3 to a maximum of 41620 (138470) $ under SSP5.

B.3.1 GDP Risk

In this subsection I run another comparative analysis in order to provide an hint about possible economic impacts, in terms of GDP lost, due to water constraints. I apply the same algorithm of the above subsection, yet, instead of updating β, I estimate, in each period t, the level of sectoral output ($\mathrm{x}_t^\star$) that is consistent with a sustainable exploitation of water (see Appendix D B.3.1). This procedure provides a measure of the implied GDP growth in a context of sustainable exploitation of Wa and it is a proxy of the possible economic loss, due to environmental hurdles, that a country might face in this century.
The procedure I follow is:

- Step 1: computing $\mathrm{WS}_t^p = \frac{\gamma_t \cdot \tilde{x}_t}{Wa_t}$, for each country i, that is the theoretical water exploitation given the technology level as assumed in Ercin and Hoekstra (2014) (γ_t) but with the sectoral output under no water constraints (i.e. OECD's forecasting).

- Step 2a: if for a country i happens that $\mathrm{WS}_{i,t}^p > 1$, then find $x{*}_t$ such that the new x_t^* (= $\tilde{x}_t \cdot \vartheta_t^*$) provides an amount of water equal to $\mathrm{Wa}_{i,t}$, to wit having $\mathrm{WS}_{i,t}^{p*} = 1$;

- Step 2a: if for a country i happens that $1 > \mathrm{WS}_{i,t}^p > 0.8$, then find $x{*}_t$ such that $\mathrm{WS}_{i,t}^{p*} = 0.8$;

- Step 2a: if for a country i happens that $0.8 > \mathrm{WS}_{i,t}^p > 0.6$, then find $x{*}_t$ such that $\mathrm{WS}_{i,t}^{p*} = 0.6$;

- Step 3: computing the absolute and relative lost of GDP, through the matrix F and Z (see note 17 pag. 9), due to water shortages.

Figure 27 draws ΔGDP, defined as the difference between (water-) sustainable GDP and GDP growth as provided by OECD. There a great variety of results due to heterogenous economic structures and environmental assets between countries, that are tied by complex inter-industrial linkages. As expected there is a serious threat to the potential economic development of China and India and to the prosperity of the most high-income economies. China shows a miscellaneous set of alternative paths of future potential GDP loss, with values ranging from 19 Tr in 2025 to 88 Tr in 2100. However the trend is far from being linear and simple, in fact after attaining the biggest harm in 2060, in each scenario but SSP5, it is able to recover better economic condition, though with high potential wastes ranging from 28.81 (SSP3) to 88.45 (ssp5) Trillions of dollar in 2100. India is the most affected country, where water constraints might be a barrier that threaten the possibility of tackling poverty and food shortages. It would experience an increasing trend of potential GDP loss if it does not act immediately through investment in better technologies and international agreements in order to exploit the potential benefit of VWT. In our context, worse economic conditions are paired with serious social water scarcity generating a dangerous mix of economic and environmental poverty. Among the other states I found several different paths with some regions almost unaffected by water shortages and others that face high risks. In particular Japan, Canada, Brazil and Russia show GDP trends very close to the unconstrained world with values fluctuating around zero (no change). However, there is a non-linear trends following a peculiar behavior under SSP1-3-4: in 2025 they suffer the biggest economic effects, with potential GDP loss ranging from -16% (Russia under SSP1) to -2.41% (Japan, SSP3). Afterwards, ΔGDP narrows and eventually, in 2100, it becomes positive (with a maximum in Brazil of +12.84% under SSP3), meaning that they find water shortages in other countries economically convenient for them. This trend arises an interesting trade-off due to heterogenous, and sometimes opposite, economic implications of environmental constraints. This might also explain the extreme need of international environmental convention to face severe and imminent ecological problems and the great difficulty to find fair, efficient and rational agreements. In any case SSP5 is the worst scenario because each country deals with an increasing potential economic loss, reaching in 2100 40 Tr in Russia and Brazil, more than 80 in EU27 and China and more than 100 Tr in USA and India. Notice that these results are due to the fact that GDP forecasts in case of SSP5 are the highest, meaning that the same environmental conditions generate greater economic impacts. Moreover in this case the technological development assumed is quite low. Change in precipitations, due to Climate Change, is not sufficient to compensate the variations in water requirements due to production needs, thus it's impact is marginal in this context.

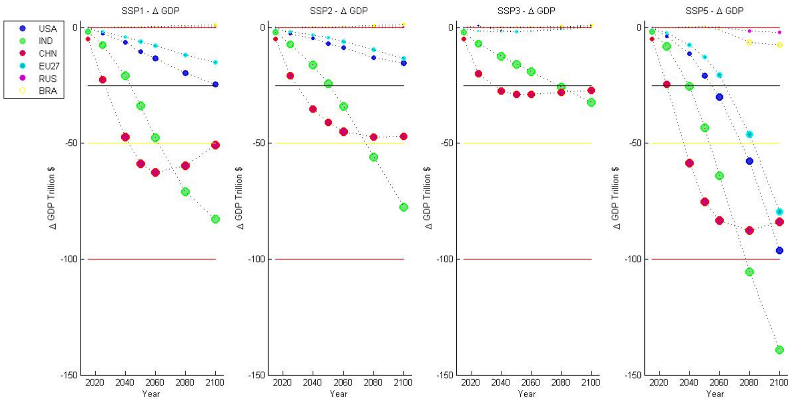


Figure 27: GDP (potential) lost in Trillion of $ under different scenarios, where bubble size is proportional to the percentage of GDP at risk due to water constraints.

Appendix C

On Ecological Economics: A Philosophical Perspective

Ecological Economics (EE) is a novel, wide and heterogeneous branch of research which aims at studying "the relationships between human housekeeping and nature's housekeeping" (Common and Stagl, 2005, p. 1). Notwithstanding the common root (*eco* from the greek oikos: 'house') the historical evolution of Ecology and Economics has been quite divergent: the former has focused its subject exclusively on the nature and its laws, the latter has studied human interactions without caring about the environmental consequences and constraints.

EE assumes that human (economic) systems are subject to natural constraints (i.e. the second law of thermodynamic). From this consideration comes up several definitions of EE, such as: "Ecological Economics seeks to ground economic thinking in the dual realities and constraints of our biophysical and moral environments" (Daly and Farley, 2011, p. xxi) or "Ecological Economics is the relationship between ecosystems and economic systems in the broadest sense, [so it represents] the science and management of sustainability" (Costanza, 1991, p. 3) or again "[EE studies] the relations between environmental conflicts and the languages of valuation. [The aim] is to explain how the unavoidable clash between economy and environment (which is studied by ecological economics) gives rise to the 'environmentalism of the poor' (which is studied by political ecology)" (Martinez-Alier, 2002, p. 10-31). Clear features come out from these definitions: there is a wide consensus that economics and ecology are strictly interwoven, therefore they must be studied jointly, although the boundaries of the disciplines are dialectical and not precisely defined. EE, thus, deals with the interactions of ecological and economic systems, as proposed by the 'Co–Evolutionary Paradigm' (Gowdy, 1994, Kallis and Norgaard, 2010). Given the contextual nature of Evolution, depending upon specific time and space scale, it is no more possible to assume time symmetry because once a path is taken, many other are irreversibly closed. This fact, jointed with the intrinsic (ontological) uncertainty, the unpredictability of the future and feedback effects (increasing non-linearity) makes the role of decision-maker of key interest, as pointed out by Funtowicz and Ravetz (1991): "The new environmental problems are characterized by the following traits: facts are uncertain, there are values in dispute, the stakes are high and decisions are urgently needed". This discipline is not thus simply driven by a cognitive interest to understand and explain the world as it is (positivism), rather, by definition, it claims how to manage natural and human systems in order to ensure a sustainable (co-)evolution. This purpose is clearly *normative* and, as many of the ecologist thinkers pointed out, the issue of stating transparently the set of ethical values is at the core of EE (Futowicz and Ravetz, 1994, Martinez-Alier, 2002).

Ecological Economics seemed to emerge as a new and different 'paradigm' (Kuhn, 1962), or better, a novel 'Pre-Analytic Cognitive act [or] Vision' (Schumpeter, 1954, p. 41). The aim of this last Section is to clarify if and how this novel approach may transcend, rather than simply opposing to, the limits of the orthodox textbook economics. The two 'schools' do not simply differ in how they conceptualise the interaction between human and ecological systems, rather EE is thought to be able to incorporate also the social dynamics and to amplify the potential application of economic studies to face some urgent socio-ecological challenges (e.g. climate change, urbanization, population growth, resources and wastes management, distribution and equity among others). However, one of the main problem of EE is its status of heterogeneous field of research in which the many contributions, although inspired by a (partially) common set of ethical values and purposes (equity and sustainability, among others), are not coordinated or developed in a structured manner. In order to answer to two important questions, *what is Ecological Economics? what is Sustainability?*, after a brief summary of Neoclassical Environmental Economics, I discuss some crucial features of EE: entropy law and irreversibility, complexity, evolution (qualitative change) and value incommensurability. Finally, I suggest that the label 'Ecological' is misleading and I introduce a new definition of Economics.

C.1 A brief overview of Neoclassical Environmental Economics

The label 'neoclassical' (NC), attached to a particular economic approach, was introduced by Veblen (1900). Even though it is far from being an homogeneous 'school of thought' (Lawson, 2013) it is commonly used as a synonymous of the mainstream perspective. The list of the main features, not pretending to be exhaustive, ascribed to the NC theory are: the methodological individualism, the acceptance of the (instrumental) rationality axiom, the axiomatic imposition of equilibrium, the maximization principle, the reliance on utilitarian ethic, the belief in an absolute reductionism, the hypothetical deductive method, the mechanicistic ontology and the deductive-nomological model of (scientific) explanation. Space and time force me to focus only on two elements which, in my opinion, are relevant to understand the differences between NC and EE: i) the relation between economic and environmental systems, and ii) the fact/value dichotomy.

NC aimed to establish a completely autonomous economic discipline where any influence from social or ecological factors were seen as 'disturbing factors' which would cancel out in an ideal economic world. From a social point of view, rather than adjust the models to take into account non-market behaviour, all behaviour are reduced to market behaviour, and all motivation ascribed to self-interest (Mirowski, 1986, Sandel, 2013). From an ecological point of view, because an isolated system has no outside, no environment, natural resources are considered scarce only inasmuch as they can be converted in market goods to fulfil alternative purposes. Indeed, the main body of mainstream economics had paid practically no attention to natural resources until the early 1970s, when NC economists began to show interest in the natural environment and they developed two new sub-disciplines: environmental economics (EV) and natural resource economics (RE). Those new fields kept the main NC assumptions: the environment is seen as another kind of capital to be priced, sometimes through fictitious market, and allocated efficiently. Why doing so? Why every value should be priced?

Daly and Farley (2011) put it clearly: "Traditional economists assume that only preferences for market goods [matter] and implicitly assumes that non–market goods contribute little to welfare [which is the ultimate end]" (p. 4). The main result, attained by Arrow and Debreu (1954), was the 'proof' that, in an ideal world, markets efficiently allocate 'scarce' resources between alternative (and competing) ends. In a world where preferences are given, in order to make 'rational' choices, to wit comparing pleasures and pains, everything must be expressed in an uniform unit of measure (reductionism), that is $money$. This conclusion follows from a crucial assumption on monetary conversion: it is alleged that markets are neutral with the respect to the process of evaluation. The reductionist program moves from the attempt to develop methods for capturing in monetary terms the 'value' of environmental assets. Consumer sovereignty requires that each value must be reduced to individual preferences. The most common method is the 'contingent valuation' in which people are asked how much they are willing to pay (WTP) to preserve some environmental goods or services, or how much they are willing to accept (WTA) in compensation for environmental loss or degradation. Many authors put in evidence several problems of these techniques, *in primis* the fact that most of the time WTA differs from WTP (framing bias). Moreover, people have limited cognitive capacities that hamper the possibility to properly evaluate all the consequences from environmental shocks, they lack of knowledge and information (Barrotta, 2013), or simply they do not want to attach a monetary value to certain kind of natural resources (value incommensurability). Another fallacy of the WTA and WTP approaches simply relies on the distributional issue: because richer people can afford higher prices for environmental goods, it does not mean that they care more about environment. These approaches are founded on a 'category mistake' (Sagoff, 2008) because they confuse private desires with public judgements. The public 'preferences' an individual expresses, as a citizen, are statements of belief about the good of the community which are open to reasoned argument. Thus the inclusion of non-hedonistic ethical judgments (e.g. attribution of environmental rights, preservation of bio-diversity) into a cost-benefit (CB) logic is illegitimate because it is inconsistent with the CB rationale itself. These judgments cannot be priced because they do not concern the expected benefits to those who make them.

Sandel (2013) makes clear that markets are far from being neutral: once a good is transformed into a commodity only who is rich enough to afford it can enjoy from its consumption. The distribution is therefore crucial in the process of evaluation. Secondly, he claims that markets 'corrupt' the value of specific goods (for instance renting parts of the body for marketing purposes, renting uterus, trading rights for CO_2 emissions and so forth) when they are monetised because they are evaluated with inferior or distorting tenets. A very simple example may clarify the point. Sandel (2013) reports a recent initiative introduced in a primary school, in Dallas (USA), in order to stimulate students to read more: two dollars per book. Independently from the success of this operation, what matters here is to underline that the monetisation of the 'enjoyment from reading', and of the attitude to learn more, alters the frame in which children perceives the value of reading. There is an inversion between means and ends: insofar pupils gain money from reading, then the end becomes to earn more, while learning is transformed into a mean of this new purpose. This practice makes the value of reading perfectly substitutable with any other remunerative activity. To wit, a child may prefer to sell lemon juice rather than study if she can earn more. At the end of the process we could observe an increase in the number of juices sold, a richer child but a (potential) read-lover less. There are at least two main consequences: the commodification of the world alters the process by which people develop their own preferences and, secondly, environmental policy needs to answer to public democratic debate, not to mechanisms borrowed from the market. This stance is in line with a broader concept of rationality and with the request of pluralism made by ecological economists, as discussed in the next subsection.

I have to add another caveat to the process of commodification based on the alleged belief that Economics is a value-free science as advocated by Robbins (1932), who asserted in his Essay: "Economics is entirely *neutral between ends*; [....] in so far as any end is dependent on scarce means, it is germane to the preoccupations of the economist"(p. 24, emphasis added) and further supported by Friedman (1953). It is concerned with ends in so far as they affect the disposition of means. The rejection of the fact/value dichotomy moves both from within and outside the market system: i) there is, as seen, a categorical mistake Sagoff (2008) when one wants to reduce any value to preference, and ii) there are moral limits to what can be included in the market process (Barrotta, 2013, Sandel, 2013). Let assume that there exist an unique common measure upon which compare alternative choices and that the $market$ is the best institution to find the 'true' value of goods. Everything becomes comparable and, most important, substitutable. To wit, if a person is indifferent between the preservation of the Amazon forest and a given amount of money, then the two option must be equal in every (relevant) aspect. Regrettably, once the forest is destroyed it is not possible to compensate the ecological damage through money, not even if all the externalities are internalized in the price. One may rebut this point, claiming that money might be invested in order to compensate for the damages. Let assume that we have the time, the technology and the knowledge sufficient to restore the very same (ecological) functions of the forest; other two caveats may arise. First of all, the potential aesthetic satisfaction from the enjoyment of the forest is lost forever and the $rights$ of those people who were against the monetary evaluation of natural stock gone without any possible compensation (in fact they refuse to put a price to the forest, therefore refund them with money seems unreasonable). Secondly, how much can we extend this kind of reasoning? What is the price of the whole stock of forests all over the world? And of the whole natural resources? If rational choice must be based simply on monetary comparison, then we should accept either that there exist a finite price for the whole stock and flows from nature (that is to conceive a world without any natural resource but with an incredible amount of capital, though it is difficult to imagine made of what!) or that, if that price does not exist (or it is infinite), then we cannot decide whether we prefer a world without nature or not. Obviously this seems absurd. Physical laws, ecological limits and moral commitments posit absolute boundaries to the extension of markets. Indeed, from a political point of view, if in democracy one head is one vote, within markets 'one dollar is one vote'. This subtle difference implies vast asymmetries inasmuch as economic inequality grows. A society utterly governed by markets leads to opposite results than what Popper (1945) viewed for his *Open Society*: because markets do not care about motivation and justification, they are closed to any critical debate and therefore each problem would be solved in an authoritative mode. Its mechanistic nature would, automatically and necessarily, force the whole society to organize its life based on a given vector of price.

After World War II, NC focused on the study of economic growth, seen as a panacea solution to attain welfare improvement, poverty reduction, jobs creation and so forth. From a theoretical point of view, this target is based on the assumptions seen above plus the non-satiety assumption for which more consumption must always be preferred (that means that humans are doom to be always unsatisfied!). The chain of NC reasoning can be resumed as follow: economic reality is an independent entity which works in a deterministic and mechanical way, it is composed by independent individuals who rationally fulfil their (given) own preferences, with respect to exogenous constraints. Because they receive utility only from the consumption of market goods and they can decide only through arithmetic calculation, everything must be monetised. Finally, if one aims to increase the global welfare, continuous economic growth is the only conceivable solution. How is it possible a continuous economic growth in a world of limited resources, space and time?[1]

In order to combine the growing request for sustainability and intergenerational equity, NC economists replied with the concept of 'Weak Sustainability', which is based on the very strong assumption of $substitutability$ among different forms of capital (physical, natural and human). It states that an economy is sustainable if it saves more than the combined depreciation of natural and man-made capital Pearce and Atkinson (1993). As seen, the necessary precondition is the monetary evaluation of each capital stock. It appears an odd inversion where nature is viewed as a subsystem of the economic world, or more precisely, it represents a general practice in which any conceivable problem is reduced in terms of economic evaluation neglecting the real (physical and ecological) effects. This position stands behind the Whitehead's 'fallacy of misplaced concreteness' by which he meant the error of treating an abstract model, made with the purpose of understanding one aspect of reality, as if it were adequate for understanding everything, or entirely different things, things that had been abstracted from in making the model (Whitehead, 1929).

C.2 Entropy Law and Strong Sustainability

EE asserts that it is impossible to abstract the economy from its environment, rather the ecological economist should study how they interact and which actions should be done to pursuit a sustainable Co-Evolution of them. This worries becomes more and more stringent inasmuch as the economic sub-system approaches to the size of the earth, which is all that we have. Though subtle, this difference make NC and EE paradigms incompatible.

Physical laws and Economics are more interwoven than one would

[1]See for an illustrative example Georgescu-Roegen (1960). Moreover, Georgescu-Roegen (1971) critics the economic assumption of time symmetry by distinguishing the Time (stream of consciousness), which is irreversible, from time (measures of an interval). Moreover even if we neglect any Entropic constraints, most economic process (e.g. urbanization) requires a time to be converted in a way to restore the initial condition (uncontaminated nature) that is far longer than human existence.

expect *prima facie*: EE is the nearest descendant of the Second Law of Thermodynamics (SLT), which states that the Entropy (dissipation of available energy/matter) of any closed system is doomed to increase indefinitely. The pioneering studies of Georgescu-Roegen (henceforth GR) went even further in claiming that "[T]hermodynamics is at bottom a physics of economic value - as Carnot unwittingly set it going- and the Entropy Law is the most economic in nature of all natural laws" (Georgescu-Roegen, 1976, p. 8-9) which implies that *"[O]ur whole economic life feeds on low entropy"* (Georgescu-Roegen, 1971, p. 277, original emphasis). GR did not simply rely on an analogy, rather he established the manifold consequences of the SLT, for the economic process (and for the academic activity), that can be resumed as: i) the $anthropomorphic$ origin of any science and form of knowledge; ii) the $irreversibility$ and the unidirectional path of actual phenomena; iii) the $qualitative\ change$ of the material (and organic) universe which is involved in an evolutionary process, and iv) the inescapable $absolute\ scarcity$ of low entropy and the unavoidable natural laws and limits.

Admittedly the concept of **Entropy** is not easy to catch for an economist by training, actually "it is not easily understood even by physicists" (ter Haar, 1959, p. 37). Following GR, I report the most tractable, for my purposes, definition of Entropy thought as "an index of the amount of *unavailable energy* in a given thermodynamic system at a given moment of its evolution. [An] equivalent formulation is that the entropy of a *closed system* continuously (and *irrevocably*) increases toward a maximum, [i.e.] all kinds of energy are gradually transformed into heat and heat becomes so dissipated in the end that man can no longer use it" (Georgescu-Roegen, 1976, p. 7-8, original emphasis). The very qualitative distinction between low (available) and high (unavailable) entropy is by no means objective, indeed energy is considered available inasmuch as can be transformed into work devoted for whatever human activity. It serves an anthropomorphic telos: the '*enjoyment of life*'. It implies that the observer is not only non-neutral in its epistemological endeavour (Heisenberg principle), but rather its own Pre-Analytical Vision shapes the context in which natural (and social) laws are drawn. Another crucial feature that matters here is the concept of closed, but not isolated, system. EE starting point is the acknowledgment of the fact that economy, as any other human activity, is embedded in the natural system and therefore it cannot be abstracted from it. The economic system is not self-sufficient because it needs a continuous inflow of low entropy from the natural environment in order to fulfil its purposes, actually "[T]he economic process consists of a continuous transformation of low entropy into high entropy, that is, into *irrevocable waste* or, with a topic term, into pollution" (Georgescu-Roegen, 1971, p. 281, original emphasis). From a physical point of view, low entropy represents the 'ultimate mean' of any economic activity and there are essentially only two sources of it: terrestrial stocks of (non-renewable) concentrated minerals and (renewable) solar flow of radiant energy. The first is limited in the absolute amount, while the second in its rate of arrival. Jointly, they represent an absolute scarcity for the fulfilling of unlimited human desires or, in other words, "any time we produce a Cadillac, we do it at the cost of decreasing the number of human lives in the feature" (Georgescu-Roegen, 1976, p. 59). Although the debate on technological progress cannot be treated here, one point deserves to be clarified in order to make the above statement meaningful. The biologist Alfred Lotka introduced in the early 1920s the fundamental distinction between the *endosomatic* use and the *exosomatic* use of energy by humans. The former is due to body organs and is fairly distributed among humans, while the second refers to the instruments produced by man but not belonging to his body. Human history has developed through a rapid adaptations of exosomatic organs (hammer, machines, etc.) that depend on terrestrial low entropy. If it is true that "the price of technological progress has meant a shift from the more abundant source of low entropy – the solar radiation – to the less abundant one – the earths mineral resources" (Georgescu-Roegen, 1971, p. 304), then a faster technological progress would mean a faster transformation of low entropy in irrevocable wastes and, therefore, a lower level of available resources for future generations. The concerns of many ecological economists for equal *intra*– and *inter*– generation distribution stands on the fact that the exosomatic evolution has turned production into a social undertaking.

Inasmuch as the economy grows, and its $size$ approaches to that of the earth, we pass from the 'cowboy' economy (Boulding, 1966) to the so called 'full-world' (Daly and Farley, 2011). The trade–off between the potential welfare-gain due to economic service and the (possible) loss of ecological services and functions (with negative impact on human welfare too) becomes more stringent. This fact, together with the limit of economic evaluation, claims for the combination of economic and physical indicators (e.g. footprints) to trace the techno-economic feasibility and sustainability of current production processes. This view led to the introduction, as opposed to Weak Sustainability, of the term '*Strong Sustainability*' (Munda, 1997) which is based on the assumption that certain sorts of 'natural capital' are deemed critical (e.g. water), and not readily substitutable by man-made capital. Baumgartner and Quaas (2010) identify four core attributes of (Strong) Sustainability: $i)$ focus on the relationship between humans and ecological systems, $ii)$ orientation towards long-term (uncertain) future, $iii)$ normative foundation in the idea of justice and $iv)$ concerning for non-wastefulness of limited natural resources in order to not jeopardize future generations. Fair enough, but how do we attain it?

Daly (1976) argued in favor of a 'Steady-State' economy with two constant elements (in the medium term), population and stock of artifacts, while everything else (technology, distribution, information, etc.) is allowed to change. However, GR alerted that this dream is doomed to fail because "even with a constant population and a constant flow per capita of mineral resources, mankind's dowry will ultimately be exhausted if the career of the human species is not brought to an end by other factors" (Georgescu-Roegen, 1971, p. 296). From this standpoint many authors posit the challenge of a controlled and voluntary 'Degrowth' which aims at reducing the material consumption without decreasing the well–being toward a fair distribution of resources both within and between generations. Though fascinating, also this position faces many problems. GR, *in primis*, recalled that any society based on exosomatic tools will inexorably dissipate the available energy/matter unless it reverts its evolution to a 'berry–picking economy'. Secondly, many developing countries are now living in a state of poverty and deprivation such that the search for economic improvements seem more urgent than environmental concerns. Finally, one must face the *vexata quaestio* of what needs, other than the biological ones, are necessary for humans to be humans and to have a decent life. Once we have established the optimal bundle of consumption, how long can a constant population be maintained with a constant level of consumption? Actually this is not a technical problem, rather a $moral$ one. In order to provide a meaningful answer we should debate on the length of the horizon of our (current generation) responsibility. If it seems fair to be worried for the destiny of human beings in the next 100-200 years, it seem out of our imagination to feel responsible for the fate of humans who will live after a thousand (or say million!) years from now.

In order to understand the reasons and the need of a pluralistic and multi-dimensional (extra-economic) stance, I have to add a further issue. GR dedicates a whole chapter[2] to the problem of $measure$ both in science and economics, most notably how scholars define cardinal measure. Geometry and mechanics are based on two attributes measurable with cardinal numbers: indifferent distance (length) and indifferent time interval, each one expressing qualitatively homogeneous entities which only vary in quantity. The search for cardinal measures enable the scientist to aggregate, along a common scale, by "indifferent subsumption and subtraction in a definite physical" (Georgescu-Roegen, 1976, p.98, original emphasis). He identifies other two kind of measures: weak cardinality (quantified qualities) where some qualities (e.g. heat, hardness, etc.) are transformed into cardinal numbers, at the expense to leave some qualitative residuals out from paper-and-pencil calculations; while purely ordinal measures regard to qualitative differences not reducible to cardinal number. An example is given by historical dates that cannot be reduced to cardinal number or subsumed in any meaningful way. If the economic world were composed by quantum units, with stable prop-

[2]See "Measure, Size and Sameness: Some Object Lessons from Physics", (Georgescu-Roegen, 1976, Ch. IV, p. 95-113).

erties, then there would be no problem in measuring them with cardinal numbers, nor in converting them into a common scale (money) with a strict monotonic transformation. The epistemological consequence in economics should be the triumph of mathematical formalism, and proportional laws, and the exclusion of any 'disturbing factor'. However, the very invocation of these 'disturbing factors' (psychology, sociology, history, low entropy, etc.) is the proof that some qualitative residuals have been left out. Obviously, the attempt of describing economics through pure ordinal variables would be pernicious; while recognizing that most of the economic phenomena are quantified qualities is crucial because it introduces the concept of size. In modern terms this is translated in the debate on optimal scale, so important mostly from a macro ecological-economic perspective: "The nearer the subsystem approaches the total system in scale, the more it must become like the total system in its basic characteristics: finitude, non-growth, material closure, and reliance on the flow of sunlight as its main energy source. The path of progress for the economy must shift from quantitative growth to qualitative development" (Daly, 2007, p. 27). The recognition of a limit to the process of (monetary) reductionism stands behind the effort of many contemporary ecological economists to compute the ecological indirect effect of economic activities in order to provide extra-market knowledge to the problem of attaining sustainability. The roots of this stance stand on the writings of Popper-Lynkeus (1912) and, most notably, of Neurath (1973). He moved his theory in response to von Mises who claimed that without monetary conversion (unit of measurement) there would be impossible any rational decision. Instead, Neurath focused on the ethical and political dimensions in which each decision must be judged. In modern terms, it is a recognition that "Social costs and social benefits have to be considered as extra-market phenomena; they are borne and accrue to society as a whole; they are heterogeneous and cannot be compared quantitatively among themselves and with each other, not even in principle" (Kapp, 1970, p. 49). Moreover, recognizing that even the most abstract branches of knowledge, logic and mathematics, incorporate unprovable and hence arbitrary assumptions, implies the impossibility of ethical neutrality. On the contrary principles and values must be stated explicitly and they must become part of dialogue and of the political process (Funtowicz and Ravetz, 1991).

The strengths of the concept of sustainability are also its weaknesses. If one wants to be open to plural and irreducible stances, omnicomprehensive, fair with the current and future generations, concerned about natural limits and ecological balances, then one should accept the conflict between different positions and the vagueness of these concepts. However, I do believe that the pros are more than the cons. Once one admits the value-laden nature of economic knowledge, the purpose-laden origin of economic process and the inexorable conflict of exosomatic societies, then the concept of sustainability seems to be adequate not so much for its content, but rather for its tenets. I think we should look at it as an empty-box (rather than a black-box) which continuously needs to be filled with contingent and heterogeneous ethical purposes based on the perceived urgent (global and local) challenges where anyone, from the scientist to the layman, participate in the process of problem-solving. Democratic participation and critical debate are important ingredients of this process. Given its focal importance I will pass through this concept again and again in what follows.

C.3 Incommensurability and Ends

Incommensurability is the pillar of EE, however in order to understand its role I should briefly recall the never–ending debate within philosophy of Science. Gattei (2008) provides a clear overview of this concept in science and its evolution. The term incommensurability derives from the standard employment of this concept in geometry and mathematics: "two quantities are said to be incommensurable if there is no common measure whole units of which divide both of them" (p. 74). In philosophy of Science the term has been introduced to question whether the scientific knowledge might be regarded as a cumulative enterprise, understood as a mere accumulation of new problems, solutions and standards, resulting in increasing (quantitatively and qualitatively) knowledge. This topic is vast and complex, but only one point deserves to be mention in this context, that is the debate on rational decisions among competing scientific theories. Here incommensurability stands for the impossibility to decide only on the base of pure rational thinking because there is not a neutral language (Feyerabend, 1975), and not even a neutral algorithm (Kuhn, 1962), and because it does not exist a meta-rationality (Frola, 1964) that, a priori, provides the standards and the criteria for a rational choice. Though these observations were posited by 'irrationalists' philosophers, we find similar conclusions (at least with regard to the process of decision, abstracting from any ontological contention) from other opponents. Geymonat (1945) observes that we should look at historically determined relationships to make sense of the development of theories, and their selection (without invoking any metaphysical incomparability). Even Popper (1945) thought that reasoning would be regarded as a social process of inter–subjective confrontation, therefore societies should set up those institutions which facilitate critical debates (i.e. 'democratic control') avoiding any authoritarian answer. If historical, social and political factors have a role in the development of scientific theories (with more or less agreement), why should we get rid of them in case of economic decisions? How incommensurability could be a resource, rather than a limit, when dealing with economic and ecological systems? I develop two focal issues with which, hopefully, I argument in favour of a pluralistic approach to economic epistemology in order to supersede the reductionist program and the NC monism. The first one is the problem of Qualitative change and the emergence of complexity; while the second refers to the political consequences of multi-level ends-means relation.

Recognizing the **evolutionary** nature of biological and social systems implies an (economic) epistemology devoted to the study of complex systems governed by non-linear relationships, characterized by the possible 'emergence of (unexpected) novelties' by combination (Heinzel, 2012). For instance, in his classic *The Great Transformation*, Polanyi (1944) showed that the economic system is embedded as a component of human culture, and like our culture, it is in a constant state of evolution characterized by qualitative changes in the economic structure, human interactions and institutions. Complexity is a multidisciplinary concept derived from mathematics and physics, however extra complications arise in economics due to the nature of social interactions. This is linked with the understanding of how tightly or loosely coupled are processes at different scales (O'Neill, 2004), which helps to elucidate hierarchies of interacting systems. The latter observation is the ontological justification for the vision of a multi-level reality, where each strata is conceived as irreducible (contra-reductionism) to those at lower level, though they may depend on them. The dependence of economic systems on the Entropy Law makes this stance evident: each economic process feeds by low entropy but the enjoyment of the output of production is a result of a 'mental state' which is not reducible neither to the physical characteristic of goods nor to the 'amount' of available energy used. It poses a limit to the current efforts, of many ecological economists, to compute the indirect effect of economic activity on the available resource (i.e. footprint) or to reduce the whole economic process to the amount of energy embedded in each product. Georgescu-Roegen, again, noticed that the economic process depends on the sorting activity, of low entropy, of humans who purposively convert the flux of available energy (and matter) into the final output of the economic process: the enjoyment of life. He captures the two essential features of the hierarchical view of reality and teleological nature of economy when he admitted that "we cannot arrive at a completely intelligible description of the economic process as long as we limit ourselves to purely physical concepts. Without the concepts of *purposive activity* and *enjoyment of life* we cannot be in the economic world. [....] The economic process, to be sure, is entropic in each of its fibers, but the paths along which it is woven are traced by the category of utility to man. It would therefore be utterly wrong to *equate* the economic process with a vast thermodynamic system [....] which allow no discrimination between the economic value of an edible mushroom and that of a poisoned one." (Georgescu-Roegen, 1971, (p. 282-283, original emphasis). This point needs to be coupled with a discussion around the ends-means relation.

Values, such as liberty and equality, are sometimes said to be incommensurable in the sense that their value cannot be reduced to a common measure. Daly (1991) put it paradoxically: how can it be that the only things that are supposed to have value in public discourse are value-free (and I dare to add ends-free) facts? The problem of value incommensurability is twofold: it regards a single individual when she faces hard choices and the society as a whole, when conflicting interests (and ideologies) clash. Ends are not exogenous but they are generated in the very process of action. Means and ends mutually interact and determine. As noted by Crespo (2007) the **ends-means** relation is not linear, rather it can be divided between: i) ends that are only means for attaining something else (first-order or instrumental ends), ii) ends that are desirable in themselves and that are parts of the final end (second-order or constitutive ends), and iii) ends which are only desirable in themselves (third-order or final ends). Even admitting the Utilitarian ultimate end, hedonistic satisfaction, there is no reason in principle to conceive the other intermediate ends as purely means considered as commensurable and interchangeable. For example, self–interested people may find satisfaction by the accumulation of wealth, by increasing political power or by having a career in a professional work, which are constitutive ends. If one admits that claiming 'power is twice more important than career' is odd, if not inconceivable, then one has to recognize that the monetary reductionism is unattainable unless one accepts the validity of 'wealth is twice more important than career.' How should one decide among them? Once one accepts that the final end cannot be grasped directly and that we have to pass from its parts, it might be recognized that incommensurability could be a resource rather than a limit. Even though the debate on ends is not possible within the instrumental rational logic, it does not mean that it is impossible to put reasons in favour or against certain ends, or even to propose new ends (e.g. sustainability). Following this line of thought the question is shifted from "how to allocate scarce means to efficiently fulfil given ends?" to "how to set up those social institutions which facilitate a critical debate on the ends that are currently pursued in the society in order to improve them or to reduce the possible conflicts?"

Based on the arguments exposed so far, many ecological economists (Funtowicz and Ravetz, 1991, Martinez-Alier, 2002, among others) claim for an extension of the participation in the decision process, beyond experts, by including local communities and layman. This view is strictly tied with the Popperian idea of Rationality, in a broader sense, and the Senian's quest of the role of ethics in economic decisions. When we move from the social realm to the scientific arena, Popper advocates in favour of what has been labelled as a *pancritical rationalism*,[3] for which being rational requires the complementary notion of reasonableness. Here we find all the ingredients present both in the Senian theory of economic choice and, as seen, in the EE stance. The most important one is recognizing that rationality is social and critical. Depending on how we learn to be rational we may have heterogeneous economic attitudes, mostly based on the social structure of norms, beliefs and rules of conduct. Why hedonistic self-interest attitude should be regarded as the only (and scientifically relevant) *raison d'être* of economic agents? Sen (1977) recognized that, though important, it is not the only source of a person's choice. Rather, morality and ethics (e.g. commitments, trust and sympathy) play a crucial role, especially when dealing with public goods such as environmental services, bio–diversity preservation and clean air.

Finally, a crucial prerequisite toward a rational debate on ends stands upon the process of 'self-criticism' in which evaluating our own preferences and values. Recognizing that they are not exogenous is crucial to understand human choices and, above all, to establish democratic solutions to urgent problems, without succumbing to any sort of tyranny (consumers sovereignty implies the 'tyranny of tastes'). Self-awareness rises from the fact that humans are not only users of symbols but also the object of the symbolism. Neglecting the fact that people are actively involved in the process of choice, by thinking about their preferences in the elaboration of choice theory, seems an arbitrary (and normative!) 'choice'. Acknowledging this crucial feature of human beings is the first step toward the concept of (consumer and firms) *responsibility*,[4] in par-

[3]See (Popper, 1945, p. 225).

[4]The concept of consumer's responsibility is captured by the parameter δ of the Evolu-

ticular with respect to ecological systems and future generations.

C.4 Concluding Remarks

This Appendix briefly overviews two different branch of Economic studies, i.e. NC and EE, underlying the implication of somehow different Visions. EE, notwithstanding its limitations, is thought to be able to provide a framework capable to embrace the major stances coming from philosophy of Science, ecology, anthropology (with its psychological and sociological facets) and economy itself. Value incommensurability has been introduced as a resource, rather than a limit, and the pluralistic approach of EE should facilitate the process of conciliation and debate between conflicting ends. This approach is crucial because it is focused on human responsibility which requires the need to think and to critically debate on which state of the world is better rather than another. Rational debate on moral issues is possible and necessary. Popper's irrational belief on rationality is completely in accordance with the EE stance, at least when there are suitable institutions which facilitate this process. Markets cannot be such institution because, by equating money with decisional power, they distort the choice in favor of more affluent people, independently from their reasons or expertise. Regrettably, textbook economics cannot deal with conflictual ends with its narrow logic. Modern standard economics is based on commensuration and commensuration is only possible when each value is reducible to price. Nevertheless, as noticed by Crespo (2007) there are also frequent occasions on which the relevant decision criteria on ends are purely economic and where standard tools might work. Economics should open the door to non-academic problem solving processes where local (rural, aboriginal, urban or whatever) communities and layman are taken into account both in defining the main issues and in proposing alternative solutions, as exposed in Chapter 4.

I am not suggesting any concrete proposals. I would only like to stress that, given the previous conclusions I propose that 'Ecological' may be

tionary Game exposed in Chapter 4.

seen as a misleading label and even superfluous. Even though it is based on the Entropy Law and natural limits, it does not mean that its approach should be limited to treat always and necessarily the environmental implications of the economic process. Indeed, admitting that economy is embedded in its environment should be seen as obvious as stating that economic process are made by human. Not for that we call it 'Human' economics. Rather, this Vision amplifies the NC approach by broadening its anthropological and physical content. EE is focused on the evolutionary features of qualitative change, time irreversibility and epistemic uncertainty, on ends incommensurability and class conflicts, physical laws and natural limits (as we currently know) and bounded rationality all of which hold to human systems without any need to add the 'Ecological' label. Indeed, we find many predecessor of EE with no primary concerning on ecological issues in Shumpeter, Neurath, Malthus, Sen and as we have seen even Popper, among many others.

Finally, I dare to introduce a new definition of Economics, not pretending to be exhaustive but rather evocative of the direction where (ecological) economics should move: *Economics is the human practice which aims to provide new knowledge on the relation between absolute scarcity (low entropy), relative scarcity, social and individual ends in order to boost the realization of those institutions which facilitate a critical debate on incommensurable ends and the definition of new ends and new (non-violent) solutions towards the conciliation of the exosomatic development of society (with its burden of class and environmental exploitation) and the improvement of human well-being with the respect to (inescapable) natural limits*.

References

Acemoglu, D., V. M. Carvalho, A. Ozdalgar, and A. Tahbaz-Salehi (2012). The network origins of aggregate fluctuations. *Econometrica 80*(5), 1977–2016. 10, 16, 28, 32, 41

Agrawal, A. (2008, March 5-6). The role of local institutions in adaptation to climate change. Technical report, Social Dimensions of Climate Change, Social Development Department, The World Bank, Washington DC. 77

Alcamo, J., M. Florke, and M. Marker (2007). Future long-term changes in global water resources driven by socio-economic and climatic changes. *Hydrolog. Sci. J. 52*(2), 247–75. 44, 45, 71

Aldasoro, I. and I. Angeloni (2015). Input-output-based measures of systemic importance. *Quantitative Finance 15*(4), 589–606. 10

Allan, J. A. (1993). Fortunately there are substitutes for water otherwise our hydropolitical futures would be impossible. *Priorities for water resources allocation and management, ODA, London*, 13–26. 13

Allan, J. A. (2003). Virtual water - the water, food, and trade nexus. useful concept or misleading metaphor? *Water International 28*(1), 106–113. 12

Andreoni, V. and A. Miola (2014). Climate vulnerability of the supply-chain: Literature and methodological review. Technical Report 26994, European Commission, Joint Research Centre, Institute for Environment and Sustainability. 11, 15

Ang, B. W. and F. Liu (2001). A new energy decomposition method: perfect in decomposition and consistent in aggregation. *Energy*. 9

Antonelli, M., R. Roson, and M. Sartori (2012). Systemic input-output computation of green and blue virtual water flows with an illustration for the mediterranean region. *Water Resources Management 26*(14), 4133–4146. 7, 12

Arrow, K. and G. Debreu (1954). Existence of an equilibrium in a competitive economy. *Econometrica 22*, 265–290. 145

Arto, I., A. Gently, J. Rueda-Chantuche, A. Villanueva, and V. Andreoni (2012). Global resources use and pollution: production, consumption and trade (1995-2008). Technical report, European Commission - JRC Scientific and Policy Report. 22

Arto, I. e. a. (2012). Water use, water footprint and virtual water trade: a time series analysis of worldwide water demand. In *20th International Conference of Input-Output Techniques. C. Lager. Bratislava, Slovakia.* 8, 20, 25

Barnaby, W. (2009). Do nations go to war over water? *Nature 458*(7236), 282–3. 7

Barrat, A., M. Barthelemy, and A. Vespignani (2008). *Dynamical processes on complex networks.* New York: Cambridge University Press. 9

Barrett, S. (1994). Self-enforcing international environmental agreements. *Oxford Economic Papers 46*, 878–894. 75

Barrotta, P. (2013). Economia e natura. *Spazio Filosofico*. 145, 147

Baumgartner, S. and M. F. Quaas (2010). What is sustainability economics? *Ecological Economics 69*(3), 445–450. 152

Bodansky, D., E. Diringer, J. Pershing, and X. Wang (2004). Strawman elements: Possible approaches to advancing international climate change efforts. Technical report, Washington: Pew Center on Global Climate Change. 77

Boulding, K. (1966). The economics of the coming spaceship earth. *Creative Commons Attribution - Share Alike license*. 152

Brown, A. and M. D. Matlock (2011). A review of water scarcity indices and methodologies. Technical report, University of Arkansas. 49

Calvo, E. and S. J. Rubio (2012). Dynamic models of international environmental agreements: A differential game approach. In *International Review of Environmental and Resource Economics*. 76

Carr, J. A., P. D'Odorico, F. Laio, and L. Ridolfi (2013). Recent history and geography of virtual water trade. *PLoS ONE 8*(2). 10

Carraro, C., J. Eyckmans, and M. Finus (2006). Optimal transfers and participation decisions in international environmental agreements. *Review of International Organizations 1*(4), 379–396. 76

Carraro, C. and D. Siniscalco (1993). Strategies for the international protection of the environment. *Journal of Public Economics* (52), 309–328. 75

Carvalho, V. M. (2012, December). Input-output netword: a survey. Technical report, European Commission, CRISIS project. 9, 10, 16

Cazcarro, I., R. Duarte, and J. Sanchez-Chaliz (2013). Economic growth and the evolution of water consumption in spain: A structural decomposition analysis. *Ecological Economics 96*, 51–61. 9

Chapagain, A. and A. Hoekstra (2007). Water footprints of nations: Water use by people as a function of their consumption pattern. *Water Resources Management 21*(1), 35–48. 12, 13, 48

Colmer, J. (2011). Asymmetry, optimal transfers and international environmental agreements. forthcoming in Oxford Economic Papers. 76

Common, M. and S. Stagl (2005). *Ecological Economics: an Introduction*. Cambridge University Press. 142

Contreras, M. G. A. and G. Fagiolo (2014, December). Propagation of economic shock in io network- a cross country analysis. *Physical Review E 90*(062812). 10, 16

Costanza, R. (1991). *The Science and Management of Sustainability*. Columbia University Press, New York. 142

Courtois, P., J. Pereau, and T.Tazdait (2004). An evolutionary approach to the climate change negotiation game. *Louvain Economics Review 70*(1), 31–51. 76

Crespo, R. F. (2007, August). Practical comparability and ends in economics. *Journal of Economic Methodology 14*(3), 371–393. 158, 160

Dalin, C., M. Konar, N. Hanasaki, A. Rinaldo, and I. Rodriguez-Iturbe (2012). Evolution of the global vwt network. *PNAS 109*(16), 5989–5994. 10, 50

Daly, H. E. (1976, May). The economics of the steady-state. *American Economic Review*, 15–21. 152

Daly, H. E. (1991). *Steady State Economics* (2nd ed.). Washington, D.C.: Island Press. 158

Daly, H. E. (2007). *Ecological Economics and Sustainable Development,*. Edward Elgar. 154

Daly, H. E. and J. Farley (2011). *Ecological Economics: Principles and Applications* (Second ed.). Island Press. 142, 145, 152

De Fraiture, C. e. a. (2007). Looking ahead to 2050: scenarios of alternative investment approaches. water for food,water for life: a comprehensive assessment of water management in agriculture. *Earthscan, London, UK*, 91–145. 45, 124 de Zeeuw, A. (2008). Dynamic effects on the stability of international environmental agreements. *Journal of Environmental Economics and Management 55*(2), 163–174. 76

Dellink, R. e. a. (2013). Consequences of climate change damages for economic growth: A dynamic quantitative assessment. *OECD Economics Department Working Papers 1135*. http://dx.doi.org/10.1787/5jz2bxb8kmf3-en. 46

Dietzenbacher, E. and B. Los (1998). Structural decomposition techniques: Sense and sensitivity. *Economic System Research 10*(4), 307–324. 9, 113

Dietzenbacher, E. and B. Los (1999). Structural decomposition analyses with dependent determinants. *Economic Systems Research 12*(4), 497–514. 109

Distefano, T., G. Marin, and M. Riccaboni (2014). Global virtual water trade: Integrating structural decomposition analysis with network theory. SEEDS Working Papers. 50

D'Odorico, P., J. Carr, F. Laio, and L. Ridolfi (2012). Spatial organization and drivers of the virtual water trade: A community-structure analysis. *Environmental Research Letters 7*(3). doi:10.1088/1748-9326/7/3/034007. 10

Ebenstein, A. (2012). The consequences of industrialization: Evidence from water pollution and digestive cancers in china. *Review of Economics and Statistics 94.*(1), 186–201. 63

Edenhofer, O. e. a. (2012). Workshop report of the intergovernmental panel on climate change workshop on socio-economic scenarios. Technical report, IPCC Working Group III Technical Support Unit, Potsdam Institute for Climate Impact Research. 46, 51, 75

Elliott, M., B. Golub, and M. O. Jackson (2014). Financial networks and contagion. *American Economic Review 104*(10), 3115–3153. 16

Endres, A. (1995). Zeitschrift fur umweltpolitik. *Zurekonomie Internationaler Umweltschutzvereinbarungen 8*, 143–178. 90

Endres, A. and M. Finus (1998, September). International environmental agreements: How the policy instrument affects equilibrium emissions and welfare. *Journal of Institutional and Theoretical Economics (JITE) / Zeitschrift fur die gesamte Staatswissenschaft 155*(3), 527–550. 89, 90

Ercin, A. and A. Hoekstra (2012). Water footprint scenario for 2050 - a global analysis and case study for europe. *Environment International 64*, 71–82. 44, 45, 46, 48, 57, 64, 69, 72, 124

Ferng, J. (2009). Applying io analysis to scenario analysis of ecological footprint. *Ecological Economics 69*(2), 345–354. 45

Feyerabend, P. K. (1975). *Against Method. Outline of an Anarchistic Theory of Knowledge*. London: New Left Books. 156

Finus, M. (2001). *Game Theory and International Environmental Cooperation*. Edward Elgar Publishing Limited. 90

Friedman, M. (1953). *Essays in Positive Economics*. University of Chicago Press. 147

Frola, E. (1964). *Scritti metodologici*. Turin: Giappichelli,. 156

Funtowicz, S. and J. R. Ravetz (1991). A new scientific methodology for global environmental issues. In R. Costanza (Ed.), *Ecological Economics: The Science and Management of Sustainability*, pp. 137–152. New York: Columbia University Press: 137152. 143, 155, 159

Futowicz, S. and J. Ravetz (1994). The worth of a songbird: Ecological economics as a post-normal science. *Ecological Economics 10*(3), 197–207. 91, 143

Gattei, S. (2008). *Thomas Kuhn's 'linguistic turn' and the legacy of logical empiricism: incommensurability, rationality and the search for truth*. Ashgate Publishing Limited. 155

Georgescu-Roegen, N. (1960). Economic theory and agrarian economics. *Oxford Economic Papers New Series 12*(1), 1–40. 149

Georgescu-Roegen, N. (1971). *The Entropy Law and Economic Process*. Harvard University Press. 149, 150, 151, 152, 157

Georgescu-Roegen, N. (1976). *Energy and Economic Myths. Institutional and Analytical Economic Essays*. Pergamon Press Inc. 150, 151, 153

Geymonat, L. (1945). *Studi per un nuovo razionalismo*. Turin: Chiantore. 156

Glasserman, P. and H. Young (2015). How likely is contagion in financial networks? *Journal of Banking and Finance 50*, 383–399. 16

Gowdy, J. (1994). Coevolutionary economics: The economy, society and the environment. *Kluwer Academic Publishers, Dordrecht*. 143

Heal, G. and B. Kristrom (2002). Uncertainty and climate change. *Environmental and Resource Economics 22*, 3–39. 76

Heinzel, C. (2012). Schumpeter and georgescu-roegen on the foundations of an evolutionary analysis. *Cambridge Journal of Economics*. 156

Hewings, G. J. D., M. Sonis, and D. Boyces (2009). *Trade, Networks and Hierarchies.* (1st ed.). Springer-Verlag Berlin Heidelberg. 10

Hodgson, G. (1988). *Economics and Institutions*. Cambridge: Polity Press.

Hoekstra, A. (2014). Water scarcity challenges to business. *Nature Climate Change 4*, 318–320. 44

Hoekstra, A. and A. Chapagain (2008). *Globalization of water: Sharing the planet's freshwater resources*. Blackwell Publishing, Oxford. 7

Hoekstra, A. and A. Chapagain (2011). *Globalization of Water: Sharing the Planet's Freshwater Resources*. Blackwell publishing. 48

Hoekstra, A. and P. Hung (2002, September). Virtual water trade: A quantification of virtual water flows between nations in relation to international crop trade. Technical Report 11, UNESCO-IHE, Delft, The Netherlands, The Netherlands. 13

Hoekstra, A. and J. van den Bergh (2003). Comparing structural decomposition analysis and index. *Energy Economics 25*(1), 39–64. 9

Hoekstra, A. Y., A. K. Chapagain, M. M. Aldaya, and M. M. Mekonnen (2011). *The Water Footprint assessment manual. Setting the global standard.* (1st ed.). Earthscan. 8, 13, 48

Hoel, M. (1992). International environment conventions: The case of uniform reductions of emissions. *Environmental and Resource Economics 2*, 141–159. 75, 90

Jeppesen, T. and P. A. Andersen. Commitment and fairness in environmental games. In N. Hanley and H. Folmer (Eds.), *Game Theory and the Environment*, Chapter 4, pp. 65–83. Cheltenham, UK: Edward Elgar. 76

Kallis, G. and R. B. Norgaard (2010). Coevolutionary ecological economics. *Ecological Economics 69*, 690–699. 143

Kapp, K. (1970). *Social costs, economic development, and environmental distruption*. London: University Press of America. reprinted on 1983. 154

Kolstad, C. D. (2007, January). Systematic uncertainty in self-enforcing international environmental agreements. *Journal of Environmental Economics and Management 53*(1), 68–79. 76

Kolstad, C. D. (2011). Bridging reality and the theory of international environmental agreements. In R. W. Hahn (Ed.), *Climate Change and Common Sense: Essays in Honour of Tom Schelling*. Oxford University Press. http://dx.doi.org/10.1093/acprof:oso/9780199692873.003.0005. 105

Konar, M., C. Dalin, S. Suweis, N. Hanasaki, A. Rinaldo, and I. Rodriguez-Iturbe (2012). Water for food: The global virtual water trade network. *Proc. Natl. Acad. Sci. 109*(16), 5989–5994. 7, 10, 31, 36, 50

Kuhn, T. (1962). *The Structure of Scientific Revolutions,*. Chicago University Press. 143, 156

Lawson, T. (2013). What is this 'school' called neoclassical economics? *Cambridge Journal of Economics 37*, 947–983. doi:10.1093/cje/bet027. 144

Lenzen, M., D. Moran, A. Bhaduri, K. Kanemoto, M. Bekchanov, A. Geschke, and B. Foran (2013). International trade of scarce water. *Ecological Economics 94*, 78–85. 8, 52

Leung, C. and H. C. H (2007). Weighted assortative and disassortative networks model. *Physica A: Statistical Mechanics and its Applications 378*, 591–602. doi: 10.1016/j.physa.2006.12.022. 35

Lucas, R. E. (1977). Understanding business cycles. In *Carnegie-Rochester Conference Series on Public Policy*, Volume 5. 9

Lutz, C. and K. Wiebe (2012). Consumption-based carbon emissions in a post-kyoto regime until 2020. *EcoMod 3798*. 45

Madani, K. (2013). Modeling international climate change negotiations more responsibly: Can highly simplified game theory models provide reliable policy insights? *Ecological Economics 90*, 68–76. 105

Martinez-Alier, J. (2002). *The EnvEnvironmental of the Poor*. Edward Elgar. 143, 159

McGinty, M. (2005). International environmental agreements among asymmetric nations. *Oxford Economic Papers New Series 59*(1), 45–62. 76

McGinty, M. (2010). International environmental agreements as evolutionary games. *Environmental and Resource Economics 45*(2), 251–269. 76

Mekonnen, M. M. and A. Y. Hoekstra (2010). A global and high-resolution assessment of the green, blue and grey water footprint of wheat. *Hydrol. Earth Syst. Sci. 14*, 1259–1276. 12, 47

Meserve, R. A. (2008). An introduction to energy and climate change. *Bulletin of the American Academy (Winter)*, 29–32. 76

Miller, R. and P. Blair (2009). *Input-Output Analysis. Foundations and Extensions.* (2nd ed.). CAMBRIDGE UNIVERSITY PRESS. 14, 17, 58, 60, 71, 109

Mirowski, P. (1986). Mathematical formalism and economic explanation. *The Reconstruction of Economic Theory Recent Economic Thought 8*, 179–240. 144

Moore, M. O. (2011). Implementing carbon tariffs: A fool's errand? *World Economy 34*, 1679–1702. doi: 10.1111/j.1467-9701.2011.01406.x. 42

Munda, G. (1997). Environmental economics, ecological economics and the concept of sustainable development. *Environmental Values 6*(2), 213–233. 152

Neurath, O. (1973). *Empiricism and Sociology*. Reidel, Dordrecht and Boston. 154

Newman, M. (2002, November). Assortative mixing in networks. *Physical Review Letters 89*(20). 35

Newman, M. and M. Girvan (2004). Finding and evaluating community structure in networks. *Physical Review E 69*(2). 37

Oliver, J., G. Janssens-Maenhout, M. Muntean, and J. Peters (2014). Trends in global co2 emissions. Technical report, PBL Netherlands Environmental Assessment Agency and EU Joint Research Centre, Ispra. 76

O'Neill, J. (2004). Ecological economics and the politics of knowledge: the debate between hayek and neurath. *Cambridge Journal of Economics 28*, 431–447. 157

Ostrom, E. (2009). A polycentric approach for coping with climate change. *The World Bank Development Economics, Washington, DC*. 77

Pavlova, Y. and A. de Zeeuw (2013). Asymmetries in international environmental agreements. *Environment and Development Economics 18*(1), 51–68. 76, 89

Pearce, D. and G. Atkinson (1993). Capital theory and the measure of sustainable development: an inicator of 'weak' sustainability. *Ecological Economics 8*, 103–108. 149

Polanyi, K. (1944). *The Great Transformation*. Farrar and Rinehart. 156

Popper, K. (1945). *The Open Society and its Enemies*. Routledge. 148, 156, 159

Popper-Lynkeus, J. (1912). *Die allgemeine Naehrpflicht als Loesung der sozialen Frage. Eingehend bearbeitet und statistisch durchgerechnet. Mit einem Nachweis der theoretischen und praktischen Wertlosigkeit der Wirtschaftslehre*. Carl Reissner, Dresden. 154

Rees, W. (1992). Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment and Urbanisation 4*(2), 121–130. 13

Reimer, J. (2012). On the economics of virtual water trade. *Ecological Economics 75*, 135–139. 7

Ridoutt, B. G., S. J. Eady, J. Sellahewa, L. Simons, and R. Bektash (2009). Water footprinting at the product brand level: case study and future challenges. *J. Cleaner Prod 17*, 1228–1235. 49

Robbins, L. (1932). *An Essay on the Nature and Significance of Economic Science*. London: Macmillan. 147

Rockstrom, J., M. Lannerstad, and M. Falkenmark (2007a). Assessing the water challenge of a new green revolution in developing countries. *PNAS 10*, 6253–6260. 45

Rose, A. and S. Casler (1996). Input-output structural decomposition analysis: A critical appraisal. *Economic Systems Research 8*(1), 33–62. 9

Rosegrant, M., X. Cai, and S. Cline (2003). Will the world run dry? global water and food security, environment. *Sci. Policy Sustain. Dev. 45*(7), 24–36. 44

Roson, R. and M. Sartori (2015). A decomposition and comparison analysis of international water footprint time series. *Sustainability 7*(1). doi:10.3390/su70x000x. 9, 25, 123

Rothausen, S. and D. Conway (2011). A review of water scarcity indices and methodologies. *Nature Climate Change 1*, 210–219. 45

Rubio, S. J. and A. Ulph (2007). An infinite-horizon model of dynamic membership of international environmental agreements. *Journal of Environmental Economics and Management 54*(3), 296–310. 76

Sagoff, M. (2008). *The Economy of the Earth* (Second ed.). Cambridge University Press. 146, 147

Sandel, M. J. (2013). *What money can't buy: The Moral Limits of Markets* (First ed.). Penguin. 145, 146, 147

Sartori, M. and S. Schiavo (2014). Virtual water trade and country vulnerability: A network perspective. Working Paper Series- ISSN 1973-0381. 10

Schade, C. and D. Pimentel (2010). Population crash: prospects for famine in the twenty-first century. *Environment, Development and Sustainability 12*, 245–262. 7

Schlosser, C. e. a. (2014). The future of global water stress: An integrated assessment. *Earth's Future 2*(8), 341–361. 72

Schumpeter, J. (1954). *History of Economic Analysis*. London:Allen & Unwin. 143

Scott, K., A. Owen, and J. Barrett (2013). Estimating emissions associated with future uk consumption patterns. Technical report, Committee on Climate Change. 46

Sen, A. (1977). Rational fools: A critique of the behavioural foundations of economic. *Philosophy and Public Affairs 6*(4). 159

Sen, A. (1988). *On Ethics and Economics*. Blackwell Pub.

Serrano, M. and E. Dietzenbacher (2010). Responsibility and trade emission balances: An evaluation of approaches. *Ecological Economics 69*(11), 2224–2232. 8, 9

Smakhtin, V., C. Revanga, and P. Doll (2005). *Taking into Account Environmental Water Requirements in Globalscale Water Resources Assessments*. Comprehensive Assessment of Water Management in Agriculture. 50

Sonis, M. and G. J. D. Hewings (1998). Economic complexity as network complication: Multiregional input-output structural path analysis. *The Annals of Regional Science 32*(3), 407–436. 9

Su, B. and B. Ang (2012). Structural decomposition analysis applied to energy and emissions: aggregation issues. *Economic Systems Research 24*(3), 299–317. 9, 109, 110, 111

Tamea, S., J. A. Carr, F. Laio, and L. Ridolfi (2014). Drivers of the virtual water trade. *Water Resources Research 50*. doi:10.1002/2013WR014707. 10

ter Haar, D. (1959). The quantum nature of matter and radiation. In R. Blin-Stone (Ed.), *Turning Points in Physics*, North-Holland, Amsterdam. 150

Van Oel, P. R., M. M. M., and A. Y. Hoekstra (2009). The external water footprint of the netherlands: Geographically-explicit quantification and impact assessment. *Ecological Economics 69*(1), 82–92. 13

Vasconcelos, V. V., F. C. Santos, J. M. Pacheco, and S. A. Levinf (2013). Climate policies under wealth inequality. *PNAS 111*(6), 2212–2216. 76

Veblen, T. (1900, February). The preconceptions of economic science. *The Quarterly Journal of Economics*. 144

Velazquez, E., C. Madrid, and M. J. Beltran (2011). Rethinking the concepts of virtual water and water footprint in relation to the production-consumption binomial and the water-energy nexus. *Water Resour Manage 25*, 743–761. doi:10.1007/s11269-010-9724-7. 12

Vorosmarty, C., P. Green, J. Salisbury, and R. Lammers (2000). Global water resources: vulnerability from climate change and population growth. *Science 289*(5477), 284–288. 61, 70

Whitehead, A. (1929). *The Function of Reason*. Princeton, NJ: Princeton University Press. 149

Wiedmann, T., R. Wood, J. C. Minx, M. Lenzen, D. Guanef, and R. Harris (2010). A carbon footprint time series of the uk - results from a multi-region input-output model. *Economic Systems Research 22*(1), 19–42. 8

Xu, Y. and E. Dietzenbacher (2014). A structural decomposition analysis of emissions embodied in trade. *Ecological Economics 101*, 10–20. 9, 22

Zhu, Z., F. Cerina, A. Chessa, G. Caldarelli, and M. Riccaboni (2014). The rise of china in the international trade network: A community core detection approach. arXiv:1404.6950vl. 9, 16

Zimmer, D. and D. Renault (2003). Virtual water in food production and global trade: Review of methodological issues and preliminary results. In A. Hoekstra (Ed.), *Virtual water trade: proceedings of the International Expert Meeting on Virtual Water Trade*, Number 12 in Value of Water Research Report Series. UNESCO IHE, Delft. 12