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Under a vicious air: Does corruption affect mitigation actions?

T E S I S
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Abstract

Corruption is a pervasive problem with impacts in economic and social dimensions. Most of the times it represents a burden to the economic system. It misallocates productive capital having repercussions on the optimal path of economic growth of the economy. In this thesis I evaluate the repercussions of corruption in the mitigation policies because of the shock in the economic system. To assess the impact of corruption in the climatic and economic system I use the RICE model. The RICE model accounts for the economic impacts of climate change at a global level and projects economic and climatic trajectories under different mitigation policy scenarios. The control variable modified by corruption is the saving rate. I evaluate this shock by comparing the optimal scenarios in the original RICE projections and the outcomes of the modified RICE. The impacts of corruption result in a negative impact in the economic output and as a result in a reduction of CO_2 emissions. The overall impact of corruption is a reduction of total global welfare and an increase in the social cost of carbon.

Resumen

La corrupción es un problema persistente que afecta dimensiones sociales y económicas, principalmente representando un costo al sistema económico. La corrupción genera asignaciones ineficiente del capital productivo repercutiendo en la senda óptima del crecimiento económico. La presente tesis evalúa las repercusiones de la corrupción en las políticas de mitigación a través del impacto en el sistema económico. Para evaluar las repercusiones de la corrupción en la economía y la emisiones de CO_2 se usa el modelo RICE. El modelo RICE contabiliza los impactos económicos del cambio climático a nivel mundial y proyecta trayectorias económicas y climáticas en tres escenarios diferentes de políticas de mitigación. La variable de control que se modifica por efecto de la corrupción es la tasa de ahorro, el resultado de este cambio se contabiliza al comparar los escenarios de mitigación óptimos en las proyecciones iniciales del RICE y las que se generan bajo el cambio en la tasa de ahorro. A partir de esta comparación se demuestra que la corrupción afecta negativamente en la producción económica y esto reduce el nivel de emisiones de CO_2. A nivel agregado, la corrupción reduce el bienestar total del mundo e incrementa el costo social del carbono.

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"A generous mind often disdains the interested thought of extorting new favours from its benefactor, by what may be called the importunities of its gratitude. But to preserve and to increase his esteem, is an interest which the greatest mind does not think unworthy of its attention. And this is the foundation of what I formerly observed, that when we cannot enter into the motives of our benefactor, when his conduct and character appear unworthy of our approbation, let his services have been ever so great, our gratitude is always sensibly diminished. We are less flattered by the distinction, and to preserve the esteem of so weak, or so worthless a patron, seems to be an object which does not deserve to be pursued for its own sake."
Adam Smith, The Theory of Moral Sentiments (II.iii.1.4).

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Acronyms

BAU	Business As Usual
CLCC	Corporate Legal Corruption Component
COP21	Twenty-first Session of the Conference of the Parties
CO_2	Carbon Dioxide
CPI	Consumer Price Index
CPI	Corruption Perception Index
EIA	Energy Information Administration
EOS	Executive Opinion Survey of the World Economic Forum
EU	European Union
GDP	Gross Domestic Product
GDS	Gross Domestic Savings
GHG	Green House Gas
GMM	Generalized Method of Moments
GNDI	Gross National Disposal Income
GNS	Gross National Savings
GSR	Genuine Saving Rate
GtC	Gigatonnes of Carbon
IAM	Integrate Assessment Model
IMF	International Monetary Fund
INDCs	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
NOMAD	Nonlinear Optimization by Mesh Adaptive Direct Search
OECD	Organisation for Economic Co-operation and Development
OHI	Other High Income
RICE	Regional Integrated Model of Climate and the Economy
SCC	Social Cost of Carbon
SDG	Sustainable Development Goals
SMEs	Small and Medium Size Enterprises
SO_2	Sulfur Dioxide
TI	Transparency International
UCM	Unobserved Components Model
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
VAT	Value-added Tax
WGI	World Bank's Worldwide Governance Indicator

Introduction

Climate change is a worldwide phenomenon and it is one of the most urgent problems that need to be tackled. On September 25th 2015 the United Nation established the new Sustainable Development Goals (SDG) where 150 world leaders adopted the new 2030 Agenda. Its main objectives are to eliminate poverty, protect the planet and ensure prosperity for all (UN, 2016). Every goal has a target to be completed in the next 15 years; from the 17 goals 6 has a direct implication about climate change and the environment. As part of this new global agenda, on December 2015, world leaders met in Paris for the twenty-first session of the Conference of the Parties (COP21) to make new pledges to keep the global temperature rise below a 1.5ºC and 2ºC threshold. On November 4th 2016, 107 out of 197 countries have already rectified the Paris Agreement (UNFCCC, 2016).

By October 31, 155 countries have already submitted their Intended Nationally Determined Contributions (INDCs) which outline the actions each party will follow in order to achieve the below 2ºC threshold. Developing countries are sending two INDCs, one version is intended to be achieved on their own and the second one under financial aid of third parties. Even though climate change is a problem that should be faced in coordination within all countries, there is no homogeneity among all the parties. The Paris Agreement recognizes differences between, mainly, developed and developing countries. In the agreement they establish more flexibility for the developing countries' INDCs, also there is a special consideration because most of these countries will suffer of stronger negative climate change effects. It is suggested that developed countries share carbon-saving technology, and mitigation and adaptation resources with developing ones and there is a compromise to support financially developing parties (UN, 2015).

If every country could achieve the same level of welfare, actions to reduce climate change will be more coordinated. Accordingly to the neoclassical growth theory, all countries with a given capital stock, population, and level of productivity can achieve, under an optimal saving path, an optimal level of welfare where every party will converge (Koopmans, 1963). That means that in the long run every country will have a homogeneous level of welfare. Following the divergence in growth economic paths among countries, there are studies that demonstrate no convergence, or convergence among clubs especially for developing countries (Baumol, 1986). In order to explain why some countries are less developed and why there is not such a convergence towards an optimal welfare a key variable that explains this difference is the quality of institutions in a country. Institutions are basic elements that shape the economy and its behavior. One key definition is the one developed by Douglass North:

> Institutions are the humanly devised constraints that structure political, economic and social interaction. They consist of both informal constraints (sanctions, taboos, customs, traditions, and codes of conduct), and formal rules (constitutions, laws, property rights). Throughout history, institutions have been devised by human beings to create order and reduce uncertainty in exchange. Together with the standard constraints of economics they define the choice set and therefore determine transaction and production costs and hence the profitability and feasibility of engaging in economic activity (North, 1991).

As a pillar that shapes human behavior, institutions are an important variable that can explain economic, political, and social life. The definition of institutions is extensive in such a way that language, money, law, systems of weights and measures, and firms are all examples of institutions (Hodgson, 2006). Since this research focus on the neoclassical growth theory the definition is narrowed to governance institutions because quality in governance institutions is the most significant for economic growth (Prakash & Potoski, 2016).

Some variables can indicate if governance institutions in a country are underperforming or if they are positively contributing to economic growth. Rule of law, bureaucratic quality, corruption in government, and risk of expropriation are the main variables that measure and determine the performance of institutions (Mehlum, Moene, & Torvik, 2006). Particularly, corruption is a variable negatively correlated with economic growth (Esfahani and Ramírez 2003, Tanzi and Davoodi 2000, Tanzi and Davoodi 1997).

Governance institutions performance is not only a key determinant of economic growth but also is a core variable for climate change. Again, corruption has a significant participation in the final result for climate change solutions. For example, mitigation solutions are not easy to implement because there are regulatory grey zones and loopholes within institutions, which in turn can incite corrupt practices. Corrupt institutions within climate governance at a local and international level increase risks for climate change and can reduce positive effects from sound climate change policies.

In order to assess these impacts, the objective of this research is to find out if corruption can affect efforts to reduce climate change through economic growth.

The hypothesis of this research is: Economic growth changes under corrupt institutions negatively affecting mitigation actions. In order to address it, I use an integrate assessment model (IAM)[1]. Since climate change should be solved as an international coordinate effort, under national sovereign actions, the selected IAM has a global perspective. I use the RICE (Regional Integrated Model of Climate and the Economy) IAM developed by William Nordhaus. It is a modified neoclassical growth model and the main objective is to determine the trade off of a region between consumption and investment in technology that can reduce CO_2 emissions. In the model, the world is divided in twelve regions: 1) United States, 2) China, 3) European Union, 4) Japan, 5) Russia, 6) Eurasia, 7) India, 8) Middle East, 9) Africa, 10) Latin America, 11) Other High Income countries (OHI), and 12) Other Asian countries. The solution of the RICE generates three main scenarios for each region; a business as usual baseline, a Pareto optimal scenario, and a limiting increase in temperature scenario. The economic and welfare projections to evaluate the hypothesis are from 2005 to 2115 and the climatic projections from 2005 to 2175.

In order to evaluate the impact of corrupt institutions in the mitigation scenarios generate by the RICE model I modify the saving rate. The saving rate is a control variable of the optimization problem in the RICE model and is a cornerstone for the mitigation outcome. Accordingly to relevant literature review that directly relates corruption and saving rates I modify this control variable. I use the data of perception of corruption reported by the World Bank's Worldwide Governance Indicator (WGI) from 1996 to 2015. Since the RICE makes mitigation projections of the regions under different scenarios, I compare the three main scenarios with the new solutions under the new saving rates. In this way I determine if corruption do have an impact in the mitigation actions against climate change.

This thesis is divided in the following sections: I define corruption, and cover the relevant literature review in chapter 1. Chapter 2 is a short review of the Ramsey model and a detailed description of the RICE model, its variables and solution process.

[1] An IAM "combines scientific and socio-economic aspects of climate change for the purpose of assessing impacts and policies" Traeger, C. (2009).

Chapter 3 explains the corruption variable, how it is measured and used, and a comparative analysis between the RICE saving rates and the adjusted net saving rates reported by the World Bank. In chapter 4 I explain the estimation strategy of the new saving rates and solution mechanism used to solve the problem. Chapter 5 presents the main economic and climatic variables outcomes; I also analyze the result of the social cost of carbon and the impact in the total welfare global and by region. Finally in the conclusions I present the main results of the thesis and possible further steps in the research.

1. Corruption

1.1. A review

Corruption has been addressed as one of the most important issues worldwide. With growing income and wealth inequality, and major corruption scandals around the Globe, people perceive this problem as an outcome of abusive systems that privilege the rich and powerful ones. It has been a pervasive topic, as an example, some of the latest and more controversial international corruption scandals are the Panama Papers and Odebrecht ones. In both cases governments and public actors from developed and developing countries have been implicated in corrupt practices. It is an international phenomenon with repercussions with multiple approaches. For the UN, "corruption undermines democratic institutions, slows economic development, and contributes to governmental instability" (UNODC, 2017) considering these impacts, in October 2003, the United Nations created the Convention against Corruption. It is the only international legally binding instrument anti-corruption with a total of 181 parties but only 140 have a ratification status for the latest update on December 2016.

The corruption problem undermines political, social, and economic aspects of the society but in this research I narrow the impacts only to the economic sphere. There are different definitions of corruption but for the purpose of this research the definition is: "the abuse of public office for private gain". This definition is the most recurrent in research papers, reports, and indicators, also used for the United Nations Convention against Corruption and the annual indicators reports by the World Bank, and Transparency International (IMF Fiscal Affairs and Legal Departments, 2016).

1.2. Literature review

In this section I review the most representative research about corruption and economic growth theory. Because of the scope in this thesis I review relevant studies about corruption and the saving rate, later, in chapter 3 I recall and explain further one of these researches (Swaleheen, 2008). I also review the line of research about corruption and the resource curse, especially the relationship among corruption, resource curse and the genuine saving rate (also known as adjusted net saving rate) which is further analyzed in chapter 3. Finally, I analyze corruption with a broader definition in order to understand how some corrupt practices are not well surveyed under the standard definition of corruption.

1.2.1 Corruption and economic growth

There is an important research line between corruption and economic growth. In general, corruption is negatively correlated with economic growth. Although some studies argue that corruption is beneficial for the economy by reducing bureaucracy and better allocating resources (Leff, 1964)(Huntington, 1968), studies that contradict these findings enumerate more negative consequences from corruption than positive economic outputs. Accordingly to those researches there are different transmission mechanisms affecting the final output. Investment is one of the main variables affected by corruption; it is penalized by bribes accounted as taxes over the dividends, therefore affecting negatively economic growth (Mauro, 1995). Infrastructure is also negatively affected by corruption via a reduction in credibility and effectiveness in government policy, reducing infrastructure growth and the gross domestic product (GDP) (Esfahani & Ramírez, 2003). Corruption disincentives investment and creates a negative tax to the capital available, both situations, leading to a lower economic growth. Also, it misallocates investment, since it is easier to collect bribes from expensive, high-technological capital. Especially developing countries spend their limited resources in exclusive-high-price technology where they can bribe more, reducing the budget for more productive resources with lower costs like education and health services (Shleifer & Vishny, 1993). These exclusive-high-price infrastructure projects are also known as "white elephants", they serve veiled interests for certain interest groups at expenses of social welfare (Robinson & Torvik, 2005).

Public assets and expenditures are also vulnerable for corrupt practices. First, there is evidence that allocation of resources by the government allows an opportunity for bribery (Ehrlich & Lui, 1999). It is estimated that there is a total of 75 trillion of dollars in public assets and they are mismanaged resulting in corrupt practices. Public assets can be a curse if there are no proper institutions to reduce rent-seeking practices (Detter & Föster, 2015). Even when there is evidence that corruption increases public investment, mismanagement of resources reduces its productivity reducing economic growth and by reducing growth there are fewer government revenues for financing productive spending (Tanzi & Davoodi, 1997).

Public assets are also undermined by corruption via taxes. Corrupt countries tend to use indirect taxes because it is easier to bribe under this scheme than under a VAT (value-added tax) regime. Countries that first adopted VAT schemes are less corrupt and report a higher VAT productivity. Corrupt countries with indirect and inefficient taxes regime have fewer available resources, undermining finance opportunities for small and medium size enterprises (SMEs) that are positively correlated to economic growth (Tanzi & Davoodi, 2000). Even in USA where most of their collected tax revenues come from a direct tax (in most states there is a progressive income tax) corruption undermines the tax scheme across states. Taxes are the source for financing public assets; entrepreneurs and other high productive actors make use of these resources contributing to the overall growth of the state. But the higher the rate of corruption, the lower the optimal rate of taxation, hence there is a reduction in the available funding for public infrastructure and a reduction in economic growth (Aghion, Akcigit, Cagé, & Kerr, 2016). The impacts of corruption come from different transmission mechanisms but of particular interest for this research, is the saving rate. In the next section I enumerate relevant literature about impacts of corruption in the saving rate.

1.2.2 Corruption and saving rates

The saving rate is a fundamental variable for economic growth; savings represent funds available for investment in capital and infrastructure. In the neoclassical growth theory it is the variable that dictates economic growth path and steady state. Any external shock to the saving rate impacts in a direct way economic growth. For OECD and developed countries, saving rates are positively correlated with corruption. This may seem counterintuitive but it is also a signal of corrupt practices. Higher saving rates reflect an unobservable component affecting income. Due to corruption, there is a higher tendency to shift economic activities to the shadows, as more people turn to shadow activities, there is a reduction in visible or registered employment and an increase in saving rates shows higher profit from unobservable activities. Therefore higher saving rates are a signal of "productive" shadow activities that pay off unreported revenues and increase disposable household income (Walther & Stiassny, 2013).

Saving rates are also negatively impact by corruption. From a sample of 100 countries during a 10 years period, it was found that the rate of corruption has a negative impact on the gross national saving rate; in contrast, there was no clear effect on the gross domestic saving rate. This differentiation represents that wealth accumulation from bribery flees abroad to avoid being detected. Higher levels of corruption show negative impacts on saving rates that translate into lower economic growth (Swaleheen, 2008). This research is later recalled because it focuses only in the corruption-saving rate relationship. Also it considers a heterogenic sample of countries and a long time period for data. Researches that link saving rates with corruption usually add a "resource curse" variable, especially those studies related to environmental issues. Even though this thesis doesn't consider a "resource curse" analysis, it is an important line of research as an institutional failure example.

1.2.3 Corruption and the resource curse

The resource curse refers to the paradox of countries rich in natural resources with low development and economic growth. A line of research attributes the economic underperformance to low quality of institutions. Historically, quality of institutions (either extractive or productive institutions) set the development and economic growth path of a country (Acemoglu, Johnson, & Robinson, 2001). Particularly, corruption is a variable that relates to low economic growth and extractive institutions (Abed & Gupta, 2002). Natural resources that are more significant for corrupt and extractive institutions are energy and mineral resources, also known as "point resources". For example, mineral and oil resource-rich countries have more pervasive corrupt practices than oil-poor countries, even under different governmental regimes, democratic or nondemocratic (Aslaksen, 2007).

Extractive and corrupt institutions are also significant for relaxed environmental policies that conducing to resource mismanage. Using six indicators of air and water pollution, it was found that higher levels of corruption are related to higher levels of pollution. This effect was stronger for developing countries (Welsch, 2004). The quality of environmental regulation worsens with higher levels of corruption and in countries with high income inequality the effect is more persistent. This approach is confirmed with a SO_2 and CO_2 emissions per capita cross-country panel data for 80 countries (He, Makdissi, & Quentin, 2007). For China, anti-corruption efforts are positive related to lower SO_2 emissions and an increase in income. It is important for China to reduce its corrupt practices because bribes are used for relaxing environmental standards, so by combating corruption there will be a stronger regulation of emissions and a reduction in SO_2 emissions (Liao, Dogan, & Baek, 2016).

Finally, a persistent topic between corruption and the resource curse is the saving rate. Resource rich countries that have consumed the dividends of resource extraction instead of investing them have lower or negative genuine savings. The negative effects in savings highly depend in the quality of institutions (Atkinson & Hamilton, 2003). Particularly, corruption is the institutional variable that explains low genuine saving rates[2] (GSR) in resource rich countries (Dietz, Neumayer, & Soysa, 2007). Lower corruption is significant for less depletion of dividends obtained by natural resources. Less corruption allows economic diversification of these dividends, relocating them for investing in human capital, productive processes and services, leading to higher GSR (Boos & Holm-Müller, 2013). In general, corruption results in lower GSR that translates into lower investment and a divergence from the optimal path of capital accumulation with and overall lower economic growth rate.

1.2.4. A broader definition of corruption

Usually in international annual published rankings, poor countries underperform for corruption indicators (TI, CPI, WGI) but the problem is also pervasive in rich countries. As mention before, these rankings are grounded in the definition of corruption as abuse of public office for private gain, so the most persistent offense accounted is bribery. If the definition of corruption takes into account "legal corruption" indicators will change. Just as the indicators mention before, this research is based on a narrow definition of corruption, as the reader can further find in the thesis, corruption indicators used here portray corruption as a more constant problem in poor countries than in rich ones. In order to have another perspective of corruption I analyze a broader definition[3] of corruption in this section.

Legal corruption is when the elites have taken power or can influence institution in such a way that they can dictate the "rules of the game". This privilege sphere has the power

[2] Genuine save=Investment in produced capital – net foreign borrowing + net official transfers – depreciation of produced capital – net depreciation of natural capital + current education expenditures. GSR is the same as the adjusted net saving rate and is further discuss in chapter 3 (Simon Dietz, 2007).

[3] In Kaufmann 2004 the suggested definition is: "exerting undue influence on public policy or in receiving a public good, to the particular benefit of the influencing agent or institution."

to influence laws and regulations, and public policies especially under vested interests creating new rules and “legalizing” corrupt practices. They create collusion with the public sector and with a narrow measure of corruption; only the public sector offense is recorded and persecuted. Legal corruption takes advantage of loopholes in the regulation to create policies that benefit private interests at expenses of public welfare. In order to capture this phenomenon (Kaufmann, 2004) uses the Executive Opinion Survey (EOS) of the World Economic Forum, particularly measuring the Corporate Legal Corruption Component (CLCC). For this ranking, 100 means the absence of legal corruption and 0 is highly pervasive legal corruption. Here, the Nordic countries continue to have a good performance; in contrast, the averages of the G-7 and the southern European countries are low. But the highest discrepancy is with the US with a rate of 30, Italy 35, Spain, Portugal, France, and Canada 40, Japan 45; scoring lower than developing countries like Chile, Botswana, Colombia and South Africa. Under this new evidence is clear that corruption is a problem present in rich and poor countries alike.

It is of particular interest for this research, the evidence of legal corruption within mitigation practices. For example, lobbying is a common practice in rich countries, and fossil fuel and renewable energy industries are not excise of it. But there is not a fair playground, for example, in the US; the oil and gas industry outnumbered clean energy lobbying by a factor of eight. In the European Union, during an important climate policy negotiation, business groups doubled the preponderance in negotiators in comparison with environmental groups. As long as there is no disclosure from business about public engagement and practices related to climate change activities there will be grey areas that allow preponderance of an elite that dictate the rules of the game. These practices are not only present within national governance but also in the intergovernmental sector. A clear example was during the Copenhagen reunion, the five most pollutant countries had three times more delegates than the five most impacted countries by climate change damages. In 2009 at the UNFCCC, between Canada, UK, and US, they accounted more than 400 registered observer organizations in comparison to China, India, and Brazil that only added to a total of 10 groups (Transparency International, 2011). It is clear a disparity in representation, and these events should guarantee for all the parties an effective and inclusive voice to avoid any grey area that allow legal corrupt practices.

Even considering a narrow definition of corruption, corrupt practices are a burden for rich countries. OECD countries, in general, rank around the 90th percentile of the WGI, but considering that these countries account for around 80 percent of the world's output, by proportion, the cost of corruption in these countries is higher than in low-income countries. Also, there is evidence that rich countries bribe abroad so corrupt indexes don't account these practices at home but at the foreign country, usually at low-income country. Transnational and multinational businesses operating in OECD countries report the same low level of corruption as in their home country. But these businesses with headquarters at an OECD country and operating abroad in a non-OECD country have illegal corporate practices similar to those of the recipient country. The highest costs from bribing are for domestic firms in non-OECD followed by multinationals companies outside an OECD country but with headquarters at an OECD country. Bribing for procurement is the most costly burden for multinational and national firms, within and outside OECD countries (Kaufmann, 2004).

Even though OECD countries and the US have conventions to forbid corrupt practices abroad, there is not a strong enough intergovernmental regulation[4] capable of persecuting and punishing these actions. Corruption undermines the development of low-income and rich countries, the lack of accountability for corrupt practices in rich countries comes from a narrow definition for measuring corruption, in a way, this scope imposes a barrier for a real accounting of this governance indicator.

[4] The UN Convention against Corruption is a pledge for better regulations to avoid corruption among countries but overall it respects autonomy and sovereignty of each country. This national governance framework subordinates any international persecution and punishing action.

2. The RICE model

The base of this analysis is the neoclassical economic growth theory[5], particularly under the Ramsey model. This section present a short review of the Ramsey model and a detailed explanation of the RICE model which main core is the Ramsey one.

2.1 The Ramsey model

Frank P. Ramsey developed the model (1928) and later contributions of Cass (1965) and Koopmans (1965) were added. In this model infinitely lived households and firms optimize their consumption and saving decisions to maximize their welfare. Their main restriction is an inter-temporal budget constraint. Decisions of the agents determine the dynamics in time of capital accumulation.

The saving rate is the main variable that determines the transitional dynamics of other variables and dictates the speed of convergence to the steady state of the model (Barro & Sala-i-Martin, 2004). The rate is a function of per capital stock *k* and it rises or falls as the economy develops. The endogenous gross saving rate is:

$$s_t \equiv \frac{Y_t - C_t}{Y_t} = \frac{\dot{K}_t + \delta K_t}{Y_t} = \frac{\dot{K}_t / K_t + \delta}{Y_t / K_t} = \frac{\dot{\tilde{k}}_t / \tilde{k}_t + x + n + \delta}{f(\tilde{k}_t)/\tilde{k}_t} = \frac{x + n + \delta}{f(\tilde{k}^*)/\tilde{k}^*} \equiv s^* \tag{2.1}$$

By determining the dynamics of capital through time, $\tilde{k}_t$, the model determines the saving rate transition, s_t, and how it adjust in the long-run. To derive the saving rate steady state lets consider first the transition for capital. In the steady state, the transition of capital, $\tilde{k}^*$, is determined by, x, the level of technology, δ depreciation rate, ρ the rate of time preferences and θ the elasticity of marginal utility:

$$f'(\tilde{k}^*) = \delta + \rho + \theta x \tag{2.2}$$

Considering a Cobb- Douglas production function determined by A, rate of productivity and the capital-share coefficient, α.

$$\begin{aligned} \tilde{y} &= f(\tilde{k}) = A\tilde{k}^{\alpha}, \\ A &> 0, 0 < \alpha < 1 \end{aligned} \tag{2.3}$$

[5] I acknowledge the Keynesian theory and its implications, especially for the saving rate but the scope of this thesis is more suitable under an IAM climate model approach. The majority of international climate studies use an IAM under the neoclassical growth theory; it is of further concern a research about IAM's under Keynesian theory.

Now for $f'(\tilde{k}) = A\alpha\tilde{k}^{\alpha-1} = \alpha f(\tilde{k})/\tilde{k}$ and substituting with (2.2):

$$\frac{f(\tilde{k}^*)}{\tilde{k}^*} = \frac{1}{\alpha} f'(\tilde{k}^*) = \frac{\delta + \rho + \theta x}{\alpha} \tag{2.4}$$

Substituting (2.4) in (2.1) results in the steady state saving rate:

$$s^* = \frac{\alpha(x + n + \delta)}{(\delta + \rho + \theta x)} \tag{2.5}$$

where α is the capital-share coefficient, x is the level of technology, n the rate of grow population, δ depreciation rate, ρ is the rate of time preferences and θ the elasticity of marginal utility. These parameters determine if the save rate falls monotonically, stays constant or rises as k increases. There is an ambiguous impact in the saving rate from a substitution and income effect. If capital stock increases there will be a reduction in the rate of return and so a reduction in the incentive to save (substitution effect) but an increase in capital will increase household disposable income resulting in a higher saving propensity and thus a higher rate of saving (income effect). The main impact is determined by θ, where a high elasticity of marginal utility shows low willingness to substitute consumption through time and the saving rate increases during the transition. The income and substitution effect cancels out when the saving rate is constant as capital stock grows toward the steady state; this is the case of the Solow-Swan model that is a special case of the Ramsey model. Finally, a low value of elasticity of marginal utility results in a monotonically reduction of the saving rate during transition.

As in the Ramsey model, the saving rate is a control variable in the RICE model and determines the transition dynamics of other main variables, like investment in the economy that determines the mitigation action modeled in the RICE.

2.2 The RICE model

In order to better illustrate the RICE model, which is the basic analytical framework of this thesis I give a general review of the whole model. Then I give a more detailed explanation of the solution process. I also describe some main variables of the RICE, and the main source that feed them. Finally I review the only consideration about corrupt practices within the model framework. The following review is based mainly in descriptions of the model by William Nordhaus (Nordhaus, 2000; Nordhaus, 2007;

Nordhaus, 2010). The main equations governing the RICE model, their variables, parameter, and unit in which are measure are listed in Appendix A. The division by region and the countries that conform each region are listed in Appendix B.

2.2.1 An Overview

It is an IAM and its main foundation is the Ramsey model. In the RICE, reduction of emissions is the outcome from optimization of the model as so is the capital investment in the Ramsey one; therefore, the accumulation of CO_2 is a "negative natural capital". The trade off is between reducing emissions and today consumption where lower CO_2 levels reduce climate change negative impacts and increase future potential consumption. Each of the twelve regions[6] in which the RICE divides the world are assumed to have a well-define set of preferences known as social welfare function, this, determines the path of consumption and investment of each region. There are three main parameters that determine consumption of the regions; the size of the generation determines the importance of the per-capita consumption, the pure rate of time preference measures the relative importance of each generation and the elasticity of the marginal utility of consumption that shapes the curvature of the utility function. These parameters are calibrated to reach the real interest rates close to the average rate of the actual ones. The model only consideration of international trade is for carbon emission permits. The model dynamics are between the economic sector and a geophysical one for climate change modeling.

The multiregional process of optimization includes a Negishi procedure in which the welfare weights equalize marginal utilities for each period with the weighted average marginal utilities, so the weigh of each region represents the share of capital stock for a period. This procedure allows an efficient optimization process but there are critiques against it because it doesn't allow income distribution between regions (Dennig, Budolfson, Fleurbaey, & Asher Siebert, 2015). If the optimization process to maximize global welfare could allow income distribution, the solution of the problem would suggest redistribution of wealth among countries or regions as a main policy advice. The use of the Negishi procedure had opened an ethical debate about global wealth inequality (Stanton, 2011). This debate is out of the scope of the present thesis but it is

[6] See appendix B for a detailed description of the twelve regions.

worth mentioning since coordination efforts among parties to stop climate change would be more harmonized under homogenous welfare among regions.

In the economic sector, each region is assumed to produce a single commodity, and the economy has the option of trading it off between consumption and investment in reducing emissions. The initial endowment of the region is a given initial stock of capital, labor and a region-specific level of technology. The optimization of consumption through time results in a level of capital accumulation. Population growth and technological change are exogenous in the baseline model. A Cobb-Douglas production function with capital, labor, and carbon-energy inputs determine the output. The two main technological changes are an economy-wide technological change, which is Hicks-neutral[7], and a carbon-energy-saving technological change that reduces the ratio of emissions to carbon-energy inputs. The United States is the reference for the projected technological change as it is assumed that all the other countries will converge to this level.

The total World investment in clean energy, and research and development of clean technology for 2015 was $242 billions of dollars. Europe invested $59.8 USD billions, Latin America $6.1 USD billions (excluding Brazil), Middle East and Africa $7.7 USD billions, and Asia-Oceania $26.8 USD billions (excluding China and India). The countries investing the most are China with $78.3 USD billions, USA $46.4 USD billions, Japan $14.4 USD billions, India $9.7 USD billions, and Brazil with $6.8 USD billions (Sawin et al, 2017). These amounts fall short for the investment assumptions of the RICE, it is of further research considerations pondering investment in carbon-free energy technology accordingly to real data. As well, the assumption of technological change convergence among countries is difficult to achieve under the strict assumption of only carbon permits trade.

It is considered a backstop technology that can replace carbon fuels but with a relatively high price that eventually will decline over time accordingly to the IPCC studies and surveys. The IPCC studies forcast that this technology become highly competitive with carbon fuels after 2250, after this breaking point, emissions decline rapidly. There is an

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[7] "Technical progress where with any given factor proportions the average and marginal products of all factors increase in the same proportion
$Y^* = F(\lambda K, \lambda L) = \lambda F(K, L) = \lambda Y$." (Oxford reference, 2016)

optimal energy resources allocation across time with scarcity prices, also known as Hotelling rents, for low-carbon resources and higher carbon-energy prices.

The geophysical sectors of the RICE are simplified versions of complex ocean, atmosphere and climate models. They represent CO_2 emissions, carbon cycle, and radiative forcing, in a simple climate model and regional climate-damage relationships. The only green house gas (GHG) endogenous to the model is industrial CO_2 because accordingly to the IPCC, the concentration of this gas represents five times more radiative forcing than the combine effect of other non-CO_2 GHG and aerosols. The geophysical sectors are a three-box model calibrate to existing carbon-cycle models that calculate the carbon cycle. The carbon flows are through atmosphere, upper biosphere-shallow oceans and deep oceans. Climate change is captured by global mean-surface temperature and the considerations about lag and equilibrium are estimations in accordance to the IPCC studies. In this version of the RICE there is a sea level rise module in accordance with different temperature trajectories. Damages are in function of sea level rise, and CO_2 concentrations are region-specific. Just for the baseline with a business as usual (BAU) scenario, the damages in 2095 are a total of \$12 trillion or 2.8% of the global GDP for an increase in the temperature from 1900 levels of 3.4Cº.

The results of the RICE are base in three policy scenarios. The baseline or BAU case, where no climate change policies are adopted. The optimal, where climate change policies maximize the economic welfare under full participation of all countries and with no climate constrain. Finally a temperature limited case which policies restrict the increase of temperature the 2ºC threshold above 1900 levels. A detailed description of the main equations governing the model can be found in appendix A.

2.2.2 Model Description

In this section I describe the solution process of the RICE model. This section is based in the review of the RICE in Dennig, 2013. For each of the twelve regions, there is an endogenised consumption-saving decision with the following utility function:

$$u(x) = \frac{x^{1-\gamma}}{1-\gamma} \qquad \gamma = 1.5 \tag{2.6}$$

The elasticity of output with respect to capital, γ, is the same as the pure rate of time preference per year, ρ=1.5%, in order to calibrate the interest rate in accordance to Ramsey model.

The population grow rate is exogenous. Total population of region *i* in period *t* is represented by L_{it}. The objective of every representative agent is:

$$\Gamma_i = \sum_{t=1}^{T} \left(\frac{1}{1+\rho} \right)^t L_{it} u(c_{it}) \tag{2.7}$$

Gross output of region *i* for period *t* is a function of capital K_{it} and labor L_{it}

$$Y_{it} = F_{it}(K_{it,} L_{it}) \tag{2.8}$$

Emissions of every region are proportional of gross output Y_{it}, also are function of a mitigation rate μ_{it}, fraction of uncontrolled emissions, and of an exogenous emission to output ratio σ_{it}, or metric tons of carbon per output in 2005 prices.

$$E_{it} = \sigma_{it}(1 - \mu_{it})Y_{it} \tag{2.9}$$

Total emissions in period *t* are regional emissions E_{it} plus exogenous emissions due to land use changes, EL_t

$$E_t = \sum_{i=1}^{12} E_{it} + EL_t \tag{2.10}$$

Net output is proportional to gross output and considers mitigation costs and climate damages

$$Q_{it} = \frac{1 - \Lambda_{it}}{1 + D_{it}} Y_{it} \tag{2.11}$$

The numerator represents abatement costs as fraction of regional output and the denominator are climate damages as fraction of regional output. A convex function of the mitigation rate defines the abatement costs.

$$\Lambda_{it} = \theta_{it}^1 \mu_{it}^{\theta_2} \tag{2.12}$$

θ_1 is an exogenous parameter calibrated in 2005 prices that equates the marginal cost of the last unit of mitigation with a full backstop green technology price, and θ_2 is 2.8.

The regional damage function is quadratic in atmospheric global mean temperature and sea-level rise. The climate module determines the temperature in this equation, which measure the concentration of greenhouse emission in the atmosphere, upper biosphere-shallow oceans and deep oceans.

$$D_{it} = D_{it}^{nonS} + D_{it}^{S} \tag{2.13}$$

The RICE solves the Ramsey saving problem for the twelve regions through the equations (2.6) to (2.13). The optimal saving rate, s_{it}^{*}, is determine without mitigation actions, μ_{it}=0, in the baseline scenario (BAU). With this saving rate, consumption is define as follow:

$$c_{it}^{*} = \frac{(1 - s_{it}^{*})Q_{it}}{L_{it}} \tag{2.14}$$

From this baseline consumption the relative weights of the welfare function are determine, also known as the inverse of the marginal utility of consumption or time-varying Negishi weights (v_{it}).

$$v_{it} = \frac{u'(c_{it}^{*})^{-1}}{\sum_{j=1}^{I} u'(c_{jt}^{*})^{-1}} \tag{2.15}$$

Given these weights the mitigation policy is chosen from the following welfare function:

$$W = \sum_{t=1}^{T} \left(\frac{1}{1+\rho}\right)^{t} \sum_{i=1}^{I} v_{it} L_{it} u(c_{it}) \tag{2.16}$$

Mitigation policy determines a non-zero mitigation rate μ_{it}, and given a carbon tax τ_{it} mitigation rates for every region are:

$$\mu_{it} = \left(\frac{\tau_t \sigma_{it}}{\theta_{it}^{1} \theta_2}\right)^{\frac{1}{\theta_2 - 1}} \tag{2.17}$$

Mitigation rates are determined given a tax rate, τ_{it}, that maximizes a region's economic output given gross climate damages and net mitigation costs.

From equation (2.7) lets define the decision utility as $\Gamma_i(\vec{s}_i,\vec{s}_{-i},\vec{\tau})$ of a representative agent of region i, with a carbon tax path $\vec{\tau}$, a region saving rate stream $\vec{s}_i$, and other regions saving streams as $\vec{s}_{-i} = (\vec{s}_1,\dots,\vec{s}_{i-1,}\vec{s}_{i+1},\dots,\vec{s}_{12})$. It is a well defines tax path given mitigations levels' from equation (2.17). The saving rates of every region combined will determine the global gross output therefore determining emissions and damages and considering the mitigation rate it will result in a total net output.

Given a fix tax path, a region's representative agent utility will depend on the saving rates streams of all the other regions. This is because the increase in temperature is determined by emissions of all regions, these, are a function of the regional's output which is given by capital accumulation that is settle through the saving rates. Therefore the choice of saving rates is strategic.

2.2.3 RICE data

The latest version of RICE is from 2010 and the latest update was in 2012. It runs for 60 10-year periods beginning in 2005 (2005-2014) and being 2595 (2595-2605) the last period. Most of the variables are defined as a flow per year but some are in flow per decade.

Population data is from the UN estimates with projections up to 2300. Output is Gross Domestic Product (GDP) in constant prices and all regions' GDPs are converted into 2005 US international prices by purchasing power parity exchange rates. This data is taken from the WB and the IMF. Projections of GDP growth are also from the IMF. Data for CO_2 emissions are from the US Energy Information Administration and Carbon Dioxide Information Analysis Center.

Technological change is considered to converge to a frontier established by the US. Carbon-energy inputs and industrial emissions are measured in units of carbon weights. Energy-related parameters are calibrated using historical GDP and CO_2 emissions since 1960. CO_2 emissions reductions are according to a cost function that is drawn from national and global models made by the IPCC, also the cost of the backstop technology is taken from these analysis. Energy consumption considers nonelectric coal consumption, nonelectric natural gas consumption, electricity consumption, and consumption of petroleum products, these data is taken from the Energy Information

Administration (EIA). As energy prices, the model considers electricity prices, petroleum product prices, coal prices, and natural gas prices also taken from the EIA.

Finally, saving rates follow a path in accordance to the Ramsey model and within a range given by the model calibration for a real interest rate. Rates are higher in low-income regions (from 25 to 35 per cent of the GDP) and lower for rich countries (from 15 and 25 percent of the GDP). Over the decades, saving rates will be lower as economic growth and population decline.

2.2.4 Considerations of corruption for the RICE

The RICE model has exogenous variables that dictate the final outcome of the analysis. Under basic assumptions the modeler can either choose a tax or cap-and-trade regime for better allocation of CO_2 emissions per country. A quantity-type system is more prone to corruption than a price regime like emission tax. Emission permits create scarcity of the tradable resources leading to perversions in the market. Resource rents from this mismanagement of cap-and-trade permits can be used for unproductive activities reducing economic growth. Permits can be underpriced and traded globally in a way that gains from the transaction are underreported. On the other hand, a tax scheme doesn’t create scarcity situations or monopolies in emissions management. Revenues obtained from taxed emissions in the domestic market reduce the opportunity for rent-seeking practices (Nordhaus W. D., 2007). In the RICE model, the only consideration to avoid corrupt practices is to choose an optimal emission tax that better allocates resources than an international cap-and-trade regime. In order to control any inherent opportunity for corrupt practices within the model, all the modeling is done under a tax regime.

3. Measuring corruption and the adjusted net saving rate

In this section I explain the underlying methodology and the proper use of the "control of corruption" variable. I use this variable to measure corruption for the twelve regions of RICE and I use it for the main development of the analysis (Chapter 4). Also I compare the optimized original saving rates of the RICE with the saving rates report by the World Bank known as adjusted net saving rates[8]. This comparison elucidates differences among methodologies and a fairer distribution of damages by the World Bank methodology.

3.1 Control of corruption

Corrupt practices are hard to measure because most of the illicit activities try to eliminate any record or trace of them. In order to assess the impacts of corruption worldwide indicators reflect measure of perception of corruption within a country, so is the case of Transparency International (TI), Corruption Perception Index (CPI), and World Bank's Worldwide Governance Indicator (WGI). Because of the periodicity of data sample I use the WGI index for corruption. It reports for 200 countries from 1996 to 2015. From 1996 to 2002 data is biennial being the first period 1995-1996, from 2003 until 2015 is annual. Control of corruption variable reflects the definition of corruption (as well as this research) as the abuse of public office for private gains.

WGI index uses data from 31 data sources from four different sources[9] mainly: Surveys from households and firms, commercial business information, non-governmental organizations, and public sector organizations. These data feed six different governance indicators but because of the scope of this research I only focus in "control of corruption". There have been an increase in data sources through out the development of the indicator, up to today where it is used a total of 31 data sources. For some countries, in the 1996 report, there was only one data source available that measure "control of corruption" (e.g. Afghanistan, Belarus, Chad) and six were the maximum available sources. Indicators are more precise since the number of data sources available had increased as the indicator measuring methodology explains.

In order to capture the most precise measurement of the indicator, WGI uses a statistical tool known as the unobserved components model (UCM). It is used under the

[8] Equivalent to the genuine saving rate reviewed in section 1.2.3.
[9] The 31 data sources are listed in appendix C

assumption that each data source is measuring an imperfect signal of a deeper underlying notion of governance difficult to observe directly (Kaufmann, Kraay, & Mastruzzi, 2010). The UCM solves this problem because for each data source it isolates informative signals of an unobserved component and combines optimally all the data sources to get a best possible signal. It is assumed that the observable score of country *j* on indicator *k*, y_{jk}, is a function of an observable signal for country *j*, g_j, and an error term ε_{jk},

$$y_{jk} = \alpha_k + \beta_k(g_j + \varepsilon_{jk}) \tag{3.1}$$

α_k and β_k are parameters for the unobserved signal for country *j*, g_j for the observed data from source *k*, y_{jk}. The aggregate governance indicator is a standard random variable with mean zero, unit standard deviation and with a range approximately from -2.5 to 2.5. The differences in units from the data sources are captured by the parameters α_k and β_k. The error term $\varepsilon_{jk,}$ captures two main uncertainties between observable data and the real governance: errors in perception from experts or sampling variations, and possible variations from the definition of an indicator by WGI and the one reflected in a survey or assessment. The variance of the error, σ_k^2, captures these two uncertainties, the indicator is more precise as smaller is the variance. The estimate of unobserved governance is constructed from α_k, β_k, and σ_k^2. It has a normal distribution with mean:

$$E\left[g_j \middle| y_{j1},\ldots,y_{jk}\right] = \sum_{k=1}^{K} w_k \frac{y_{jk} - \alpha_k}{\beta_k} \tag{3.2}$$

This conditional mean is the estimate of governance, it is a weighted average of rescaled scores and rescales the observed data in common unit previously chosen. Each source has a weight given by:

$$w_k = \frac{\sigma_k^{-2}}{1 + \sum_{k=1}^{k} \sigma_k^{-2}} \tag{3.3}$$

The weight is higher as σ_k^2 has a smaller value that means that sources with more informative signals are given more weight.

The uncertainty of the estimate of governance is captured by the standard deviation of the distribution of governance conditional to observed data:

$$SD\left[g_j \middle| y_{j1},\ldots,y_{jK}\right] = \left(1 + \sum_{k=1}^{K} \sigma_k^{-2}\right)^{-1/2} \tag{3.4}$$

The standard deviation is lower as more data sources are available, as *K* rises, and more precise the data source is, σ_k^2 is smaller. This number is reported as standard error or confidence intervals, and is useful for a correct interpretation for the estimates. In order to make a cross-country comparison the size of the confidence intervals should be compare. First, if they overlap that mean no statistical significant difference even if the point estimates are different. For this research I use the average of point estimates for region, this is consistent with results reported in the WGI webpage. Some data sources are region specific meaning the confidence intervals within regions are prone to overlap, meaning low statistical significant difference so the region can be taken as a homogenous block.

The comparison of the data among years is a key element for this research and it follows the WGI recommendations. First, as in the cross-country comparison, if for two periods the confidence intervals overlap, it means no statistical significant difference; second, data sources have increased through the years and because of the use of the UCM method, reported confidence intervals have increase during the evolution of the reports. Comparison in time should consider long intervals among years, like decades, because comparing from 2003 to 2004 point estimates, most of the data has overlapping confidence intervals but from 2003 to 2013 confidence intervals are less prone to overlap. WGI advises not to interpret changes in time of estimates as trends, only as relative positions over time.

I construct an index from the variable "control of corruption" for each of the twelve regions of RICE. In order to evaluate the change in time I choose three intervals: 1996 to 2004, 2005 to 2009, and 2010 to 2015. Then I use the change from the first and second interval to measure corruption for the period 2005-2014 in the RICE, and the difference between intervals 2006 to 2009 and 2010 and 2015 is taken as the measure of corruption between 2015-2025 RICE periods. I am using lag corruption data because shorter time periods than a decade show higher correlation between current and lagged estimates[10] and even for the longest first period (1996-2004) it considers only 6 points

[10] As mention in Kaufmann, 2010: "correlation between current and lagged estimates of governance is even higher when we consider shorter time periods than the decade shown here"

estimates. I am using the estimate from equation (3.1) that is a standard normal variable, with zero mean, unit standard deviation and in a range from -2.5 to 2.5 where -2.5 is the highest level of corruption and 2.5 the lowest persistence of corruption in a country. Table 1 report the value of the average of the estimate control of corruption for each period:

Table 1: "Control of corruption" estimate average for period 1996-2004, 2005-2009, 2010-2015.

	1996-2004	2005-2009	2010-2015
US	1.73	1.37	1.31
EU	1.49	1.43	1.35
Japan	1.08	1.28	1.63
Russia	-0.87	-0.94	-0.97
Eurasia	-0.54	-0.42	-0.36
China	-0.39	-0.57	-0.43
India	-0.40	-0.39	-0.51
Middle East	0.02	-0.01	-0.09
Africa	-0.60	-0.62	-0.63
Latin America	0.03	0.17	0.10
Other High Income	1.61	1.62	1.59
Other Asian	-0.51	-0.61	-0.48

Results from table 1 are relevant to calculate changes in the saving rating accordingly to a methodology describe in chapter 4. As WGI advises, these results can't describe a trend in time, but they do show that changes of positions are heterogeneous; some regions are in better position while others score lower. This heterogeneity is relevant for the final analysis of the results.

3.2 RICE saving rates and adjusted net saving rates

From the literature review, it is relevant to mention that a line of research links three main variables: saving rates, corruption and the resource curse. The methodology of this research does not consider a resource curse variable, but in order to compare other results, I am reporting in this section the adjusted net saving rates (or genuine saving sate) as published by the World Bank and compare it with the saving rates of the RICE model. They share a common background: the Hartwick's rule.

The solution of the RICE model satisfies a "weak sustainability" condition, or Hartwick's rule (Hartwick, 1977). It establish that an economy should be managed in an efficient way such that the environmental damages loss be reduced and maximize resources rents after internalizing environmental externalities. It also considers that all rents obtained from natural resources depletion should be reinvested in capital in a way that the value of aggregate stock (human, physical and remaining natural capital) increase over time. The rule emphasizes that an economy depending on non-renewable resources extraction and accumulation of reproducible capital should sustain consumption by investing in capital assets in proportion with the depreciation of exhaustion from natural resources. The adjusted net saving rate is based also in this framework, so the RICE mitigation solution and the methodology of the adjusted net saving rate rely in a common framework. But the RICE saving rate is the result of an optimization process and does not consider human capital[11], so comparing both saving rates is not straightforward but elucidates the difference in the accountability of an important economic variable affecting the economic output and the paths towards a mitigation policy.

The Environmental Economic Unit of the World Bank's Environment Department reports the adjusted net saving rate for 218 countries since 1970. It is a modified net national saving rate considering natural capital depreciation and human capital. It follows a methodology developed by (Bolt, Matete, & Clemens, 2002) define as:

$$\frac{S_A}{GNI} = \frac{\left(S - D_K + CSE - \sum_i R_{Ni} - CD - PE\right)}{GNI} \tag{3.5}$$

where S_A is adjusted net savings, *GNI* gross national income, *S* is gross savings, D_K is depreciation of fixed capital, *CSE* is capital expenditure on education, *CD* is damages from carbon dioxide and *PE* damages for particulate emissions. R_{Ni} is the rent from depletion of natural stock; it considers energy stock, metals and minerals, and forest resources. Table 2 reports the average adjusted net saving from 2005 to 2014 and 2015, and the saving rates from RICE model for periods 2005 (2005-2014) and 2015 (2015-2025):

[11] In Fankhauser and Tol (2004) the RICE is modify to include a human capital sector following the Mankiw-Romer-Weil growth model.

Table 2: Average adjusted net savings (2005-2014) and 2015, and RICE saving rates 2005 and 2015

	2005-2014		2015	
	Adjusted net saving	RICE	Adjusted net saving	RICE
US	4.57	17.85	7.41	20.15
EU	9.88	17.46	11.21	19.70
Japan	7.00	15.13	6.75	18.00
Russia	10.62	19.12	8.96	18.60
Eurasia	7.80	19.50	9.54	22.13
China	24.86	35.71	22.86	22.40
India	22.68	29.48	18.65	26.54
Middle East	15.56	25.70	9.83	24.90
Africa	-2.33	29.79	-0.79	30.13
Latin America	9.10	23.57	9.99	23.56
Other High Income	16.18	18.69	17.05	20.15
Other Asian	14.37	24.09	14.89	27.51

These two ways of measuring are quite different, and so the results reflect the discrepancy between them. The adjusted net saving rates reflect the investment in human capital (i.e. education), the resource stock depletion, and damages by pollutants and emissions. The saving rates of RICE are a result of a consumption optimization process. For the RICE, it is important to mention the difference between low and high-income countries. In this case, the saving rates follow a growth path accordingly to the neoclassical growth theory that stays that low-income countries have higher saving rates than high income and both saving rates will get to a common convergence growth rate. For the adjusted net saving rates there is not a clear difference among countries but some special case are resource rich countries dependable in natural resource rents like the ones in the African region and Latin America ones that show low saving rates (even though Latin America has a higher saving rate than USA and Japan). The methodology of the adjusted net saving rates consider damages by CO_2 emissions and it is reflected in the low saving rates of rich highly industrialized countries or regions that contribute with more emissions than low-income countries (USA, Japan). The accountability of these differences are more realistic and fair than the RICE model, whose Negishi procedure homogenize consumption and doesn't reflect distribution of damages among regions.

Since the RICE outcome is a weak sustainability mitigation solution (i.e. it uses revenues from capital to reinvest in a carbon-save technology) it is possible to compare the adjusted net saving rates that rely in the Hartwick's rule definition and the saving rate of the RICE. The underlying methodology is evident when comparing both, they tell different stories. The RICE rates are prone to converge to an optimal growth economic path and the adjusted net saving rates shows how much are the damages for the economy and the impact of investing in human capital. Even though this research doesn't cover the line of research and methodology of the adjusted net saving rate, the comparison of both saving rates calculations gives a different perspective for future research.

4. A change in RICE due to corruption

The objective of this research is to reflect, under the previous literature review, the impact of corruption in the economic growth path and how this affects the emission reduction efforts. The main variable from RICE I modify are the saving rates of the twelve regions, also, the model uses a tax regime under no trade conditions. I consider the cross-region effect of corruption, aggregating the overall effect of corruption of neighbor countries in a single weight value.

4.1 Corruption and saving rates

The first step to calculate the saving rate in the RICE model is to calculate the initial saving rate from equation (2.1) and to solve the optimization non-linear problem (equations 2.6 to 2.13). From 2005 to 2115 the saving rate is optimized (equation 2.5), afterward the rate is constant with the last period as reference. As a control of the model, if the saving rate is changed, the optimization problem should be solved again.

Following the literature review about corruption, there are studies that elucidate important relationships between corruption and the saving rate, (Swaleheen 2007, Dietz, Neumayer and Sosya 2007, Boos and Holm-Müller 2013). For this research I use the Swaleheen 2007 study. It is a panel study of 100 countries for a ten-year period using a generalized method of moments (GMM). The results show that corruption affect and is negatively correlated with gross national savings (GNS) but no effect for the gross domestic savings (GDS). GNS is the gross national disposal income (GNDI) minus final consumption expenditure. The results show that one standard deviation decrease in the corruption index reduce the GNS by 6.1%. From all other relevant studies this one quantifies a measurable impact in the saving rates and focus only in the interaction between saving rates and corruption, unlike others that include a "resource curse" variable.

The WGI "Control of corruption" is a standard normal random variable with unit standard deviation, taken from equation (3.1) and the change among point estimates is in terms of unit standard deviation. In this way the difference among corruption perceptions through time is comparable to the result from Swaleheen 2007, therefore I compute the change in the saving rate accordingly to the research results. First I compute the change in average of the estimate of control of corruption for three time periods for each region i (See section 3.1, table 1):

$$\Delta s_{i2005,2015} = \sum_{n=1}^{N} \frac{s_{it+x}}{N} - \sum_{n=1}^{N} \frac{s_{it-x}}{N} \quad (4.1)$$

Then I calculate the impact in the saving rate i.e. for every unit decrease in the standard deviation of the corruption indicator the saving rate is 6.1% higher. I calculate the impact for every region *i*.

$$\Delta s^{corr}_{i2005,2015} = \Delta s_{i2005,2015} * 6.1 \quad (4.2)$$

I report the results from equation (4.1) and (4.2) in table 3, averages of the three periods are reported in table 1 from section 3.

Table 3: Differences in the average of the estimate of corruption and the impact as a percentage of the saving rate.
For 2005 (1996-2005, 2006-2009) and 2015 (2006-2009,2010-2015)

	2005		2015	
	Δs_{i2005}	Δs^{corr}_{i2005}	Δs_{i2015}	Δs^{corr}_{i2015}
US	-0.36	-2.21	-0.05	-0.33
European Union	-0.06	-0.36	-0.08	-0.49
Japan	0.20	1.25	0.34	2.09
Russia	-0.07	-0.42	-0.03	-0.18
Eurasia	0.13	0.79	0.05	0.33
China	-0.17	-1.07	0.14	0.84
India	0.01	0.08	-0.12	-0.74
Middle East	-0.03	-0.20	-0.09	-0.53
Africa	-0.02	-0.10	-0.02	-0.10
Latin America	0.14	0.86	-0.07	-0.44
Other High Income	0.01	0.05	-0.02	-0.14
Other Asian	-0.10	-0.62	0.13	0.81

The variable $\Delta s^{corr}_{i2005,2015}$ is the change of the saving rate because of a change in the corruption variable. From this result, it can be recalculated the RICE saving rates for each region. Following the next formula I recalculate the saving rates with the effect of corruption for every region *i*:

$$s^{corr}_{i2005,2015} = s^{RICE}_{i2005,2015} + \Delta s^{corr}_{i2005,2015} \quad (4.3)$$

I report the original RICE saving rates and the $s^{corr}_{i2005,2015}$ saving rate in table 4:

Table 4: Saving rates from RICE and modify, 2005 and 2015

	2005		2015	
	s^{RICE}	s^{corr}	s^{RICE}	s^{corr}
US	17.85	15.64	20.15	20.11
EU	17.46	17.10	19.70	19.45
Japan	15.13	16.37	18.00	20.12
Russia	19.11	18.69	18.6	18.72
Eurasia	19.50	20.28	22.13	22.90
China	35.70	34.64	22.4	23.52
India	29.48	29.56	26.54	26.12
Middle East	25.70	25.50	24.90	24.48
Africa	29.78	29.68	30.13	30.26
Latin America	23.57	24.43	23.56	23.34
Other High Income	18.69	18.73	20.15	20.17
Other Asian	24.09	23.47	27.51	28.69

I use these new saving rates in the RICE model, they substitute the original ones in the three scenarios: the baseline (BAU), the optimal, and the temperature limited one, then I optimize the model with these new saving rates.

In order to solve this problem, the RICE model in Excel runs with Solver but if the optimization problem is too big, it is suggested to buy the Premium or Risk Solver. I use a free resource named OpenSolver developed by the Engineering Science department at the University of Auckland, New Zealand; it is an add-in for Excel. The add-in has different optimizations programs, the non-linear optimization program NOMAD (Nonlinear Optimization by Mesh Adaptive Direct Search) was the most suitable to solve the problem for this research. It iterates more than 1000, which is software restriction of the Solver program. The NOMAD produces a feasible and optimal solution. The results are discussed in section 5.

5. Discussion of results

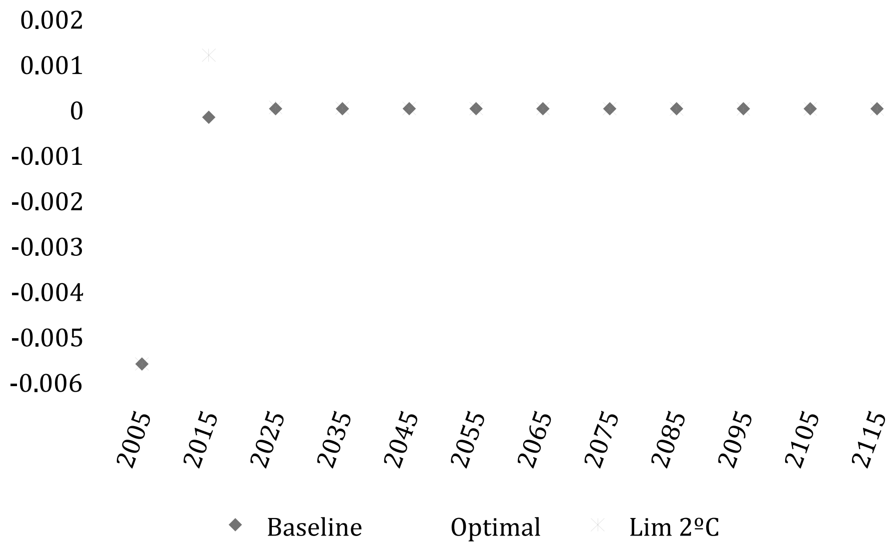
The main scenarios from the RICE that I am using to evaluate the changes due to corruption are three. The baseline (BAU) where there are no climate policies adopted. The optimal policy, where a trajectory for carbon taxes is Pareto optimal so it balances current abatement costs to the future benefit of abatement actions, it starts at 2010 with no climate constrains and full participation of all parties. Finally, there is a scenario limiting the increase in temperature to the 2°C threshold for the 1900 average. In this scenario, costs are minimized accordingly to the emissions trajectory subject to the temperature limit; it is assumed that is implemented through harmonized carbon taxes. This last scenario goes accordingly to the pledge made at the COP21 to maintain the temperature below 2°C of preindustrial temperature levels. In order to evaluate the main results, I report the modified outcome of economic variables, the variations in the climatic outcomes, variations in the social cost of carbon, and finally the welfare results aggregated and by regions. In order to graph the change in the variables I am picturing the difference between the variables in the modified scenarios and the original ones.

5.1 Economic variables

The solution of the RICE as reviewed in section 2.2.2 demonstrates the preponderance of the saving rate in the final outcome of the model. The saving rate dictates the global output that in turn determines emissions and damages that are main variables to establish a mitigation rate determining the final net output of the model. The RICE main decision is between a region's present consumption and present investment measure as a reduction in emission in order to increase possible future consumption. Since the saving rates determine capital accumulation and this is a key variable that governs investment, the saving rate is a variable that dictates the total investment in reducing emissions. Following these dynamics of the model, I show the change in consumption and investment due to the modified saving rate because of corruption. The saving rates are modified for periods 2005 and 2015, and optimized from period 2025 to 2115. The economic variables are analyzed in these periods.

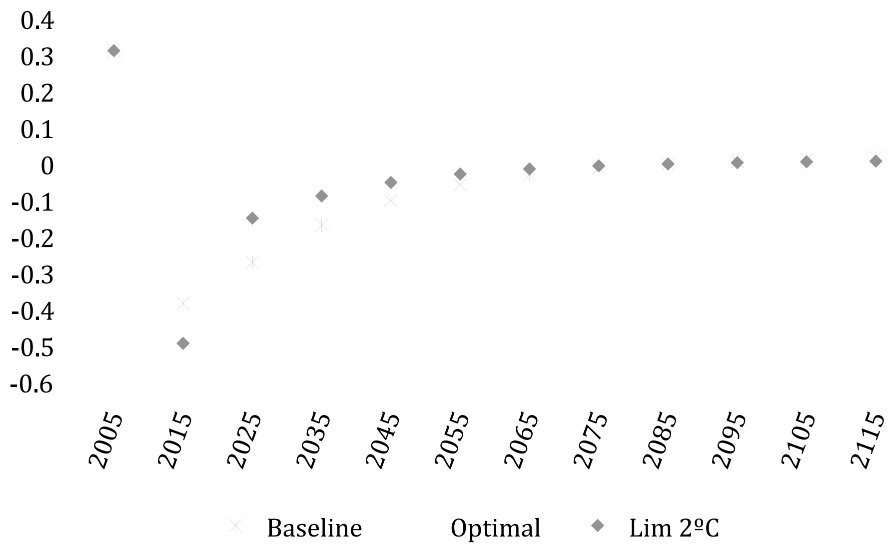
As explain in chapter 4, saving rates are modified due to corruption and changed in the RICE. After this change the model is optimized. The following figure 1 shows the difference between the modified saving rates and the original ones. First, there is a reduction in the difference of the saving rates then an increase. For the period 2025, the path of the saving rates stabilizes to the original trajectory of the model. Since the RICE in its three scenarios is optimizing the global welfare the saving rates recover the optimal path (the ones in the original model) in order to increase the level of investment, reduce emissions, and maximize total welfare. This dynamic determines the behavior of other economic variables and the trajectories in emissions and mitigation actions as further explain.

Figure 1: Difference in saving rates between modified model and original model (fraction of gross output)



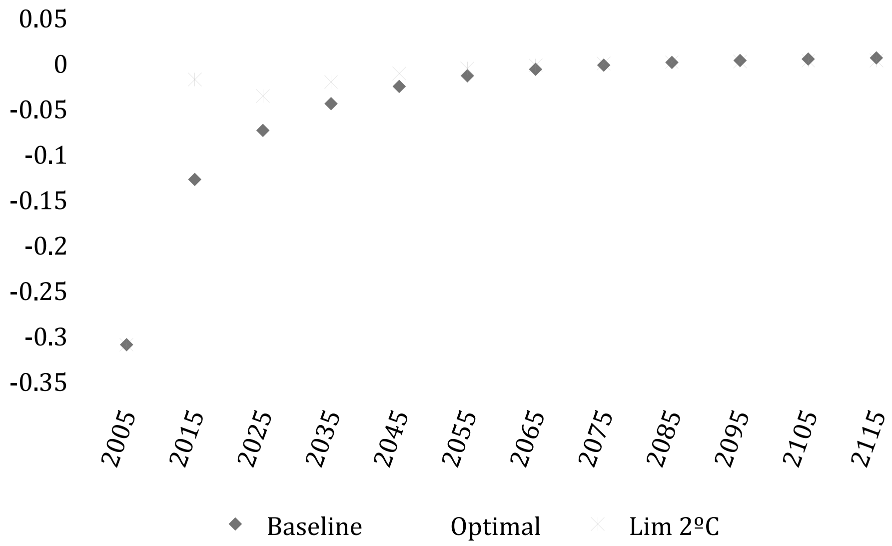
The difference in consumption in the modified framework shows an initial increase and then a reduction in the three scenarios. Even though it has a pronounce decline in the optimal and limiting scenarios, it has a more smooth transition in these two trajectories than in the baseline. For the three scenarios the path is the same as in the original model from 2085. The initial difference increase in consumption is due to a shift from the investing decision to consumption afterwards there is stabilization in the saving rate allowing a return to the path to a balance between consumption and investment. The results are in figure 2.

Figure 2: Difference in consumption between the modified scenarios and the original ones (in trillions of US dollars per year)



The change in investment shows a reduction until period 2085 in the three scenarios. For the baseline, the reduction is more pronounced and the transition to the original path is slower. In the limiting scenario, the responsive change in investment is due to the urge to invest in mitigation because of the temperature constrain and the costs it represents. This scenario imposes a costly challenge to be implemented because of the inertia in the climatic system. In the optimal scenario, the difference in investment also recovers from the reduction but at a slower pace than in the limiting scenario. Even without an impose restriction, as in the optimal scenario, the economic system in the model converges to a positive rate of investment in emission reduction. These paths are shown in figure 3.

Figure 3: Difference in investment between modified scenarios and original ones (in trillions of US dollars per year)



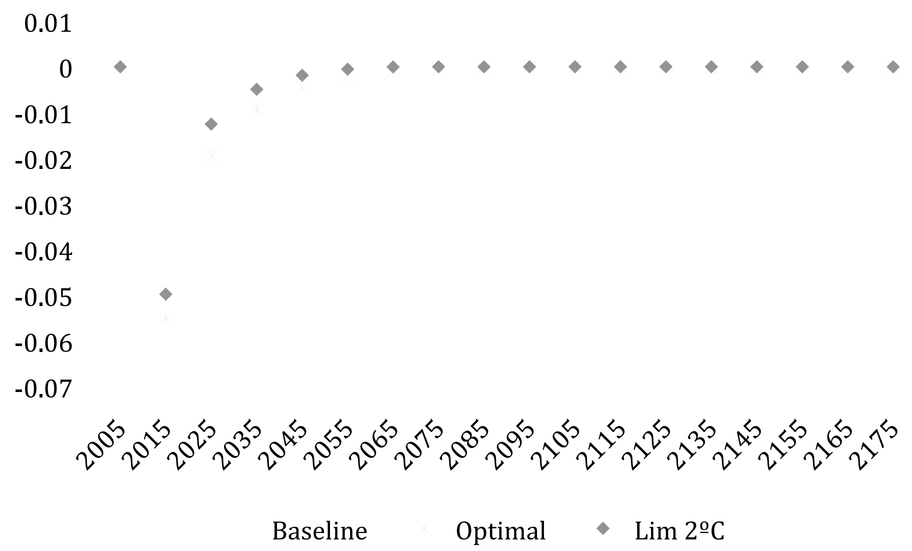
The change in saving rates because of the persistence of corruption in the first periods represent a negative shock, afterward it has a positive trajectory. Finally it stabilizes in the 2025 period. Even though, as a fraction of gross output, it represents a small change, it has considerable repercussions in consumption and investment. The positive shock in consumption represents the change in decision of the representative agent towards an increase in consumption and a reduction in investment. Since the main objective of the model is to maximize total welfare, the shift in investment is rapid to recover the level of welfare. As review in section 1.2.1 corruption shifts the optimal level of investment in an economy, for this case, the transmission mechanism is the saving rate. Due to the dynamics of the model, the disturbance from the optimal path is of 7 periods, there after it follows the optimal path of the three scenarios.

5.2 Climatic variables

As I have reviewed before, the saving rate determines the level of capital accumulation then gross output and these variables determine emission and mitigation actions. When I modified the saving rates due to corrupt practices the climatic variables also shift from original path of the three scenarios. I am reporting total carbon emissions and the atmospheric temperature. Both variables have different paths in the original model in contrast with the economic variables where the three paths are almost overlapping. The reason of the variations are the underlying assumptions and dynamics of the model, for example, the limiting scenario reaches the 2ºC threshold in period 2075 and the BAU goes above 5ºC for period 2175, in order to illustrate the original path of these variables I graph them in appendix D. The difference between the modified RICE and the results of the original are small but are worth reporting it because it reflects the dynamics in the variables due to corruption. These dynamics are analyzed here. I choose the period from 2005 to 2175, 6 periods more than in the ones reported for the economic variables. This is because there is a climatic system inertia that may lag differences in results.

The total carbon emissions reduce for the three scenarios in period 2005-2015. The mayor reduction is for the BAU scenario. As shown in graph D2, this scenario has the highest level of emissions since there is no climate policy therefore the pronounced reduction in the result. The reduction in the optimal scenario is more moderate since in this scenario mitigation actions reduce negative capital accumulation and the scheme looks to optimize total welfare. Finally the restriction of 2ºC impose a mayor restriction in emissions therefore the difference in reduction is the least pronounce. Since period 2095, the difference between the modify RICE outputs and the original ones is asymptotically zero, meaning, the shock in total emissions due to corruption are of no further consideration. The differences between variables are shown in figure 4.

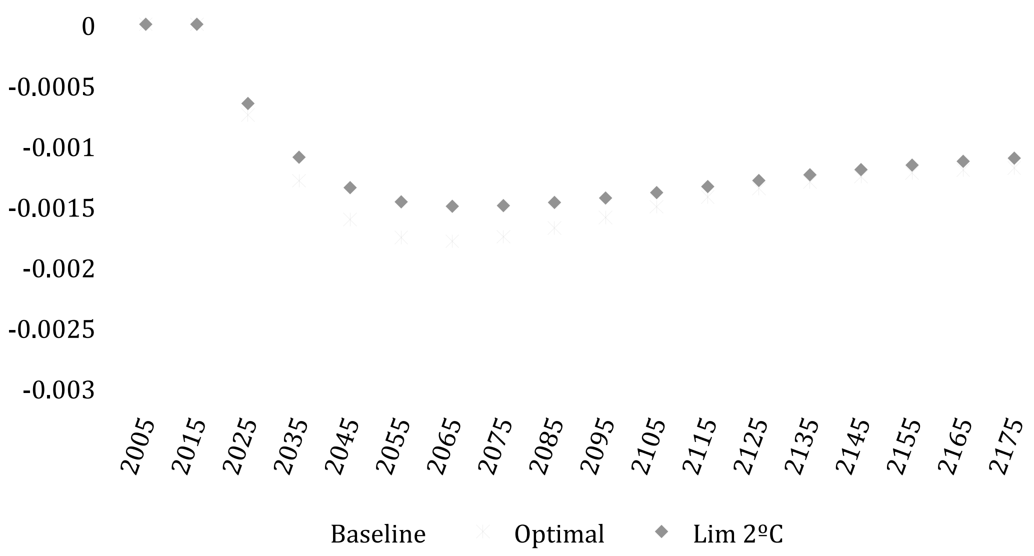
Figure 4: Difference in total carbon emission between the modify RICE and the original model (GtC per year, 2005-2175)



The atmospheric temperature report by the RICE is the change in temperature considering the year 1900 as the reference, i.e. pre-industrial levels. During 2005 and

2015 where I change the saving rate, the paths are the same as in the original RICE. The most pronounce reductions are in period 2065. This lag represents the climatic inertia, different to the emission that reflect almost immediate. The most pronounce reduction is in the BAU scenario because as in figure D1 is represented, it is the scenario with the highest rise in temperature. Intuitively, the least reduction is in the limiting scenario because of the temperature threshold imposed. These dynamic goes asymptotical up to year 2605 (not graph); the BAU scenario keeps a constant reduction of 0.00075ºC, the limiting scenario reduces constantly by 0.0009ºC and the optimal scenario reduces by 0.001ºC. The reduction in temperature reflects the reduction in gross output that reduces total emissions. The differences in temperature between the modify RICE and the original are reported in figure 5.

Figure 5: Difference in atmospheric temperature between the modify RICE and the original (ºC above preindustrial, 2005-2175)



Contrary to the findings in the literature review in section 1.2.1 the persistence of corrupt practices does not increase CO_2 emission that in turn altered the atmospheric temperature. The effect of corruption under the RICE framework is through economic growth. Corruption reduces gross output and in turn reduces emissions this reduction decreases climatic stress in the atmospheric temperature. It is worth remarking the effect in the climatic system of a two period shock in the saving rate. The effect in emissions is a shift of 7 periods and in atmospheric temperature is a lag effect of persistence effects. Even though the reduction of pressure in the climatic system may look like a positive outcome, in this case the reduction in emissions are not a result of mitigation actions. Therefore the effect in the total welfare is negative as further analyzed.

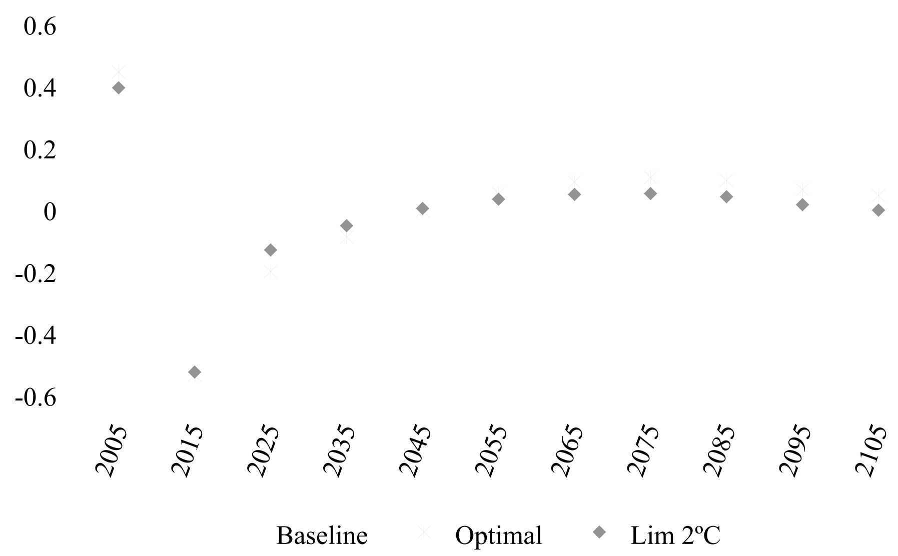
5.3 Social cost of carbon

In order to analyze the impact of corruption in the final outcome of the model I use the social cost of carbon. This variable pictures a different result because it ponders the economic variables and the climatic one in a single value. It represents how much will cost an additional ton of carbon in terms of economic units, in other words, the change in the discount value of utility of consumption define by the current consumption per tons of carbon. It is calculated with the difference between actual consumption and future consumption. The social cost of carbon (SCC) is calculated as follow:

$$SCC(t) = \frac{\partial W}{\partial E(t)} \Big/ \frac{\partial W}{\partial C(t)} \tag{5.1}$$

The numerator represents the marginal impact in welfare because of carbon emissions and the denominator the marginal welfare of a unit in consumption for period *t*. The trajectories in the original RICE outcome for the SCC are different for the three policy scenarios. The BAU scenario has the highest SCC, the SCC in the optimal is less than in the BAU, and the limiting scenario has the lowest SCC. The trajectories are pictured in figure D3 in appendix D. The change in saving rates due to corruption change the trajectory of the original SCC paths. In the first period there is an increase in the difference of the SCC as the trajectory in consumption in figure 2. Then there is a decrease reaching the lowest level in period 2025 this is a result of a reduction in consumption and the total carbon emissions. After period 2055 the difference in the SCC increases for the three policy scenarios, being the highest for the BAU scenario. The lag in the increase of the SCC is a result of the increase in consumption in the first periods and the reduction of investment, resulting in a reduction in the potential future consumption reducing the overall welfare; effects are evident in the long run and not immediately accounted. The least increase for SCC in future periods is in the limiting scenario because the reaction in consumption and investment is more rapid than in the other two policy trajectories. The difference of the SCC in the optimal scenario does not increase as much as in the BAU again, it has to do with the adjusted values of investment and consumption in the first periods. These trajectories are graph in figure 6.

Figure 6: Difference in SCC between modify RICE results and original RICE (US dollar/ tons of CO_2)



The change in the saving rates due to corruption result in a decrease and then in an increment for SCC. Since SCC represent the additional economic cost of an increase in a ton of carbon, the shift between consumption and investment is pondered within the framework of the reduction in emissions and temperature. Even if at first sight the reduction of emissions and temperature may seem a positive outcome when the change in investment is considered, the impact of corruption is negative in the first periods and in the long run. In order to assess the impact in the whole system I review the effects in total and regional welfare outputs in the following section.

5.4 Welfare

The RICE model works within the neoclassical economic theory so the total welfare is a main outcome of the model. The RICE welfare is in terms of 2005 trillions of dollars. In order to report them in 2017 US dollars I am using an annual 5% discount rate as suggested at (Nordhaus W. D., 2010) and an inflation rate of 1.25%[12]. After modifying the saving rates as detailed in chapter 4, I optimized the model to get the results in table 5. The optimized saving rates under the NOMAD optimization program are reported in appendix E.

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[12] Following the formula: $\frac{CPI_{2017}}{CPI_{2005}}$ where CPI stands for Consumer Price Index. As reported by the Bureau of Labor Statistics CPI_{2005}= 195.3 and CPI_{2017}=244.524

Table 5: Welfare, different policies (in trillions of US dollar, 2017 prices)

<table>
<tr><th></th><th>Optimized welfare</th><th>Welfare baseline</th><th>Difference</th><th>Original welfare</th><th>Difference</th></tr>
<tr><td>Baseline</td><td>5166.49</td><td rowspan="6">5166.49</td><td>0</td><td></td><td></td></tr>
<tr><td>Modify baseline</td><td>5165.93</td><td>-0.56</td><td></td><td></td></tr>
<tr><td>Optimal</td><td>5184.60</td><td>18.10</td><td rowspan="2">5184.60</td><td>0</td></tr>
<tr><td>Modify optimal</td><td>5184.03</td><td>17.53</td><td>-0.57</td></tr>
<tr><td>Lim 2°C</td><td>5176.39</td><td>9.90</td><td rowspan="2">5176.39</td><td>0</td></tr>
<tr><td>Modify 2°C</td><td>5175.81</td><td>9.32</td><td>-0.58</td></tr>
</table>

The scenario with the better outcome in terms of welfare is the optimal policy. In both cases, the original scenario and the modified one, there is a benefit of $18.1 trillion and $17.5 trillion respectively from the BAU scenario. The scenario with a restriction of 2°C has a reduced benefit. Imposing this threshold is costly reducing by half the net benefits and because of the climate system inertia it is quite difficult to obtain, although necessary accordingly to the IPCC. In order to compare the effects of corruption in the model the results between the original scenarios and the modified ones are relevant. Even in absence of climate policy, in the BAU scenario, there is a reduction in the global welfare of $0.56 trillion of US dollars. For the optimal policy scenario the reduction is of $0.57 trillion and in the scenario limiting the increase in temperature the reduction is of $0.58 trillion. Considering that the change in the saving rates is heterogeneous among the regions, the aggregate result became relevant. There are regions with an increase in the saving rate because of the reduction in corruption, still the overall result shows a reduction in the global welfare. In table 6 I report the total welfare by region.

Table 6: Welfare by region and their difference (in trillion of US dollars, 2017 prices)

<table>
<tr><th></th><th>Baseline</th><th>Modify Baseline</th><th>Optimal</th><th>Modify optimal</th><th>Lim 2°C</th><th>Modify Lim 2°C</th></tr>
<tr><td>US</td><td>1482.09</td><td>1481.62</td><td>1483.21</td><td>1482.75</td><td>1481.80</td><td>1481.33</td></tr>
<tr><td></td><td colspan="2">-0.46</td><td colspan="2">-0.47</td><td colspan="2">-0.47</td></tr>
</table>

EU	1245.05	1245.04	1247.01	1247.00	1246.62	1246.60
	-0.01		-0.01		-0.01	
Japan	330.14	330.11	330.40	330.36	330.21	330.18
	-0.04		-0.04		-0.04	
Russia	120.54	120.53	120.52	120.51	120.13	120.13
	-0.003		-0.003		-0.003	
Eurasia	59.79	59.79	59.86	59.86	59.63	59.63
	-0.001		-0.001		-0.0004	
China	268.87	268.82	271.80	271.75	269.33	269.28
	-0.05		-0.05		-0.05	
India	168.47	168.48	170.85	170.85	170.23	170.24
	0.008		0.006		0.005	
Middle East	380.18	380.18	381.65	381.66	380.65	380.65
	-0.0002		0.002		0.002	
Africa	117.62	117.62	120.72	120.73	121.01	121.02
	0.007		0.004		0.003	
Latin America	384.95	384.93	386.05	386.04	385.54	385.53
	-0.02		-0.01		-0.01	
OHI	384.06	384.07	384.60	384.60	384.16	384.17
	0.002		0.002		0.002	
Other Asian	224.75	224.74	227.93	227.93	227.07	227.07
	-0.003		-0.005		-0.007	

The results are consistent within the regions, for some of them the differences among scenarios are of equal value. There are results that seem almost undistinguishable, close to zero, although it is worth remarking that these results are in magnitude of trillions of dollars. Comparing these results with the modified saving rates of the regions there are cases of particular interest. The three regions with an improvement, in both periods, in the saving rate due to reduction in corruption are Japan, Eurasia, and OHI, from these three, only the OHI region show a positive outcome in the total welfare, the other two report a reduction in welfare. Due to a reduction in corruption, Africa and India show an increase in the saving rate but only for one period of those modified. Nevertheless their level of welfare is higher in the modified scenarios. Finally, the Middle East region has in both periods a reduction in the saving rate due to corruption but in the modified optimal and limiting scenarios report a better welfare level. These results obey the inherent dynamics of the model; low-income countries are assumed to increase their saving rates compare with high-income countries, so the increase in welfare in Africa, Middle East and India follow these dynamics. It is of relevant importance the OHI block. The inherent dynamics dictate a reduction in their saving rates; still, the reduction in corruption shows a positive outcome in total welfare. The other regions show a decrease in welfare. Even north region blocks that may benefit in the beginning of a milder temperature show a decrease in welfare, for example, Russia and the European Union.

The impact of corruption in the model through the saving rates is overall negative. The only positive impact may be the reduction in emissions and atmospheric temperature, but when these results are assessed in comparison with economic variables the results are negative. The SCC reports a sharp increase in the first periods and a moderate rise in the long run, this means that an increase in temperature is more costly under this new framework. This is due to a reduction in investment that means less mitigation investment and more present consumption. These results including the overall reduction in total global welfare confirm the negative impact of corruption through the negative effect in the prospective of an effective mitigation policy. For a regional analysis, the results show a reduction in welfare for 8 of the 12 regions reflecting that in most cases the saving rate has a negative impact due to corruption.

Conclusions

Climate change is a phenomenon that needs to be tackled from different perspectives and in coordination with all the parties. The effects may benefit some countries in early periods but in the long run, the effect will negative impact the global system and all the parties. The IAM's are useful tools where the economic and the climatic systems interact and portrait a scenario. This interaction will depend upon the variables modify and the main framework of the IAM. As used in this thesis, the RICE is an IAM under a neoclassical growth theory and the two main decision variables are the saving rate and the carbon tax.

Corruption, as climate change, is a multidisciplinary phenomenon and needs the engagement of all actors to eliminate or at least ameliorate the problem. It represents a burden, mainly to the economic system, but after reviewing other researches, there is evidence of negative outcomes in the climatic system. Corruption as well imposes a challenge because there is not a straightforward way of measuring it. The data used here is from perception of corruption and the results depend upon the definition of the variable so there are different dimensions of the problem properly reflected in the data.

To evaluate the effects in the climatic and economic system, an IAM results a useful tool. The RICE is suitable because it combines the economic and climatic system and allows modifying the saving rate that is a variable affected by corruption accordingly to some studies. By modifying the saving rates due to corruption, the results in the 12 regions of the RICE were heterogeneous. Some regions reported a reduction in corrupt practices fostering an increase in their saving rates but for most cases corruption is more persistent in the regions lowering their saving rates.

The impact of corruption in the economic system is reflected mainly in consumption and investment. The change in the saving rates due to corruption produces a shift from investment to present consumption. In the RICE model, investment represents reduction in emissions because it reduces negative capital accumulation (or CO_2 emissions) increasing consumption in the future. The change in the investment decision affects future consumption reducing overall welfare. Even considering the dynamics of the model that constantly are optimizing and iterating the variables to obtain a feasible and optimal solution, the impact of the change in the saving rates due to corruption is negative on welfare.

The climatic system results show a reduction in emissions and temperature. This is because emissions are an outcome of the productive economic system and with a reduction in the economic system there are less emissions. The change in temperature is lagged because of the climatic inertia of the system but this change is due to the reduction in the economic system. Even though it may look like a positive effect the reduction in emissions is not significant enough to increase future well being of the society. The SCC is the variable pondering economic changes and climatic changes, it reflects the cost of and addition ton of CO_2. This variable shows an initial sharp increase in the cost, then a reduction, and finally a consistent and moderate increase in the SCC. It reflects the initial shift from investment to consumption, then the reduction in the emission of CO_2 and in the long run it reflect the effect of the reduction in investment in the first periods decreasing future consumption. As the evidence in corrupt studies indicates corruption reduces or misallocates investment reducing economic growth and overall welfare. In the RICE a reduction in investment indicate a reduction in mitigation efforts so corruption represents a burden to climatic policy.

In the comparison among policy scenarios in the resulting total global welfare the impact of corruption is clear. Comparing the optimal BAU with the modify version there is a reduction of $563 billions of US dollars in 2017 value. The optimal scenario reports a loss of $570 billions of dollars and the policy scenario limiting global temperature to 2ºC has a reduction of $579 billions of dollars in total welfare. The reduction in the BAU scenario is reflecting the negative impact in consumption mainly but since there is no climatic policy there are not loss due to a change in mitigation efforts. In the optimal and limiting scenario the reduction in welfare is a reflection of the reduction of capital use for mitigation actions and the negative impact in future consumption.

In a regional analysis the impact of corruption may seem counterintuitive of the main perception of corruption by region. For example, Africa shows better welfare even though it is consider with high persistence of corruption or US that usually presents a low perception of corruption; it has the most pronounce reduction in welfare. This obeys that the data measuring corruption does not reflect a trend in time for each region but a change in position relative to previous ranks, in this case, the US shows more corruption from previous years and in the region of Africa there have been a reduction in corruption. US in particular has an increase in perception of corruption through the measured years and it reflects in the most pronounce reduction in relative welfare from all the regions.

The reduction of welfare and the increase of SCC are the main variables showing the negative impact of corruption. Due to availability of data and the construction of the model the only periods in which saving rates are modified are 2005 and 2015. Even though is a small period, the change in total welfare is considerable. The outcome indicates that reducing corruption will improve the economic performance allowing for more effective mitigation actions.

The present thesis is an effort to incorporate corruption within an IAM framework. These are models usually used to evaluate climate policies by international experts that dictate global mitigation policies, so it is of special interest to include a variable as relevant as corruption. It is of further concern incorporating corruption as an endogenous variable within the RICE as other academic efforts have been made to incorporate corruption in the Ramsey model (Ellis & Fender, 2006) and the Solow model(Farida & Ahmadi-Esfahani, 2007). Incorporating corruption as an endogenous variable will elucidate more relevant interactions between climatic and economic variables under a corrupt environment.

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Appendix A

This section enumerates the main equations governing the RICE model, the variables, and parameters. This section is the same as in Nordhaus 2010 Supporting information only minor changes in the notation were made and some equations were added.

(A.1) Welfare:

$$W = \sum_{t=1}^{T} \left(\frac{1}{1+\rho} \right)^t \sum_{i=1}^{I} v_{it} L_{it} u_{it}(c_{it})$$

(A.2) Utility function

$$u(x) = \frac{x^{1-\gamma}}{1-\gamma}$$

(A.3) Output before damages and abatement:

$$F_{it}(K,L) = A_{it} K_{\gamma} L^{1-\gamma}$$

(A.4) Abatement costs as fraction of output

$$\Lambda_{it} = \theta_{it}^1 \mu_{it}^{\theta_2}$$

(A.5) Climate damages as fraction of output

$$\Omega_{it} = \frac{D_{it}\left[T_t, SLR_t, M_t^{AT}\right]}{\left(1 + D_{it}\left[T_t, SLR_t, M_t^{AT}\right]\right)}$$

(A.6) Regional damage function

$$D_{it} = D_{it}^{nonS} + D_{it}^{S}$$

(A.7) Damages from temperature

$$D_{it}^{nonS} = \beta_{1i} T_t + \beta_{2i} T_t^2$$

(A.8) Sea-Level Rise damages

$$D_{it}^{S} = (b_{1i} S(T_t) + b_{2i} S(T_t)^2)(G_{i,0,t-1})^{1/4}$$

(A.9) Output after damages and abatement

$$Q_{it} = \frac{1-\Lambda_{it}}{1+D_{it}} Y_{it}$$

(A.10) Composition of output

$$Q_{it} = C_{it} + I_{it}$$

(A.11) Gross output

$$Y_{it} = F_{it}(K_{it}, L_{it})$$

(A.12) Per capita consumption

$$c_{it} = \frac{(1 - s_{it})Q_{it}}{L_{it}}$$

(A.13) Law of motion of capital stock

$$K_{it+1} = 10 s_{it} Q_{it} + (1 - \delta)^{10} K_{it}$$

(A.14) Industrial emissions

$$E_{it} = \sigma_{it}(1 - \mu_{it})Y_{it}$$

(A.15) Carbon fuel limitations

$$CCum \geq \sum_{t=1}^{T\max} \left[\sum_{i=1}^{12} E_{it} \right]$$

(A.16) Total carbon emissions

$$E_t = \sum_{i=1}^{12} E_{it} + EL_t$$

(A.17) Dynamics of atmospheric carbon concentrations

$$M_t^{AT} = E_t + \phi_{11} M_{t-1}^{AT} + \phi_{21} M_{t-1}^{UP}$$

(A.18) Dynamics of carbon concentrations in biosphere and upper oceans

$$M_t^{UP} = \phi_{12} M_{t-1}^{AT} + \phi_{22} M_{t-1}^{UP} + \phi_{32} M_{t-1}^{LO}$$

(A.19) Dynamics of carbon concentrations lower oceans

$$M_t^{LO} = \phi_{23} M_{t-1}^{UP} + \phi_{33} M_{t-1}^{LO}$$

(A.20) Radiative forcings

$$F_t = \eta \left\{ \log_2 \left[\frac{M_t^{AT}}{M^{AT}(1750)} \right] \right\} + F_t^{EX}$$

(A.21) Global mean surface temperature

$$T_t^{AT} = T_{t-1}^{AT} + \xi_1 \left\{ F_t - \xi_2 T_{t-1}^{AT} - \xi_3 \left[T_{t-1}^{AT} - T_{t-1}^{TO} \right] \right\}$$

(A.22) Temperature lower oceans

$$T_t^{LO} = T_{t-1}^{LO} + \xi_4 \left\{ T_{t-1}^{AT} - T_{t-1}^{LO} \right\}$$

(A.23) Sea level rise (thermal expansion, glaciers, ice sheets)

$$SLR_t = SLR_{t-1} + \left[\sum_{j=1}^{5} \pi_{1,j} + \pi_{2.j} T_{t-1}^{AT} + \pi_{2,j} \left[T_{t-1}^{AT} - \overline{T}_j^{AT} \right] \right]$$

Variable definitions and units

A_t=total factor productivity (productivity units)

c_t=per capita consumption of goods and services (2005 US dollars per person)

C_t=consumption of goods and services (trillions of 2005 US dollars)

D_t=damages for climate change (trillions of 2005 US dollars)

EL_t=emissions of carbon from land use (billions of metric tons C per period)

E_t=industrial carbon emissions (billion metric tons C per period)

F_t, F_t^{EX}=total and exogenous radiative forcing (watts per square meter from 1900)

I_t=investment (trillions of 2005 US dollars)

K_t=capital stock (trillions of 2005 US dollars)

L_t=population and proportional to labor inputs (millions)

Λ_t=abatement cost as fraction of output

M_t^{AT},M_t^{UP},M_t^{LO}=mass of carbon in reservoir for atmosphere, upper oceans, and lower oceans (billions of metric tons C, beginning of period)

μ_t=emissions-control rate (fraction of uncontrolled emissions)

σ_t=ratio of uncontrolled industrial emissions to output (metric tons C per output in 2005 prices)

Ω_t=damage function (climate damages as fraction of regional output)

Q_t=output of goods and services, net of abatement and damages (trillions of 2005 US international dollars)

s_t=saving rate (percentage of GDP)

$S(T_t)$=amount of SLR as a function of temperature increase

SLR_t=sea level rise (relative to 1990 in meters)

T_t=temperature increase above preindustrial levels

T_t^{AT},T_t^{LO}=global mean surface temperature, temperature upper oceans, temperature lower oceans(°C from 1900)

W_t=objective function in present value of utility (utility units)

Y_t=output of goods and services, gross of abatement and damages (trillions of 2005 US dollars)

Parameters

α=elasticity of marginal utility of consumption (pure number)

b_1,b_2=parameters of SLR-related damage function

β_1, β_2= parameters of temperature damage function

CCUM=maximum consumption of fossil fuels (billions metric tons carbon)

$G_{0,t-1}$=economic growth factor between period 0 and t-1 (one plus growth rate)

γ=elasticity of output with respect to capital (pure number)

δ_K=rate of depreciation of capital (per period)

η=temperature-forcing parameter (°C per watts per meter squared)

ϕ_{11},ϕ_{21}, ϕ_{22}, ϕ_{32}, ϕ_{12}, ϕ_{33}, ϕ_{23}=parameters of the carbon cycle (flows per period)

ξ_1, ξ_2, ξ_3, ξ_4=parameters of climate equations (flows per period)

ρ=pure rate of social time preference (per year)

$\overline{T}_{jt}^{AT}$ =threshold temperatures for ice sheets in SLR equation (°C)

θ_{1t}, θ_2=parameters of the abatement cost function

v_t=Negishi parameters of the social welfare function

Appendix B

The RICE model is divided in twelve regions. In this section I enumerate the countries that conform each region. This division follows the segmentation of the RICE 2010 Excel documentation.

I. United States of America

American Samoa
Guam
United States

II. European Union

Austria
Belgium
Czech Republic
Denmark
Faeroe Islands
Finland
France
Germany
Greece
Greenland
Hungary
Iceland
Ireland
Italy
Luxembourg
Malta
Netherlands
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Turkey
United Kingdom

III. Japan

IV. Russian Federation

V. Eurasia

Albania
Armenia
Azerbaijan
Belarus
Bosnia and Herzegovina
Bulgaria
Croatia
Estonia
Georgia
Kazakhstan
Kyrgyz Republic
Latvia
Lithuania
Macedonia, FYR
Moldova
Montenegro
Romania
Serbia
Slovenia
Tajikistan
Turkmenistan
Ukraine
Uzbekistan

VI. China

VII. India

VIII. Middle East

Bahrain
Cyprus
Iran, Islamic Republic
Iraq
Israel
Jordan
Kuwait
Lebanon
Oman
Qatar
Saudi Arabia
Syrian Arab Republic
United Arab Emirates
West Bank and Gaza
Yemen, Republic

IX. Africa

Algeria
Angola
Benin
Botswana
Burkina Faso
Burundi
Cameroon
Cape Verde
Central African Republic
Chad
Comoros
Congo, Democratic Republic
Congo, Republic
Cote d'Ivoire
Djibouti
Egypt, Arab Republic
Equatorial Guinea
Eritrea
Ethiopia
Gabon
Guinea-Bissau
Kenya
Lesotho
Liberia
Libya
Madagascar
Malawi
Mali
Mauritania
Mauritius
Morocco
Mozambique
Namibia
Niger
Nigeria
Rwanda

Sao Tome and Principe
Senegal
Seychelles
Sierra Leone
Somalia
South Africa
Sudan
Swaziland
Tanzania
Togo
Tunisia
Uganda
Zambia
Zimbabwe

X. Latin America

Antigua and Barbuda
Argentina
Aruba
Bahamas, The
Barbados
Belize
Bermuda
Bolivia
Brazil
Cayman Islands
Chile
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
Ecuador
El Salvador
Grenada
Guatemala
Guyana
Haiti
Honduras
Jamaica
Mexico
Netherlands Antilles
Nicaragua
Panama
Paraguay
Peru
Puerto Rico
St. Kitts and Nevis
St. Lucia
St. Vincent and the Grenadines
Suriname
Trinidad and Tobago
Uruguay
Venezuela, RB
Virgin Islands (US)

XI. Other High Income

Australia
Canada
Hong Kong, China
Korea, Republic
Macao, China
New Zealand
Singapore

XII. Other Asian

Afghanistan
Bangladesh
Bhutan
Brunei Darussalam
Cambodia
Fiji
French Polynesia
Indonesia
Kiribati
Korea, Democratic Republic
Lao PDR
Malaysia
Maldives
Mongolia
Myanmar
Nepal
New Caledonia
Pakistan
Papua New Guinea
Philippines
Samoa
Solomon Islands
Sri Lanka
Thailand
Timor-Leste
Tonga
Vanuatu
Vietnam

Appendix C

The variable “Control of Corruption” reported by the Worldwide Governance Indicators has four different sources mainly: Surveys from households and firms, commercial business information, non-governmental organizations, and public sector organizations. Through the years the number of relevant sources have increased up to today that account for a total of 31 sources. These are the sources used in the last report.

Code	**Data source name**
ADB	African Development Bank Country Policy and Institutional Assessments
AFR	Afrobarometer
ASD	Asian Development Bank Country Policy and Institutional Assessments
BPS	Business Enterprise Environment Survey
BTI	Bertelsmann Transformation Index
CCR	Freedom House Countries at the Crossroads
EBR	European Bank for Reconstruction and Development Transition Report
EIU	Economist Intelligence Unit Riskwire & Democracy Index
FRH	Freedom House
GCB	Transparency International Global Corruption Barometer Survey
GCS	World Economic Forum Global Competitiveness Report
GII	Global Integrity Index
GWP	Gallup World Poll
HER	Heritage Foundation Index of Economic Freedom
HUM	Cingranelli Richards Human Rights Database and Political Terror Scale
IFD	IFAD Rural Sector Performance Assessments
IJT	iJET Country Security Risk Ratings
IPD	Institutional Profiles Database
IRP	IREEP African Electoral Index
LBO	Latinbarometro
MSI	International Research and Exchanges Board Media Sustainability Index
OBI	International Budget Project Open Budget Index
PIA	World Bank Country Policy and Institutional Assessments
PRC	Political Economic Risk Consultancy Corruption in Asia Survey
PRS	Political Risk Services International Country Risk Guide
RSF	Reporters Without Borders Press Freedom Index
TPR	US State Department Trafficking in People report
VAB	Vanderbilt University Americas Barometer
WCY	Institute for Management and Development World Competitiveness Yearbook
WJP	World Justice Project Rule of Law Index
WMO	Global Insight Business Conditions and Risk Indicators

Appendix D

The following figures are the trajectories of the atmospheric temperature, total carbon emissions, and the social cost of carbons in the outcome of the original RICE model. I report only the original results because the ones from the modify version of RICE are graphical similar and both trajectories overlap if graph together.

Figure D1: Atmospheric temperature for the three original policy scenarios (ºC above preindustrial 2005-2175)

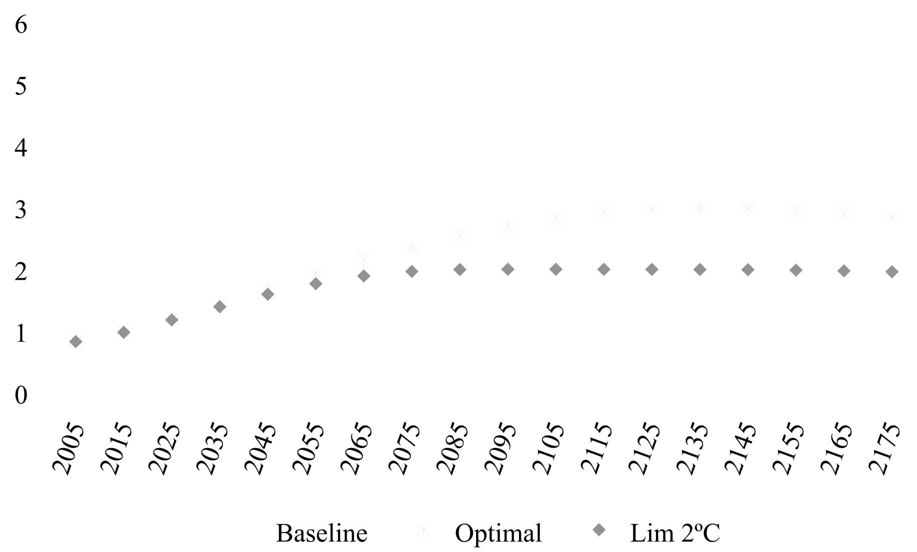


Figure D2: Total carbon emissions for the three original policy scenarios (in GtC per year, 2005-2175)

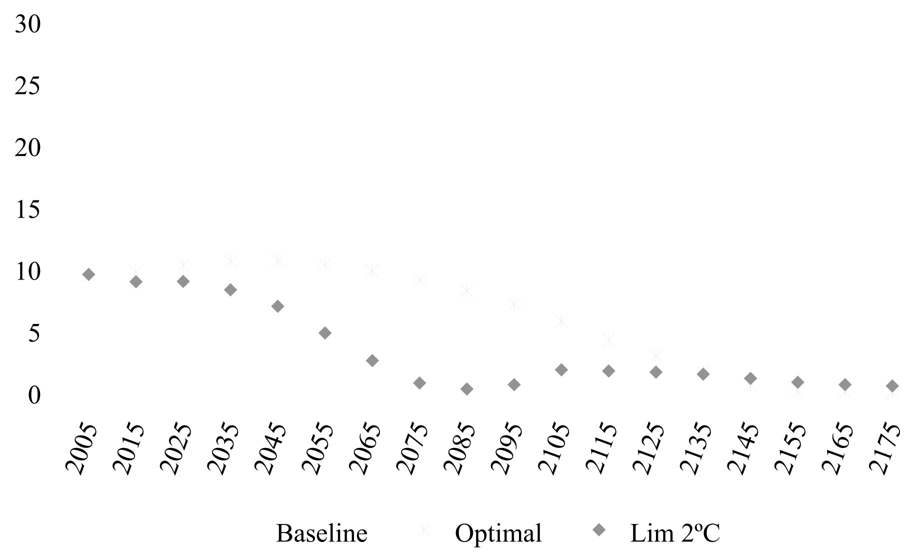
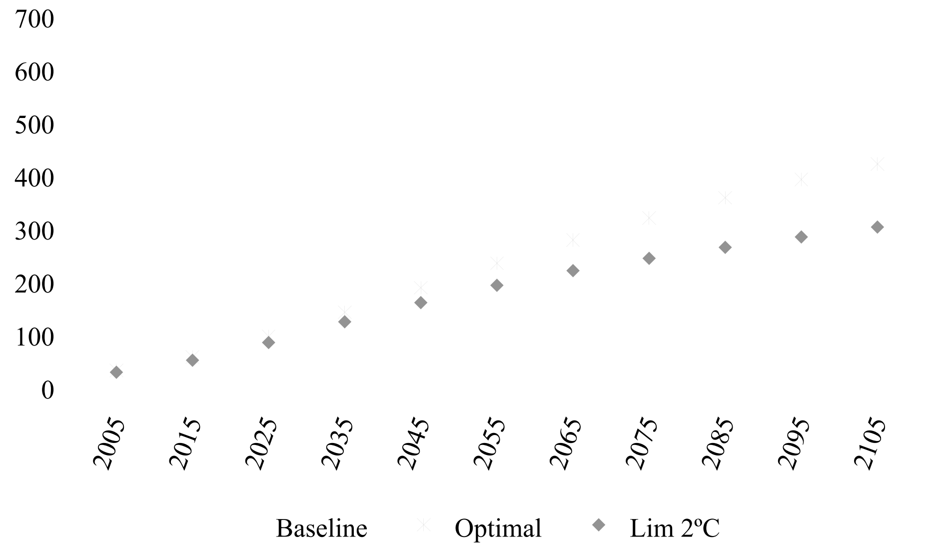


Figure D3: Social cost of carbon for the three scenarios in the original RICE (US dollars/tons of CO_2)



Appendix E

After modifying the RICE model with the new saving rate from table 4 I re-optimized the three policy scenarios; BAU, optimal, and limiting to 2ºC. The optimization is run with the NOMAD non-linear program within Excel solver tool. The optimization is only for the 2015 period even though the 2005 saving rates are also modified. The optimization of the program is set up to run for the 2015 and after. These are the results.

Table E1: Modified and optimized saving rates (fraction of gross output)

		Optimized under NOMAD		
	s^{corr}	BAU s^{corr}	Optimal s^{corr}	Lim s^{corr}
US	0.20	0.21	0.21	0.21
EU	0.19	0.20	0.20	0.20
Japan	0.20	0.18	0.18	0.18
Russia	0.19	0.19	0.19	0.19
Eurasia	0.23	0.23	0.23	0.23
China	0.24	0.23	0.23	0.23
India	0.26	0.27	0.27	0.27
Middle East	0.24	0.25	0.25	0.25
Africa	0.30	0.30	0.30	0.30
Latin America	0.23	0.23	0.24	0.24
OHI	0.20	0.20	0.20	0.20
Other Asian	0.29	0.28	0.28	0.28