Carbon leakage and green growth

Altaghlibi, M.

Carbon Leakage and Green Growth

Moutaz Altaghlibi

Carbon Leakage and Green Growth

Dit proefschrift is tot stand gemaken in het kader van EDE-EM (European Doctorate in Economics - Erasmus Mundus), met als doel het behalen van een gezamenlijk doctoraat. Het proefschrift is voorbereid aan de Faculteit Economie en Bedrijfskunde aan de Universiteit van Amsterdam en aan de Université Paris 1 Panthéon-Sorbonne.
Cette thèse a été écrite dans le cadre de programme doctoral européen EDE-EM (European Doctorate in Economics - Erasmus Mundus). La thèse a été préparée conjointment au Faculteit Economie en Bedrijfskunde, Universiteit van Amsterdam et à l'Université Paris 1 Panthéon-Sorbonne.
This thesis has been written within the framework of the EDE-EM (European Doctorate in Economics - Erasmus Mundus), with the purpose of obtaining a joint doctorate degree. The thesis was prepared in the Faculty of Economics and Business at the University of Amsterdam and in Université Paris 1 Panthéon-Sorbonne.

Carbon Leakage and Green Growth

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor

aan de Universiteit van Amsterdam

op gezag van de Rector Magnificus

prof. dr. ir. K.I.J. Maex

ten overstaan van een door het College voor Promoties ingestelde commissie,

in het openbaar te verdedigen in de Aula der Universiteit

op vrijdag 1 december 2017, te 10:00 uur

door

Moutaz Altaghlibi

geboren te Damascus, Syrië

Promotiecommissie:

Promotor:	Prof. dr. C.H. Hommes	Universiteit van Amsterdam
Promotor:	Prof. dr. A. d'Autume	Université Paris 1 Panthéon-Sorbonne
Copromotor:	dr. F.O.O. Wagener	Universiteit van Amsterdam
Overige leden:	Prof. dr. K. Schubert	Université Paris 1 Panthéon-Sorbonne
	Prof. dr. C.G.H. Diks	Universiteit van Amsterdam
	Prof. dr. C.A.A.M. Withagen	Vrije Universiteit Amsterdam
	Prof. dr. J.A. Smulders	Tilburg University
	Prof. dr. G. Lafforgue	Université Toulouse 1 Capitole

Economie en Bedrijfskunde

Acknowledgements

Reaching the end of a long journey, I am grateful to God for giving me the strength and patience to come this far. This journey started six years ago when I left my beloved country Syria for a Master's in France. Six years passed like a blink of an eye that I hardly believe I am already writing my acknowledgments. As my PhD involved a mobility between France and The Netherlands, I had the chance to meet a lot of people and to make strong friendships which I know will last for years to come.

The two people I would like to thank the most are professor Antoine d'Autume and dr. Florian Wagener. I was very lucky to have these two great supervisors to guide my way through this journey. I am grateful to Antoine for his unconditional support from the first time I met him to supervise my master thesis, and for his guidance through the PhD years and for standing beside me when I needed help of any kind. He taught me how to think analytically and how to model and implement different ideas along with having a critical view for my work. I am grateful and indebted to Florian for dedicating so much time to discuss many issues in so much detail. I am thankful to him for his patience to follow and guide my work on a weekly basis. He has been a great inspiration for me. I learned a lot from his wide knowledge in mathematics, economics and even history. I am thankful to him for being able to lift me up when I was feeling down, in his own way, and for believing in my abilities. I am thankful to him for being very constructive in his remarks and for teaching me how to write properly grammatically.

I am thankful to my promoter professor Cars Hommes for his support and guidance and for providing his aid in many situations.

I am grateful to both Cees Withagen and Katheline Schubert for always offering their help and for keeping their doors open to me to discuss many ideas, and for giving valuable remarks and suggestions during seminars and presentations. Equally, I would like to express my gratitude to the other committee members: Cees Diks, Gilles Lafforgue, and Sjak Smulders for their very relevant and valuable remarks and suggestions during the pre-defence, which helped to improve the final manuscript.

I am very thankful to the family of EDEEM program: Herbert Dawid, Ulrike Haake, and Diana Grieswald-Schulz for being very efficient in organizing such a unique program. I am indebted to the program coordinators in Paris and Amsterdam: Bertrand Wigniolle and Kees Jan van Garderen for their support and help in facilitating many issues. This program was a turning point for me. It enriched my life both socially and scientifically and I am proud to be one of its alumni.

This dissertation is dedicated to my parents, who have been there for me in good and bad times. They taught me how to focus on what really matters in this life. To my dad, the loving and hardworking father, who has high appreciation for science and education. He always made sure to provide us with everything we need when it comes to our education. To my mum, the queen of my heart, who dedicated her life for her family and who taught me the joy of giving and helping others. She has always been with me in mind and soul, even though we have been physically apart during these six years.

I am thankful to my siblings Mahmoud, Ahmad, Ghiath, Nour, and Moumen for being my support system and for taking care of my parents when I was not able to do so myself.

Like any PhD student, this journey was not an easy one, and it would have been even harder if I was not surrounded by amazing people who gave me the support and strength to get over tough times and continue my way. I am grateful to many people who has been part of my life during the years of doing this PhD: to dr. Nuhad Dimashkiyyah for encouraging me to pursue this PhD in the first place. To my uncle Mohamad Swar for always checking on me even when he was going through tough times. To Rasha Alshatti for strengthening my patience and for the colors she added to my life, and of course, for teaching me how to enjoy and appreciate good food. To my friends and brothers Ahmad Jazairi, Amjad Audeh, Ghaleb Kanj, and Omar Khadra for telling me what I need to hear, not what I want to hear, and for being always there for me in good and bad times. To Chaghaf Raman for her encouragement and support in all aspects. To Sami Rahmeh for the long walks and the relieving talks. To my cousin Mouaz Altaghlibi for always providing his assistance. To Anastasia Zhutova for the challenging tennis games and for fruitful discussions. To Lenka Wildnerova for being a true friend that I know I can always count on and for her delicious cakes. To Hyejin Cho for always remembering to celebrate my birthday and for constantly reminding me where I stand. To the Vanuzzu family: Renato, Sara, Martina, and the lovable Daniela Leonardo for always welcoming me in Italy and for making me feel like home. To my dearest friend Lama Daghestani for listening when I needed to talk. To Oussama Lachiri for being a great friend and supporter from the moment I arrived to Europe. To my roommate and dearest friend Sami Midassi for the times we shared together in Venice and Paris and for standing always beside me. To Peter Addo for teaching me to be always faithful, thankful, and optimistic. To Nicoleta Ciurila for being the perfect office mate and for providing useful suggestions when I was stuck in my models. To Sinem Bas for the amazing food and nice postcards. To Gregor Böhl for making sure we have a quite environment to work. To Eglé Jakucionyte for our constant teasing game and for her constructive comments reading my papers. To Ieva Rozentale for our coffee talks. To Can Askan Mavi for being such a good friend and companion.

In the end, acknowledgment is short, and people who helped me during this journey are too many. I thank Camille, Isabelle, Thais, Stefanija, Katrin, Julien, Guillume, Bertrand, Baris, Hamzeh, Amjad, Anna, Anne, Sandra, Salim, Marc, Mikel, Lyela, Reza, Mina, Farah, Fleur, Ghaith, Mona, Firas, Awni, Dana, Oana, Rutger, Swapnil, Marko, Jesper, Jessica, Ron, Damiaan, Federica, Ward, Franc, Christian and Victor for accompanying me on my way in this journey.

I am thankful to Marc, Wilma, José, Jolanda, Evelien, Robert, Karin, Liliana, Loïc and Anna for providing excellent help in many situations.

I am thankful to France and the Netherlands for hosting me and for openning my horizons.

I am thankful to my beloved country Syria for making me what I am. I hope that peace will find its way back to you soon.

Co-author List

- Chapter 2, entitled "*Unconditional aid and green growth*" is a joint work with my supervisor Dr. Florian Wagener. I came up with the idea of this paper in the end of the year 2014. Florian contribution was in the modelling setup — differential games — and the mathematical methodology. The analytical and programming part, along with the writing was approximatly split in half.

- Chapter 3, entitled "*Climate policy and carbon leakage with firm heterogeneity*" is a joint work with my supervisor Prof. Antoine d'Autume. We started working together on this paper in the end of 2013. I came up with the suggestion of using Melitz framework for our idea. Afterward, we worked together step by step on the modeling, programming, and the writing of the paper. The workload was approximatly split in half.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Regions around the world are witnessing unprecedented phenomena in recent years: habitat shifting and alteration (sea-level rise, desertification, .. et cetera), droughts, temperature extremes, storms and flooding, and seasons shifting. As people start perceiving changes in their conventional life patterns, concerns about climate change and global warming have been increasing. Green House Gases (GHG) such as CO2, halo carbons, methane, and nitrous oxide have been identified as main sources of global warming. These gases accumulate in the atmosphere and take decades or centuries to depreciate if no intervention is done, causing the world's temperature to rise. The main source of CO2 emissions is the burning of fossil fuels such as oil, coal, and natural gas. Accordingly, economic activity and industrial production are major contributors to these emissions. Best estimates of the global temperature predict an increase from 1.8 to 4.0 degrees over the coming century. This increase is very high and unprecedented compared to changes that took place in the last $10,000$ years and call for action (Nordhaus (2014)). Reducing CO2 emissions involves costs for economies that reduce their use of fossil fuels or switch towards new environmentally friendly production techniques and energy sources. These costs are however justified on the basis that the economic costs of no intervention would be much higher. If no interventions are made, Nordhaus (2014) argues that climate change will induce economic damages on the order of 2.5 percent of the world's GDP per year by the end of the twenty-first century. The predictions of Stern (2007) for these damages are almost the double, around 5 percent decrease of the world's GDP.

When addressing climate change, a cost-benefit analysis is usually preformed to compare the effectiveness of different policy options over long periods of time. However, such an analysis involves a comparison between present mitigation costs and future uncertain costs and benefits, and therefore the choice of an appropriate discount rate becomes very important. High discount rates induce smaller future damages, and therefore, less emission reductions today; with low discount rates, future damages would look larger, and more emission reductions are needed today. However, there is no consensus among economists on a proper discount rate for climate change. In his Dynamic and Integrated model of Climate and the Economy (DICE), Nordhaus (2014) uses on average a 4 percent discount rate per year over the next century. He argues that such high rate is necessary to reflect the fact that investments needed to reduce future climate damage to some goods should compete with investments in better substitutes, improved technology, and other high-return investments. On the other hand, Stern (2007) uses discount rates lower than 1 percent. He motivates such low rates mainly by inter-generational equity.

Economists use the economic concept "carbon price" to reflect the social cost of carbon, which is the present value of added economic damages now and in the future driven by one additional ton of carbon emissions (Nordhaus (2014)). Carbon price can be implemented through a "carbon tax" or through a "cap and trade" system. The latter option has the advantage to allocate emission reduction towards firms that are most efficient in doing so.

The global nature of transboundary pollution highlights the necessity for international cooperation to maintain the rise in global temperature below certain levels necessary for our survival. Moreover, limiting country-specific emissions help achieving the sustainability of environmental assets in order to provide the services needed for performing economic activities. The main property of public goods, such as transboundary pollution, is that their benefits are not excludable: some parties can rely on the efforts of other parties to enjoy the good without paying for it, the so-called a free riding behavior. There is a general agreement among economists on a global carbon tax as a first best solution to combat climate change. However, the implementation of a carbon tax on a global level is not easy to achieve due to the incentives for some countries to free ride on emission saving efforts by other countries in order to enjoy a better environmental quality with minimum or no costs. Moreover, the asymmetry in the views towards, and the impact of, climate change across countries poses another problem: not all countries are willing to cooperate to achieve the first best.

In the presence of free trade between countries, unilateral environmental action is also not sufficient to slow down global warming as the reduction in emissions by abating countries can be offset by emissions increase of countries with lax or absent environmental regulations, inducing so-called carbon leakage. Carbon leakage may arise from several channels (Monjon and Quirion (2010)). The first channel is called the energy price channel, where the decrease in the dependency on oil, gas and coal by countries with stricter environmental regulations drive the international prices of these materials down, which in turn increase their demand from regions with lax environmental policies, resulting in a rise in emissions of these regions. The second channel is called the competitiveness channel. Through this channel firms in countries with a more stringent climate policy bear an additional cost that their international competitors do not have. These firms can either pass the additional cost to consumers and subsequently lose market shares, or bear this cost themselves which results in reductions in their profits. In the long run, these firms may relocate towards countries with less stringent climate policies. The last carbon leakage channel is the operational channel. This channel rises a short and midterm concern that comes from the relocation of production from existing installations to production facilities outside. Carbon leakage and the distortion in international competitiveness are serious concerns for abating countries. These issues involve both trade and environmental aspects that make them complicated to study, and highlight the necessity to understand the mechanism through which they arise, in order to propose effective solutions to tackle or mitigate them.

Border adjustments (BA) have been advertised to be effective instruments to mitigate the leakage and to limit the distortion in competitiveness among trading partners. Depending on their objectives, these adjustments can be implemented on imports, exports, or both. A border adjustment on imports would impose a cost on GHG-intensive products imported by a country with stricter environmental regulations, while a border adjustment on exports takes a form of a rebate on GHG-intensive products exported from this country. If the implementing country aims to avoid or to limit competition distortion in domestic markets, due to its unilateral climate action, a border adjustment on imports is sufficient. On the other hand, if the implementing country is concerned about its competitiveness in its exporting markets, a border adjustment on exports is sufficient, as this adjustment aims to level the playing field in these markets. Whether the adjustment is imposed on imports, exports, or both, its objective is to give an equal treatment to firms across countries in terms of carbon pricing (Monjon and Quirion (2010)). We can distinguish between two types of border adjustments proposed in the literature: Border Tax Adjustment (BTA) which is simply a tariff imposed on the value of imports mainly motivated by differences in the carbon prices between trading countries, and a Border Carbon Adjustment (BCA) that is a differential taxation on the carbon content of imported goods.

The World Trade Organization (WTO)'s General Agreement on Tariffs and Trade (GATT) aims to eliminate all trade barriers between its members countries. However, under certain circumstances, exceptions for the GATT disciplines might be possible. Paragraph (b) of Article XX states that WTO members can adopt policy measures inconsistent with GATT disciplines if they are necessary to protect human, animal or plant life or health. Since BTAs and BCAs are trade measures, they face the possibility to be contested within the framework of the WTO as they might be used by the implementing country as disguised protectionism. They may be found acceptable, however, if their levels are in line with their objectives.

The successful implementation of a BCA to achieve its goals relies on estimating accurately the embodied carbon content of imports. However, if exporters are unable or unwilling to provide information about the carbon content of their exports, or if the production process is the result of a complex multi-country value chain, the implementing country has to resort to using benchmarks in order to estimate the carbon content of its imports. Cosbey et al. (2013) list several options for such benchmarks. The first option is to use the average emission intensity in the exporting country as a benchmark for the carbon content of imports. However, using such average would induce no incentive for producers with above average GHG intensities to improve their abatement or to prevent them from gaining market shares via their lower cost. The intuition is the same as in Böhringer et al. (2015), who analyze the efficiency of carbon tariffs to tackle the leakage in a Computable General Equilibrium (CGE) model. They find that a carbon tariff on the firm level provides an incentive for firms to reduce their emission intensity, and therefore, these firm-specific tariffs are more efficient in reducing leakage than those implemented on the industry level because the latter target the average firm. The second benchmark is to use the average emission intensity of the implementing country. This benchmark would be less effective to prevent leakage compared to the first one. Assuming that producers in the implementing country are relatively "cleaner", by having less polluting technology in place for example, there would be underestimation of the carbon content of imports, and in turn the less effect a BCA would have on GHG-intensive producers. The third option is to use emission intensity from best available technology as a benchmark. Such option uses the lowest assumed intensity and thus it provides the lowest level of effectiveness of BCA to prevent leakage or to affect incentives of exporter for improvement. The last option is to use emission intensity from worst practice as a benchmark. This would be the most effective option to prevent leakage because it provides incentives to all producers for improvements. However, this option may face issues related to trade law since it overestimates the intensity of many firms covered by the BCA.

In the fight against climate change, green growth of developing and least developed countries become a necessity as well. The OECD defines green growth as: "... Green growth is about fostering economic growth and development while ensuring that the natural assets continue to provide the resources and environmental services on which our well-being relies ..." (OECD (2011)). In this context, transboundary pollution can be considered as a natural asset, and thus keeping global pollution under tolerable levels, such as maintaining the average world temperature below 2 degrees, is necessary to achieve green growth.

Developing and least developed countries face a challenge to achieve green growth, because growing in a sustainable manner imposes additional costs that slow down the growth of these economies. Such cost can be related to a more expensive environmentally friendly investments relative to conventional ones. The global nature of climate change and transboundary pollution makes it in the interest of all countries to direct the growth path of developing countries towards a greener path. Giving international environmentally motivated aid is one way developed countries can help poor countries grow in a sustainable way. One could wonder here: under which circumstances is a donor country motivated to give environmentally motivated unconditional aid to a recipient developing country? What are the effects of such aid on the growth of the recipient country? Moreover, can this kind of aid induce a more sustainable path in the recipient country compared to the no aid scenario?

These questions are addressed in chapter 2, where we argue that the usual practice of giving aid conditionally is not effective, and we therefore study aid that is given unconditionally. Our framework is a differential open-loop Stackelberg game between a developed country (leader) and a developing country (follower). The leader chooses the amount of mitigation aid given to the follower, which the follower either consumes or invests in costly nonpolluting capital or cheap high-emission capital. Results show that the leader gives unconditional mitigation aid only when sufficiently rich or caring sufficiently about the environmental quality, while the follower cares about environmental quality to some extent. If aid is given in steady state, it decreases the steady state level of high-emission capital and capital investments in the recipient country and the global pollution stock, but it has no effect on the levels of nonpolluting capital and nonpolluting investments. Transitional aid accelerates the economic growth of the follower; this effect is however lower than what static growth theory predicts since most of the aid is consumed. Moreover, we find that the increase in growth takes place in the nonpolluting sector.

The Melitz (2003) model with heterogeneous firms provides a rich framework to assess the impact of climate policies on firms' competitiveness, and therefore on their production and emission levels. The model incorporates dynamic forward entry decisions for firms facing sunk market entry costs, and it introduces heterogeneity in firm-specific productivity levels. This mechanism allows to track the reallocation of resources across firms after policy shocks, and to study how firms with different productivity level are affected by the same shock. Such policy effects cannot be explained by representative firm models where the average productivity level is exogenously given (Krugman (1980)).

Several important questions arise here: how heterogeneous firms with different productivity levels are affected by a carbon tax and border adjustments? What is the role of the link between firm-specific emission intensity and its productivity level for the impact of these policies? Moreover, what are the main differences in the effectiveness of BCAs and BTAs to tackle the leakage and restore competitiveness in this context?

In chapter 3, we explore these questions where we extend Melitz (2003) model to investigate the competitiveness driven channel of carbon leakage and to study the effects of unilateral carbon tax, BTAs, and BCAs on leakage, competitiveness, and welfare. We analyze in particular how these policies affect firms across the productivity spectrum. Following Kreickemeier and Richter (2014) we stress the importance of the correlation between productivity and emissions levels. When firm-specific emission intensity is weakly decreasing with its productivity level, we find that a carbon tax in one country reduces average profitability and increases the probability of successful entry of firms, leading paradoxically less productive firms to enter the market after the tax. We conclude that both border adjustments are effective in mitigating carbon leakage and restoring international competitiveness partially. Their efficiency however depends on the objectives of the implementing country. In general, a BCA is a better instrument to mitigate the leakage in emissions than a BTA, as it targets carbon contents of imports directly; a BTA represents a more credible threat to induce cooperation however.

Another way to help developing and least developed countries to grow faster is by providing an easier access for their exports to the markets of developed countries. There are several arguments claiming that opening borders to developing and least developed countries may induce them to invest in cleaner technologies of their own accord. The first argument is that competitiveness pressure following trade openness may induce investments in the latest technology which is, in general, more environmentally friendly. The second argument is that foreign investors and multinational companies may impose common international emission standards regardless of where they invest or operate. The final argument is that countries with high environmental standards for their consumption goods implicitly impose restrictions on other countries to access their market, as exporters have to comply to these standards throughout the production process and even take them into account when making investment decisions. One way to model the latter situation is by making the openness of developed markets selective for those goods produced using a "green" nonpolluting capital while keeping trade restrictions on good produced using "brown" polluting capital. Such selective restriction can be imposed through the implementation of Border Carbon Taxes (BCT), which are in practice the same as BCAs but are not necessarily motivated by differences in the carbon price across countries. Several questions can be explored in such a setting: what is the dynamic impact of different BCT configurations across countries on welfare and growth paths across trading partners? What are the effects of initial asymmetry in development levels on the transitional growth paths across countries? How does carbon leakage evolve dynamically, and how effective is the BCT instrument in tackling it?

In chapter 4, I answer these questions where I theoretically analyze the growth and welfare impacts of BCTs across trading countries. I build a trade model with dynamic investment decisions using a Ramsey growth model. The government in each country can invest either in costly nonpolluting capital or in cheap polluting capital. The model is solved numerically for an open loop Nash equilibrium to study different configurations of BCTs across countries. I find that a unilateral BCT is welfare enhancing for the country that applies it and it is an effective tool to shift the growth of the other country towards greener path, even when countries are not concerned about the environment. Results show that a bilateral BCT becomes welfare enhancing for both countries if governments care sufficiently about the environmental quality of their citizens. Moreover, the asymmetry in initial development levels across countries induces a slower growth for the initially poorer country only if the other country is richer in the polluting capital. Furthermore, the model shows that trade openness should be achieved gradually along the development path of countries.

Chapter 2

Unconditional and Green Growth

2.1 Introduction and literature review

Through the 2015 Paris Climate Agreement all countries acknowledge the negative impact of climate change to each country regardless of its development level. Countries at a low level of development face the challenge to accomplish economic growth while preserving environmental resources at the same time. Growth is usually accompanied with high levels of pollution, especially in the early stages of economic development; as climate change is a global rather than national problem, it is therefore in the interest of all countries to direct the growth path of poor countries towards 'green' rather than 'brown' growth, that is, towards building nonpolluting instead of high-emission industrial capital.

The first best solution to solve the climate change problem proposed in the literature is to implement a unique carbon tax among all countries. In practice most developing and least developed countries have weak and underdeveloped institutions, making the enforcement of an efficient climate policy difficult (Dixit et al. 2012). Another solution is for developed countries to voluntarily donate environmentally motivated aid: this mechanism is envisaged by the Paris Agreement, under which each country specifies a 'Nationally Determined Contribution'. The agreement has been criticised precisely because these contributions are voluntary and there is no enforcing mechanism in place.

While we think that the agreement may possibly run into a common pool problem, we disagree with the statement that an agreement based on voluntary contributions cannot possibly help to mitigate the emissions problem. The present paper shows that a fully developed country can have an environmentally motivated incentive to provide a developing country with mitigation aid, making both countries better off.

The OECD defines green growth as: "... Green growth is about fostering economic growth and development while ensuring that the natural assets continue to provide the resources and environmental services on which our well-being relies ..." (OECD (2011)). In this study, we consider transboundary pollution as a natural asset. Keeping global pollution under tolerable levels, such as maintaining the average world temperature below 2 degrees, is necessary to achieve green growth in the long run. In the short run, investing in non-polluting capital means that these investments are not taking place in the polluting sector, and therefore, lower transitional pollution.

Generally, aid can be donated either unconditionally or conditional on the recipient country investing in certain kinds of nonpolluting capital. It has been argued that aid conditionality may not work optimally because of institutional failures, as highlighted by Adam and O'Connell (1999). Using a noncooperative infinite horizon framework, in this article we therefore investigate situations in which it a donor may give unconditional aid, and we determine the optimal amount of aid to be granted. We also analyse the effects of this aid on the growth of the recipient country and the direction of the resulting growth. We find that in some configurations aid is given, either over a finite period of time or indefinitely. In our model, most of the aid is used to increase consumption, which relieves the recipient country from the need to invest deeply in a high-emissions 'brown' industry, and allows it to build up a non-polluting 'green' industry instead.

Analysis of the steady state shows that unconditional aid decreases the steady state levels of the brown capital in the recipient country, while it has no effect on the steady state level of the green capital: effectively, it substitutes output from the fully developed country, which is assumed to be produced by fully green capital, for the output of brown capital of the developing country. Moreover, giving unconditional aid decreases the stock of global pollution. Our model shows that the fully developed country gives mitigation aid only if the sensitivity of the developing country on pollution damage is neither too low nor too high: if the weight is too low, aid will not change the behaviour of the recipient; if the weight is sufficiently high, the recipient will invest in its green capital stock by its own accord. We conclude that unconditional aid may Pareto-improve the situation of the two countries.

Our study is related to several strands of the literature: aid motivations, aid-growth, conditionality problems, climate finance, green investments, and dynamic games. We find it useful to give brief review of these strands in order to justify the framework we use and to highlight our contribution.

2.1.1 Aid motivations

Donors might be motivated to give aid by several incentives, such like: ethical international equity concerns, historical relations, political and strategic reasons, or poverty alleviation and growth promotion in the recipient country (Alesina and Dollar 2000, Rajan and Subramanian 2008). Sometimes the need to secure a global agreement might include transfers between countries. Other motives include strategic environmental concerns, donors caring about global environmental quality. The 2015 Paris Climate Agreement represents an example of these motives, where environmentally motivated transfers were an essential aspect to secure the agreement.

The literature distinguishes between two kinds of environmentally motivated donations: mitigation transfers and adaptation transfers (Eyckmans et al. 2016). Mitigation transfers aim at reducing emissions in the recipient country; therefore they can be considered as a public good benefiting all countries. Payoffs from these reductions are realised immediately. Adaptation transfers aim at boosting climate resilience in the recipient country. They can be considered as a private good that benefits only the implementing country, and the associated payoffs are realised in the future.[1]

[1] For other kinds of donor's incentives we refer to Lahiri and Raimondos-Moller (2000).

2.1.2 Aid-growth literature

The literature on conditional aid focuses mainly on identifying the effectiveness of foreign aid on the economic growth of recipient countries. Hansen and Tarp (2000) mention two basic theoretical models in this literature: the Harrod and Domar growth model with a stable linear relationship between growth and investment in physical capital, and the two gaps model of Chenery and Strout (1966).

Adam and O'Connell (1999) address the 'institutional failures' problem by examining the effect of foreign aid, focusing on the role and limitations of conditionality when the government may not work in the public interest. Boone (1996) stylises the importance of political regime in the recipient country for aid effectiveness.

No solid evidence about the effect of development aid on growth has been provided in empirical work. Many studies like Boone (1996) have found that there is no effect, or even if it does, it is lower than what the Harrod and Domar model predicts. Mosley (1986) highlights the fact that on the micro level there seems to be a positive effect of aid, while on the macro level it is hard to determine any systematic effects of aid on growth (macro-micro paradox). Hansen and Tarp (2000) propose a classification of the empirical cross-country work on aid effectiveness, concluding that the existing literature supports the proposition that aid improves economic performance, and that there is no macro-micro paradox to resolve. Rajan and Subramanian (2008) find no systematic effect of aid on growth regardless of the estimation approach, the time horizon, or the types or sources of aid. Doucouliagos and Paldam (2008) conducted a meta-analysis of the effectiveness of development aid on growth; they found no significant positive effects. Mekasha and Tarp (2013) re-examined key hypotheses of Doucouliagos and Paldam and concluded that the effect of aid on growth is positive and statistically significant, and that there is no evidence to suggest presence of publication bias. Rajan and Subramanian (2007) suggested that any beneficial effects of additional capital on growth might be offset by adverse spillovers effects; for example, aid in a foreign currency leads to the appreciation in the exchange rate which affect exports adversely — Dutch disease — which might explain the ineffectiveness of aid on economic growth.

2.1.3 Conditionality problems

When one country grants aid to another country for a specific purpose, moral hazard is an issue, as the actions of — typically — the recipient country may deviate from what is initially agreed on after the aid payment has taken place. Conditionality is the typical mechanism to deal with moral hazard situations between recipient and donor countries (Svensson 2000). Using conditionality, donors try to influence policy and to induce reforms in recipient countries; they also try to make sure that the promised aid flow will be used effectively, according to the donor's criteria (Azam and Laffont 2003).

Easterly (2003) mentions that aid agencies and intermediaries usually impose conditions on loans before they are granted, and evaluate their effect after they are completed. However, in practice minimal effort is made to ensure that aid conditions are fulfilled, or that the subsequent evaluation of aid effectiveness is conducted. He emphasises a fundamental problem related to conditionality: both success and failure of the recipient to satisfy conditions are used to justify giving more aid. He notes that one of the reasons to keep giving aid, even after conditions are not met, is when a new government takes over power: this government is usually given a clean record from aid agencies. Another issue, highlighted by Mosley (1996), is that aid agencies and multilateral aid institutions suffer from an agency problem, due to the internal delegation process. He argues that these institutions might be led to give more aid than the minimum amount needed to get a specific outcome, or, equivalently, to ask for less effort for a given level of aid, as large disbursements would enhance the career prospects of the officer in charge. An additional issue, studied by Svensson (2003), is budget pressure: in most donor organisations allocation and disbursement decisions are separated, which results in disbursing committed funds to a fixed, already designed, recipient. This, in turn, results in not shifting resources towards countries where they can be utilised most effectively. Mosley et al. (1995) highlight a problem that is faced by some World Bank country loans officers: when the enforcement of conditionality might be in conflict with some other goals of the bank, one way of proceeding is to disburse an urgent payment in order to avoid a potential default on outstanding loans; this is similar to what happened in the Greek crisis of 2015. Both

Svensson (2003), and Mosley et al. (1995) argue that the current working system is biased towards disbursing aid regardless of the reform effort. Imposing general conditions on every recipient country irrespective of its specific economic and social characteristics tends moreover not to work. Finally, intermediate aid organisations sometimes push aid, or give loans, to countries where these resources are not effectively used, in order not to have an unallocated balance which could be used as a reason to lower future budgets from donor countries (Easterly 2003). In this way 'spending the budget' becomes a goal by itself (Edgren 1996, Paldam 1997).

As a result of these investigations, the credibility of aid conditionality can be questioned, and we conclude that conditionality to some extent fails to achieve its purpose in practice. This may serve as an explanation of the empirical evidence of the ineffectiveness of aid on economic growth on the macro level.

2.1.4 Climate finance literature

Under the terms of the 2009 Copenhagen Accord, which were later re-emphasised by the 2015 Paris Climate Agreement, developed countries engaged in providing climate finance up to $100 billion per year, starting from 2020 onwards, to help developing countries reduce their emissions and adapt to the consequences of climate change.

A literature on climate finance that relates to our study has been emerging. Eyckmans et al. (2016), in a two period Stackelberg game, use a framework in which a donor cares about the well-being of the recipient, while using a binding global emissions constraint to address the climate change externality. They study the interaction between climate finance and development aid by comparing three types of transfers from a donating developed country towards a receiving developing country: development, mitigation, and adaptation aid. They found that a large part of the intended effect of transfers dissipates as the follower reallocates its own resources to achieve the balance it prefers. Pittel and Rübbelke (2013) develop a two regions model to study the difference between transfers that subsidise mitigation efforts and financial adaptation transfers that are conditional on mitigation efforts. They conclude that the outcome depends strongly on the productivity of mitigation and adaptation technologies. Heuson et al. (2012) introduce a static two region model of mitigation and adaptation with different types of transfers from the developed region, and conclude that there are many instruments of climate funding that could yield Pareto improvements for donor and recipient countries. Therefore, transfers might induce an implicit cooperation between regions.[2]

2.1.5 Green investments literature

According to the 14 July 2009 Report by the United Nations Environment Programme (UNEP), green investments are not a luxury anymore; instead, they are a social and legal responsibility. The report argues that if investment consultants and other parties do not include environmental, social and governance (ESG) aspects into their services, they face "a very real risk that they will be sued for negligence". Eyraud et al. (2011) provide a definition of green investments from a macroeconomic perspective: "The investment necessary to reduce greenhouse gas and air pollutant emissions, without significantly reducing the production and consumption of non-energy goods". Rozenberg et al. (2014) compare two policies for the optimal switch towards green capital: having a climate tax or subsidising green investments in one economy. They found that the climate tax is optimal, but if the environmental conditions are not at a critical level, subsidising green capital is a good long term policy. Claude et al. (2012) use a dynamic model with two jurisdictions to discover the properties of price-based policies to control environmental externalities, introducing temporary heterogeneity between jurisdictions in the initial stocks of infrastructure which diminish over time. They conclude that the optimal policy scheme may require to simultaneously tax one jurisdiction and subsidise the other for a period of time. The policy chosen in each jurisdiction depends on the degree to which stocks are complements or substitutes.

[2] Bowen et al. (2012) discuss development, climate vulnerability, and adaptation.

2.1.6 Dynamic games

There is a body of literature that uses dynamic games to study international transfers for different environmental motivations. Our study contributes to this literature. Van Soest and Lensink (2000) studied a differential game where aid contracts are introduced to preserve a forest stock in the recipient country. They conclude that conditioning aid only on the forest stock increases conservation in the long run but only slightly on the short run. A more active short run policy would be to condition transfers negatively on current deforestation. Martín-Herrán et al. (2006) use a Stackelberg differential game framework with financial transfers to help developing countries to preserve their rainforests. They found that, under certain conditions, both the long and the short run size of the rainforest can be increased by adopting a feedback information type for both players. Fredj et al. (2004) study a differential Stackelberg game between two countries in order to design an aid program that aims at conserving rainforests located in the recipient country. They consider a transfer function which takes into account both the forest size and the deforestation rate; they conclude that making the transfer function dependent on the deforestation rate in addition to its dependency on the forest stock would induce slower deforestation. Cabo (2002) used a differential infinite horizon game to analyse the feasibility and optimality of sustainable economic growth in a North–South trade model. He studies the effect of this growth upon the dynamics of the natural resources stocks, where capital transfers of both physical and human capital from North to South are possible. He distinguishes between two scenarios depending on the effect of capital transfers upon South. In both cases, South is found to be able to produce the same amount of an intermediate good and to reduce the risk of resource depletion. Finally, Tornell and Velasco (1992) studied a differential game between parties who have access to a common technology. They found that under some configurations introducing a less productive private technology ameliorates the tragedy of the commons and improves welfare, as the inferior technology creates a lower bound on the rate of return of the common access asset, and therefore, a ceiling on the appropriation rate. Using this mechanism, the authors explained the problem of capital flight from poor towards rich countries as a consequence of the poorly defined property rights in the developing countries, where investing abroad represents a recourse to the tragedy of commons.

2.1.7 Our contribution

In our model, a possible donor is a developed sovereign country for which greenhouse gas emissions by another sovereign country constitute an externality, and which gives aid in order to induce the developing country to reduce these emissions. We therefore investigate endogenously given aid in a noncooperative differential game framework where the donor, North, is a Stackelberg leader and the recipient, South, a Stackelberg follower. We have argued that the practical effectiveness of conditionality is questionable. The leader, motivated by environmental considerations, therefore announces an aid programme, where aid is given unconditionally and independently of the actual actions of the recipient follower. This gives the recipient country the choice to use the aid in a way that achieves its best interests. If under these conditions, there is a positive aid flow towards the follower, it will be a Pareto-improvement. At the same time, it provides a lower bound on the effect aid can have on the growth of the recipient (Azam and Laffont 2003).

The failure to achieve a stable global agreement on climate change is the starting point of the paper. Also, it is assumed that each country knows the extent to which its decisions impose costs on the other country. These two assumptions justify the use of a Stackelberg setting. In addition, as aid is a gift, moving sequentially is natural, that is, aid is a unilateral action that can be followed by other unilateral actions.

We consider open-loop Stackelberg equilibria. In order to achieve time consistency, we extend the game by introducing a binary state variable, *trust*, which starts at the value 1 when the leader is credible on the aid profile announced at the beginning of the game. This parameter switches to 0 whenever the leader deviates from the aid schedule announced. When *trust* has the value 0 , the follower assumes that no aid will be forthcoming any more and optimizes its investment strategy under this assumption. This is analogous to the trigger strategy mechanisms in repeated games. Accordingly, the leader has an incentive to stick to its announced aid profile as long as, for every

$t > 0$, its discounted welfare under commitment (*trust*=1) exceeds that under defaulting (*trust*=0). As long as this is the case, the announced aid profile is time consistent. We show in section (2.5.3) that a subset of open-loop Stackelberg equilibria is time consistent under this extension.

Among the papers mentioned above, Eyckmans et al. (2016) is closest to ours. We depart from existing literature by analysing unconditional aid in a theoretical dynamic model, using a noncooperative infinite horizon framework. Unlike Eyckmans et al. (2016), we employ a Ramsey framework to model South's growth, with endogenous capital investment processes for green and brown capital respectively. Damage flows from global pollution, affecting the welfare of both countries, address the pollution externality. We treat unconditional aid as a component of national income of the recipient country, rather than assume a direct relationship between aid and investments as in Rosenstein-Rodan (1961) and in the Harrod and Domar model. From the donor's perspective, in our model unconditional aid is a mitigation transfer. To the recipient, aid acts as development aid, influencing consumption and total investment, as well as mitigation aid, by influencing the relative investments in green and brown capital. We follow Eyckmans et al. (2016) by not considering global welfare: each country takes only its own welfare into account when taking its decisions. Our model also links the green investments literature and climate finance literature; to our knowledge only Claude et al. (2012) study a similar link.

The next section presents the model and the dynamic optimisation problem of each player. Then we give theoretical results about the steady state of the resulting Stackelberg equilibrium dynamics. To analyse the transient dynamics, numerical techniques are necessary. We discuss their methodology before turning to the results and the conclusions.

2.2 The model

2.2.1 The aid game

In our framework, all countries care about the consumption and the quality of the environment of their citizens, which translates into an intertemporal tradeoff between short term consumption benefits and long term environmental costs. A country can grow by either investing in costly, non-polluting, 'green' capital or cheap, high-emission, 'brown' capital. We assume that both kinds of capital are equally productive. Investment in brown capital contributes through emissions to degradation of the global environmental quality, which is a public good affecting both developed and developing countries alike. Developing countries are assumed to have credit constraints, as low credebility to pay back outstanding debts and the high possibility of defaulting make it hard for these countries to have access to financial markets. Developed countries trying to avoid future environmental degradation may be motivated to give aid to developing countries, helping these countries to achieve economic growth with minimal effect on the environment. Since the adverse effects of climate change are felt over a long time, it is natural to study this problem in an infinite horizon framework.

We study a Stackelberg differential game between two countries: The leader, which will be called 'North', is a developed country; the follower, 'South', a developing country. North's decision variable is the amount of aid that it gives to South; this lessens North's consumption budget. North is assumed to be unable to observe how South uses the aid it receives; aid therefore automatically becomes unconditional. South's decision is how to allocate its output and the aid it receives from North between consuming, investing in brown capital, or investing in green capital.

We solve for open-loop Stackelberg equilibria: this means that North's aid schedule is fixed at the initial time, and that the amount of aid given depends merely on the date, but not on any other variable. A closed-loop approach, where the amount of aid would depend on the current state variables, would involve similar problems as discussed above in the context of conditionality: South would need strong institutions to measure and report the capital stocks correctly, and in practice the lowering of aid as a consequence of an adverse stock evolution might easily give rise to political tensions. The open-loop approach avoids this, as the aid schedule is fixed and known beforehand. Of course, for an announced aid schedule to be credible, it needs to be time consistent. This issue will be addressed in Section 2.5.3.

2.2.2 South's decision problem

We begin by describing South's decision problem, given North's aid schedule a_t.

Consumption

South's citizens are assumed to be identical and to be represented by an infinitely lived representative agent, who gains utility $u(c_t)$ from consuming c_t of a generic good and dis-utility $D(E_t)$ from environmental degradation represented by a damage function of a global pollution stock E_t. The discounted intertemporal welfare of the South's representative consumer can be written as:

$$W = \int_0^\infty e^{-\rho t}(u(c_t) - D(E_t))dt. \tag{2.1}$$

Here ρ denotes the time preference rate. The utility function u and the damage function D are assumed to be, respectively, increasing and concave and increasing and convex, i.e. $u' \geq 0$ and $u'' \leq 0$; $D' \geq 0$ and $D'' \geq 0$. Furthermore, we assume that the Inada conditions hold, that is, $u'(c) \to \infty$ as $c \downarrow 0$ and $u'(c) \to 0$ as $c \to \infty$.

Production

Output comes from production processes using either brown capital $K_{b,t}$ or green capital $K_{g,t}$ as factors of production. For our purpose, we focus on physical capital as the only variable input for production and leave the inclusion of labor as a second variable input for future research. We have two production functions F_b and F_g, for brown and green capital respectively. South's total output is:

$$Y_t = F_b(K_{b,t}) + F_g(K_{g,t})$$

The functions F_b and F_g are assumed to be increasing and concave: $F_b' \geq 0$, $F_g' \geq 0$, and $F_g'' \leq 0$, $F_b'' \leq 0$. Capital stocks are assumed to be a model of energy plants. Furthermore, energy production is assumed to be proportional to the available capital stock in every period. Since energy in general is equally productive regardless of its source, we consider a separable production function for South in brown and green capital, where both kinds of capital are equally productive. Accordingly, this function yields two separate specific consumption goods that are perfect substitutes to the final consumer. This separability reduces the degree of non-linearity in the model and makes it feasible to provide an analytical characterization of the steady state.

South's invests, per unit time, $I_{b,t}$ in brown capital and $I_{g,t}$ in green capital. The investment costs $C_i(I_{i,t})$ are assumed to be increasing and convex: $C_i' \geq 0$ and $C_i'' \geq 0$ for $i \in \{b, g\}$. Both types of investment are assumed to be irreversible: once an investment has been made, the resulting capital cannot be transformed to a different type of capital.

Along with its output from the production process, South may receive aid from North. At each point of time South allocates its output and the aid it receives between consuming, investing in green capital and investing in brown capital, taking into account its budget constraint

$$F_b(K_{b,t}) + F_g(K_{g,t}) + a_t \geq c_t + C_b(I_{b,t}) + C_g(I_{g,t}). \tag{2.2}$$

Investment costs are assumed to be quadratic:

$$C_i(I_{i,t}) = \frac{\beta_i}{2} I_{i,t}^2, \qquad i \in \{b, g\},$$

where $\beta_i > 0$ is the rate of increase of the marginal investment costs. We assume that brown investments are cheaper than green investments, i.e. $\beta_b \leq \beta_g$. The price of the generic good is normalised to 1.

Capital dynamics are assumed to take the same form for both kinds of capital

$$\dot{K}_{i,t} = I_{i,t} - \delta K_{i,t}, \quad K_{i,0} \text{ given}, \qquad i \in \{b, g\}. \tag{2.3}$$

Each type of capital increases with new investments and depreciates with a uniform capital depreciation rate δ.

Production processes involving brown capital emit greenhouse gases, which accumulate in the atmosphere. Pollution is therefore transboundary, affecting consumers in both countries. The dynamics of the pollution stock is given as:

$$\dot{E}_t = \alpha K_{b,t} - \vartheta E_t, \qquad E_0 \text{ given.} \tag{2.4}$$

That is, pollution emissions are proportional to the amount of installed brown capital, with an emission intensity α; without emissions, the pollution stock decreases at the natural decay (absorption) rate ϑ.

South's policy

South maximizes its intertemporal welfare, taking into account capital and pollution dynamics. That is, South maximizes the objective functional (2.1) subject to the budget constraint (2.2), the dynamic constraints (2.3) and (2.4).

The current value Hamiltonian of the intertemporal maximisation problem is given in Appendix 2.7.1, together with the optimal policies. The necessary conditions for the co-states μ_t, $\nu_{b,t}$, and ν_{g_t} of, respectively, the pollution stock, South's brown capital, and South's green capital read as

$$\dot{\mu}_t = D'(E_t) + (\rho + \vartheta)\mu_t, \tag{2.5}$$

$$\dot{\nu}_{b,t} = -u'(c_t)F_b'(K_{b,t}) + (\rho + \delta)\nu_{b,t} - \alpha\mu_t, \tag{2.6}$$

$$\dot{\nu}_{g,t} = -u'(c_t)F_g'(K_{g,t}) + (\rho + \delta)\nu_{g,t}. \tag{2.7}$$

They are complemented by initial conditions for the states E_t, $K_{b,t}$ and $K_{g,t}$ and, since there are no terminal conditions on the states, by the transversality conditions

$$\lim_{t\to\infty} e^{-\rho t}E_t = 0, \quad \lim_{t\to\infty} e^{-\rho t}K_{i,t} = 0, \qquad i \in \{b, g\}, \tag{2.8}$$

which hold whenever the state variables are uniformly bounded away from 0.

2.2.3 North

Consumption

North's citizens are, analogously to South's, represented by an infinitely lived agent who gains utility from consumption and dis-utility from environmental degradation. We use a superscript n to denote North's variables. The discounted intertemporal welfare of North's representative agent is

$$W^n = \int_0^\infty e^{-\rho t}(u^n(c_t^n) - D^n(E_t))dt, \tag{2.9}$$

where u^n and D^n are respectively assumed to be increasing and concave and increasing and convex: that is, $(u^n)' \geq 0$, $(u^n)'' \leq 0$; $(D^n)' \geq 0$, $(D^n)'' \geq 0$. Moreover, we assume that the Inada conditions hold, that is, $(u^n)'(c) \to \infty$ as $c \downarrow 0$ and $(u^n)'(c) \to 0$ as $c \to \infty$.

North can only affect the pollution stock through influencing the investment decision of South by giving it aid. As motivated in the introduction, we assume that North is unable to observe South's state variables, and it can therefore condition aid only on time.

Production

We assume further that North is a fully developed country having only green capital, which is moreover at the steady state level. This level is at least equal to the sum of the steady state levels of South's brown and green capitals. North's production processes use only green capital K_g^n; therefore, North's total output is:

$$Y_t^n = F_g^n(K_{g,t}^n);$$

here F_g^n denotes North's production function, which is assumed to be increasing and concave, that is $(F_g^n)' \geq 0$, $(F_g^n)'' \leq 0$. North has to decide at each point of time how to allocate its output between consumption and unconditional aid to South. Its budget constraint takes the form:

$$Y_t^n = c_t^n + a_t. \tag{2.10}$$

Moreover, North can choose whether or not to give aid to South, but it cannot force South to pay aid back; hence there is a positivity constraint on aid:

$$a_t \geq 0. \tag{2.11}$$

As Stackelberg leader, North is assumed to be able to credibly commit to the aid profile it announces.

North's dynamic optimisation problem

Since we have a Stackelberg open-loop game, North will choose the amount of aid that maximizes the intertemporal welfare of its representative consumer, subject to its budget constraint (2.10), the aid positivity constraint (2.11), as well as South's first order conditions (2.2), (2.3), (2.4), (2.5)–(2.7), along with the transversality conditions from South's problem (2.8).

The Lagrangian associated to the maximisation of North's social welfare can be found in Appendix B.1. We indicate by $\kappa_{b,t}$ and $\kappa_{g,t}$ North's shadow prices of South's brown and green capital, while ψ_t represents North's shadow cost of global pollution. The Lagrange multiplier attributed to the aid positivity constraint is denoted ξ_t; North's shadow price of South's marginal valuation of the pollution stock is denoted τ_t, and North's shadow prices of South's marginal valuation of brown and green capital are denoted $\lambda_{b,t}$ and $\lambda_{g,t}$ respectively.

The maximum principle yields equations (2.2)–(2.7), (2.10) and (2.11), as well as:

$$\dot{\kappa}_{b,t} = (\rho+\delta)\kappa_{b,t} - F_b'(K_{b,t})\left((u^n)'(c_t^n) - \xi_t\right) + \lambda_{b,t}u'(c_t)F_b''(K_{b,t}) - \alpha\psi_t, \tag{2.12}$$

$$\dot{\kappa}_{g,t} = (\rho+\delta)\kappa_{g,t} - F_g'(K_{g,t})\left((u^n)'(c_t^n) - \xi_t\right) + \lambda_{g,t}u'(c_t)F_g''(K_{g,t}), \tag{2.13}$$

$$\dot{\psi}_t = (\rho+\vartheta)\psi_t + (D^n)'(E_t) - \tau_t D''(E_t), \tag{2.14}$$

$$\dot{\lambda}_{b,t} = -\frac{\kappa_{b,t}}{\beta_b u'(c_t)} - \lambda_{b,t}\delta, \tag{2.15}$$

$$\dot{\lambda}_{g,t} = -\frac{\kappa_{g,t}}{\beta_g u'(c_t)} - \lambda_{g,t}\delta, \tag{2.16}$$

$$\dot{\tau}_t = -\tau_t\vartheta + \alpha\lambda_{b,t}, \tag{2.17}$$

$$0 = \xi_t a_t, \tag{2.18}$$

$$\begin{aligned}\xi_t = (u^n)'(c_t^n) &+ \frac{u''(c_t)}{u'(c_t)^2}\left(\frac{\kappa_{b,t}\nu_{b,t}}{\beta_b} + \frac{\kappa_{g,t}\nu_{g,t}}{\beta_g}\right) \\ &+ u''(c_t)\left(\lambda_{b,t}F_b'(K_{b,t}) + \lambda_{g,t}F_g'(K_{g,t})\right).\end{aligned} \tag{2.19}$$

Equations (2.12)–(2.17) are differential equations for North's co-states. Equation (2.18) is the complementary slackness condition, and (2.19) the expression for the Lagrange multiplier ξ_t, which also has to satisfy the positivity condition $\xi_t \geq 0$ for all $t \geq 0$.

These conditions have to be complemented by initial and terminal conditions. We already have the initial conditions for the states E_t, $K_{b,t}$ and $K_{g,t}$ and the terminal conditions (2.8) on the co-states of South's problem. Moreover, both South's states and South's co-states are states of North's problem. Since there is no terminal condition on South's states and no initial condition on South's co-states, there will be a terminal transversality condition on North's co-states of South's states, that is, on $\kappa_{i,t}$ and ψ_t, and an initial transversality condition on North's co-states of South's co-states, that is, on $\lambda_{i,t}$ and τ_t. These conditions read as

$$\lim_{t\to\infty} e^{-\rho t}\psi_t = 0, \quad \lim_{t\to\infty} e^{-\rho t}\kappa_{b,t} = 0, \quad \lim_{t\to\infty} e^{-\rho t}\kappa_{g,t} = 0, \tag{2.20}$$

again assuming that the corresponding states are uniformly bounded away from 0, and

$$\lambda_{b,0} = 0, \quad \lambda_{g,0} = 0, \quad \tau_0 = 0. \tag{2.21}$$

2.3 Steady state analysis

In this section we present a comparative statics analysis for the steady state levels of South's capital and consumption, and we give sufficient conditions for a positive aid flow to occur at steady state.

To analyse the steady state levels of South's capital and consumption, it is sufficient to study a rest point of the evolution equations (2.3) – (2.7) of South's states and shadow prices. The solution procedure for the steady state can be found in Appendix 2.7.1. One of the results is the relation

$$F_g'(K_g) = (\rho + \delta)\delta\beta_g K_g, \tag{2.22}$$

which determines the steady state levels of South's green capital. It states that the ratio of the steady state marginal productivity of green capital $F_g'(K_g)$ over the steady state marginal cost of green investments $\beta_g K_g$ equals the product $(\rho + \delta)\delta$, which increases with the capital depreciation rate δ and the time discount rate ρ. In particular the steady state level of green capital, and consequently that of green investments, is not affected by the aid received from North.

It follows directly from (2.4) that the steady state level of emissions E is a function of the steady state level of brown capital

$$E = \frac{\alpha}{\vartheta} K_b. \tag{2.23}$$

The steady state levels of consumption and brown capital are determined jointly by the two equations

$$F_b'(K_b) = (\rho + \delta)\delta\beta_b K_b + \frac{\alpha}{\rho + \vartheta}\frac{D'(\frac{\alpha}{\vartheta}K_b)}{u'(c)} \tag{2.24}$$

and

$$c = F_b(K_b) + F_g(K_g) + a - \frac{\beta_b \delta^2}{2} K_b^2 - \frac{\beta_g \delta^2}{2} K_g^2. \tag{2.25}$$

We note first that if the pollution emission intensity $\alpha = 0$, or if there is no marginal damage from global pollution, that is, if $D'(E) = 0$ for all E, there is no distinction between green and brown capital, and equation (2.24) has same form as equation (2.22). Since we have assumed that $\beta_g \geq \beta_b$ and that brown and green capital have the same productivity, we conclude that the steady state level of brown capital with no pollution is at least equal to the steady state level of green capital. This is natural, as green investments are more expensive than brown ones.

Equations (2.24) and (2.25) readily furnish information about the effects of parameter changes on the steady state levels c and K_b of consumption and brown capital. We begin with the effect of an increase in the aid flow a.

Theorem 1 *If the aid flow a rises, the steady state level K_b of brown capital falls, the steady state consumption level c rises, while the steady state level K_g of green capital is unaffected.*

Consequently, the steady state levels I_b of brown investment and E of the pollution stock fall as well, whereas green investments I_g are also unaffected.

Finally, South's total welfare rises.

The next result investigates the effects of changing the investment cost parameters β_g and β_b and the capital depreciation rate δ.

Theorem 2 *If the cost of green investments β_g rises, the consumption level c and the level of green capital K_g fall, while the level K_b of brown capital rises.*

If the costs of brown investments β_b rises, the consumption level falls and the green capital level K_g is unaffected.

If the capital depreciation rate δ rises, the green capital level and the consumption level fall.

Finally, for small positive values of the emission intensity α, the brown capital level falls if either the cost of brown investments or the capital depreciation rate rise.

Finally, we have a result on parameters affecting the pollution stock.

Theorem 3 *Assume that $D(E) = (\eta/2)E^2$. If either the natural decay rate ϑ falls, the emission intensity α rises, or the weight η of environmental quality rises, then both the consumption level c and the brown capital level K_b fall. The green capital level K_g is unaffected.*

Moreover, for small positive values of the emission intensity α, the pollution level rises with increasing values of α, while it falls with increasing values of the natural decay rate ϑ.

These theorems are proved in Appendix 2.7.1, except the last statement of theorem 3, which we shall discuss now.

The effect on the global steady state pollution depends on the elasticity of brown capital at steady state with respect to emission intensity, for

$$\frac{\partial E}{\partial \alpha} = \frac{K_b}{\vartheta}\left(\frac{\alpha}{K_b}\frac{\partial K_b}{\partial \alpha} + 1\right).$$

The elasticity $\epsilon_\alpha = \frac{\alpha}{K_b}\frac{\partial K_b}{\partial \alpha}$ is negative, therefore the effect of α on E is positive if and only if $\epsilon_\alpha > -1$. Clearly this elasticity is 0 if $\alpha = 0$, yielding that E rises with α for small values of α.

The dependence of the steady state level of pollution on the natural decay rate can be written as

$$\frac{\partial E}{\partial \vartheta} = \frac{\alpha}{\vartheta^2}K_b\left(\frac{\vartheta}{K_b}\frac{\partial K_b}{\partial \vartheta} - 1\right);$$

the effect of ϑ on E is positive if and only if the elasticity $\epsilon_\vartheta = \frac{\vartheta}{K_b}\frac{\partial K_b}{\partial \vartheta} > 1$. If the emission intensity α is zero, industrial production does not affect the pollution level. Conversely the natural decay rate cannot affect the steady state level of brown capital: this results in the fact that $\partial K_b/\partial \vartheta = 0$, and hence that $\epsilon_\vartheta = 0$ if $\alpha = 0$. By continuity, for small but positive values of α, we have that ϵ_ϑ is close to zero, which results in the steady state pollution level decreasing as ϑ increases.

The next result gives a sufficient condition for a positive aid flow to occur in steady state

Theorem 4 *Assume that* $D^n(E) = (\eta^n/2)E^2$*. If either North's output* Y^n *or North's weight* η^n *of environmental damage are sufficiently large, then there is a positive aid flow from North to South in steady state.*

This theorem is a direct consequence of Theorem 5, proved in appendix (2.7.2).

To conclude, aid decreases the steady state level brown capital, brown investments, and the stock of global pollution, it increases South's consumption and total welfare, and it has no effect on the steady state level of green capital or green investments. Moreover, in certain circumstances it is in North's interest to provide South with mitigation aid, which effectively amounts to North buying off the need to build brown capital, and by that, buying off the resulting pollution.

2.4 Methodology

Next to the steady state, we are also interested in the growth path towards it, and its dependence on the parameter change, its 'comparative dynamics'. If there are to be any aid transfers, we expect the bulk to be effected during the growth phase of South, which is, by definition, not in steady state. Solving the model analytically is however beyond our capabilities; we have therefore resorted to numerical simulations.

In this section we present the numerical methods which we used to determine the Stackelberg open loop equilibria of the dynamic game, and we motivate our calibration of the model parameters.

2.4.1 Numerical Solution

Section 2.2.2 formulated the necessary conditions of South's decision problem in the form of a boundary value problem over an infinite time interval, involving six nonlinear differential equations, together with initial and terminal conditions; North's boundary value problem features twelve nonlinear differential equations. We adapt a numerical approach taken from Grass (2012).

In general, boundary value problems deriving from infinite horizon optimisation problems with m state variables are characterised by the following elements: a $2m$-dimensional system of differential equations, determining solution paths $z_t = (x_t, y_t) \in \mathbb{R}^m \times \mathbb{R}^m$, where x_t is the state evolution and y_t the co-state evolution; a specification of the initial states x_0, which yields m initial conditions; a specification of m asymptotic transversality conditions, which are typically satisfied by a solution of the system that tends to steady state values $\hat{z} = (\hat{x}, \hat{y})$.

In order to solve for such solution paths numerically, we approximate the asymptotic conditions by conditions that hold for a large, but finite, time T. Following Grass (2012), we impose the following 'asymptotic transversality condition'

$$M^T \begin{pmatrix} x_T - \hat{x} \\ y_T - \hat{y} \end{pmatrix} = 0; \tag{2.26}$$

here the columns of the matrix M form a basis spanning the orthogonal complement to the stable eigenspace at steady state, M^T denoting the transpose of M. The geometrical content of (2.26) is that the vector $z_T = (x_T, y_T)$ is contained in the stable eigenspace of the steady state $\hat{z}$, and therefore approximately in the stable manifold of the steady state. Note that (2.26) consists of m scalar conditions on the $2m$-dimensional vector z_T. The $2m$ differential equations, together with m initial state conditions and m asymptotic transversality condition then form a boundary value problem over the finite time interval $[0,T]$. As $T \to \infty$, the solution curves of the approximate problem tend uniformly to solution curves of the original problem.

Specifically, South's boundary value problem consists of equations (2.3)–(2.7), together with initial conditions at $t = 0$ for the three states $K_{b,t}$, $K_{g,t}$, and E_t, and the transversality conditions (2.8). The initial conditions are South's initial capital stocks $K_{b,0}$ and $K_{g,0}$, and the initial pollution stock E_0.

North's problem involves twelve differential equations: the state equations (2.3)–(2.7) and the co-state equations (2.12)–(2.17), as well as twelve boundary conditions. The first six of these are equal to South's boundary conditions, the initial conditions for the states and the transversality conditions (2.8) for the co-states. In addition, boundary conditions on North's co-states are furnished by the transversality conditions (2.20) and the initial conditions (2.21).

2.4.2 Functional forms

We assume that both South's and North's representative agent have a constant intertemporal elasticity of substitution utility

$$u(c) = u^n(c) = \frac{c^{1-\sigma}}{1-\sigma}.$$

In computations, we take $\sigma = 0.5$. We take Cobb–Douglas production functions with the factor labour taken constant; we assume moreover that green and brown technology are equally productive, yielding

$$F_b(K) = F_g(K) = \frac{\Omega}{1-\gamma} K^{1-\gamma} \qquad \text{for all } K.$$

In computations we set $\Omega = 0.6$ and $\gamma = 0.75$.

The damage functions are assumed to be quadratic:

$$D(E) = \frac{\eta}{2} E^2, \qquad D^n(E) = \frac{\eta^n}{2} E^2, \qquad \text{for all } E.$$

The parameters η and η^n govern the weight of the environmental quality in the welfare of each country.

2.4.3 Calibration

To calibrate the parameters in our model, we take a wind energy plant as a model for green industrial capital, and a traditional coal or gas energy plant as a model for brown capital.

The relative cost β_g/β_b of green investments with respect to brown is calibrated as the ratio between investment costs of a wind plant to that of a coal/gas plant. Salvadore and Keppler (2010) estimate that the specific overnight construction costs of most coal-fired plants range between 1000 and 1500 USD/kWe, while those of a gas-fired plants range between 400 and 800 USD/kWe. In contrast, for nuclear and wind generating technologies overnight construction costs range between 1000 and 2000 USD/kWe. Accordingly, we calibrate β_g/β_b to range between 1 and 2.5.

For the emission intensity α of brown capital we use the average emission intensity of a coal energy plant, which is estimated to be 0.888 tonnes CO_2/MWh, while for a gas plant those estimates average at 0.499 tonnes CO_2/MWh, as reported by WNA (2011). Salvadore and Keppler (2010) reported an investment cost between 9–18 USD/MWh at a 5% discount rate, while at a 10% discount rate the investment costs range between 17.5 and 30 USD/MWh. Therefore, at a 5% discount rate we get an emission intensity of 5% – 10% per unit of capital invested in a coal plant, while at a 10% discount rate, the emission intensity ranges from 3% to 6%. For a gas plant, investment costs range between 5.5 – 9 USD/MWh at 5% discount rate, and therefore, the emission intensity ranges between 5% – 9% of each unit of capital invested in a gas plant.

Damage from global pollution stock is likely to be a persistent problem for a long time, and small values, between 1.5% (Stern) and 4.5% (Nordhaus), are usually used for the time discount rate ρ. However, in order to be consistent with the calibration of other parameters we use ρ between 5% - 10%. This does not greatly affect the results obtained.

The investment cost parameter β_b represents the rate of increase of the marginal investment cost in brown capital per unit of investment. We use values of β_b ranging between 2% and 9%.

Depending on the estimated life time for a wind energy plant (around 40 years), we use the same depreciation rate for both types of capital, resulting in a range for δ between 2.5%–5%.

Higher values of the parameters η and η^n imply that governments care more about the environmental quality of their consumers when taking decisions. We choose different values of these parameters to test different assumptions about the weight of environmental quality between North and South.

Annual carbon emissions from burning fossil fuels in the United States are about 1.6 gigatons (billion metric tons), whereas annual uptake is only about 0.5 gigatons, resulting in a net release of about 1.1 gigatons per year. This implies that only 31% of the U.S carbon emissions are absorbed naturally (Sundquist et al. 2008). Using this, and an estimated emission rate between 5% and 9%

of installed capital at a 5% discount rate, we arrive at a natural absorption rate of installed capital between 1.55% and 2.8% at a 5% discount rate. The resulting benchmark values for parameters can be found in Appendix 2.7.3.

2.5 Results

For the analysis of the growth dynamics, we set low initial values for brown and green capital as well for the pollution stock, as we are interested in the situation that South initially falls in the 'least developed' class of countries.

2.5.1 North's allocation of aid

We start the analysis with investigating the aid allocation of North in equilibrium, and how it is affected by parameter changes.

We know from the steady state analysis that North will give aid in steady state if either its output is sufficiently high, or if it values environmental quality highly enough. If South does not care at all about the environment, that is if $\eta = 0$, there will be no incentive for North to give any aid to South, as South will never make green investments. On the other hand, we find that if South cares a lot, that is, if η is sufficiently large, then again there will be no incentive for North to give aid, as South will make sufficient green investments on its own accord. The benchmark parametrisation describes therefore an intermediate situation.

Figure 2.1 shows the benchmark aid profile over time. There is an initial time interval where no aid is given: this is when South's stocks of brown capital and global pollution are still at low levels. It is only when South's brown capital stock is sufficiently large that North starts giving aid. Although most of the aid is consumed, a part of it enables South to invest in green capital and thereby to lessen its emissions. North's decision to give aid is motivated only by environmental reasons — there is no 'warm glow' term in its utility function — and therefore it should be considered as mitigation aid. The hump shaped aid profile follows from the profile of brown investments,

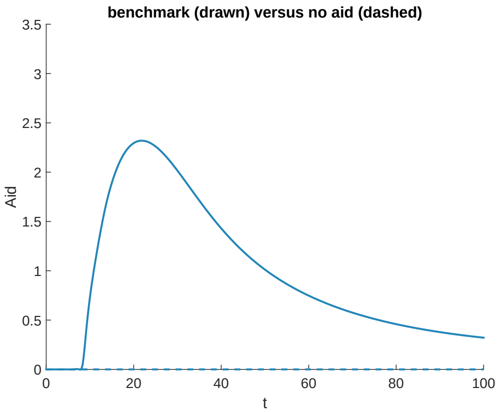


Figure 2.1: Aid profile over time (benchmark)

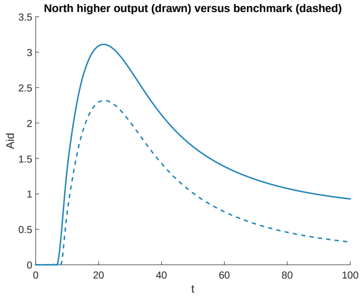
and thus emissions, in South. These correspond to an Environmental Kuznets curve: countries at a low development level tend to increase their emission until average income reaches a certain point over the course of their development.

Figures 2.2 and 2.3 show changes in the aid profile with respect to changes to different parameters, compared to the benchmark profile. In these figures, a dashed curve represents the benchmark aid profile, while the solid curve indicates the aid profile after the change. In all cases, the parameter has been increased or decreased by 20% with respect to its benchmark value.

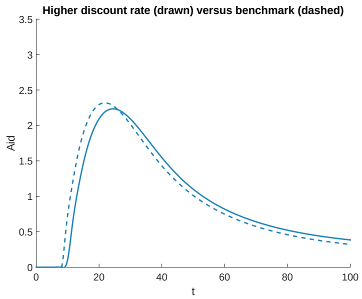
Effects of changing capital parameters

Figure 2.2 illustrates the effects of changing parameters that affect the industrial output of North or South. Figure 2.2a shows the effect of increasing North's output: the level of aid is higher. This finding is in line with the result of Theorem 4 on steady state aid. However, aid starts at almost the same time as in the benchmark case, which suggests that even if North is richer, it is not interested in giving aid if South's emissions are still low and do not cause North much damage.

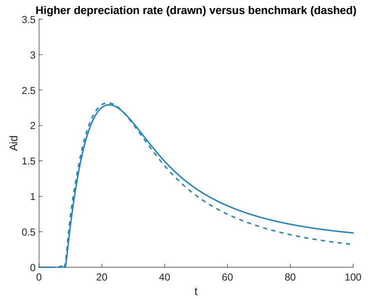
Figure 2.2b increases the discount rate, which both decreases aid and shifts the aid profile to the future, because the long term effects of environmental pollution impact North's welfare less. Increasing the depreciation rate δ, as in Figure 2.2c, has a similar but smaller effect, although the



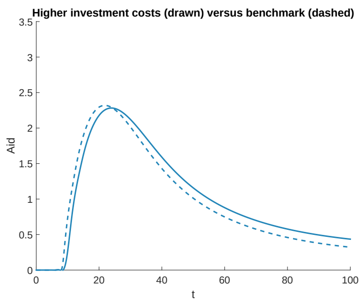
(a) Increasing North's output Y^n



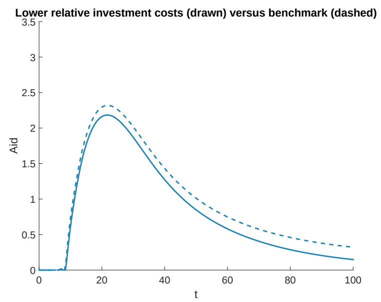
(b) Increasing time discount rate ρ



(c) Increasing depreciation rate δ

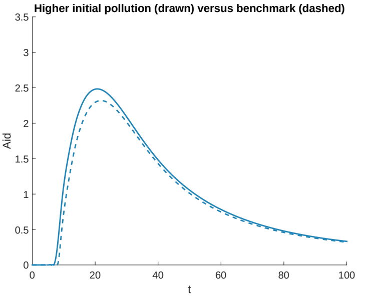


(d) Increasing both β_b and β_g while keeping β_g/β_b constant

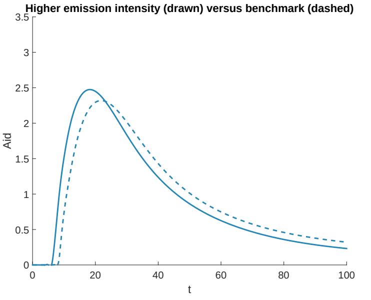


(e) Decreasing β_g while keeping β_b constant

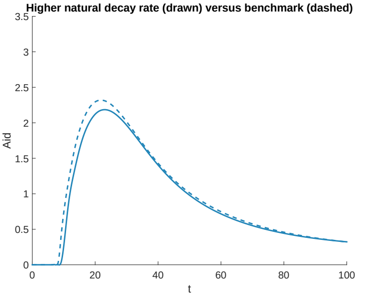
Figure 2.2: Influence of capital-related parameter changes on the aid profile



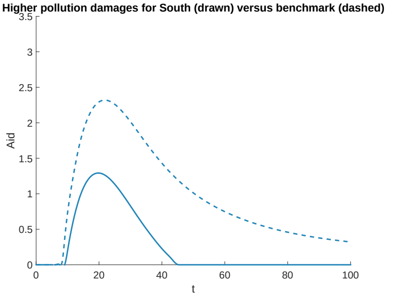
(a) Increasing initial pollution E_0



(b) Increasing emission intensity α



(c) Increasing natural decay rate ϑ



(d) Increasing South's weight of environmental quality η

Figure 2.3: Influence of environmental parameter changes on the aid profile

explanation is different: if capital depreciates quickly, brown capital is less quickly at a critical level. Moreover, it is inefficient to start enabling South too early to invest in green capital.

Higher values of the rate of increase in the marginal cost of investments β_g and β_b, while keeping their ratio constant, imply again that South needs more time to build up capital towards critical levels, implying a shift of the aid profile into the future, as seen in Figure 2.2d.

If the cost β_g/β_b of green investments relative to brown investments falls, aid goes down, for South is less constrained when building up its green capital.

Effects of changing environmental parameters

Figure 2.3 documents the consequences of changes to environmental parameters. The first panel, Figure 2.3a, shows the effect of an increase in the initial pollution stock: this aggravates the environmental conditions and leads North to start giving more aid more quickly, as already a smaller stock of green capital build by South improves the situation.

Higher emission intensity of brown capital makes the aid programme start sooner, Figure 2.3b: as brown capital emits more pollution, more damages from pollution are realised sooner by North.

If the natural decay rate of pollution increases, Figure 2.3c, the pollution stock decreases faster and South's emissions take longer to reach critical levels. Together this makes the problem less urgent for North, whose aid programme is reduced.

Finally, Figure 2.3d shows that if South's consumers put more weight on environmental quality, their incentive to build green capital increases, which in turn lowers North's incentive to give aid dramatically.

2.5.2 South's use of the aid

We turn to South consumption and investment decisions. First we analyse these as function of the model parameters. Then we study the how South allocates the aid it receives from North between consumption and total investments, and how it allocates investment aid between brown and green investments.

Aid increases consumption and green growth

Transboundary pollution is considered as a natural asset necessary for development and for economic growth. Keeping global pollution under tolerable levels, such as keeping the average global temperature below 2 degrees, is necessary to achieve sustainable growth, and thus green growth. Therefore, in this study we measure green growth in the long run by a decrease in global pollution levels. In the short run, investing in non-polluting capital means that these investments are not taking place in the polluting sector, and therefore, lower transitional pollution and higher green growth.

The decisions of South how to allocate aid show how efficiently aid promotes economic growth of the recipient country as well as the effect of aid on the direction of growth.

In order to identify the choice of South for both decision processes we compare the time paths of South's controls when it receives aid to those when it does not, holding all parameters constant.

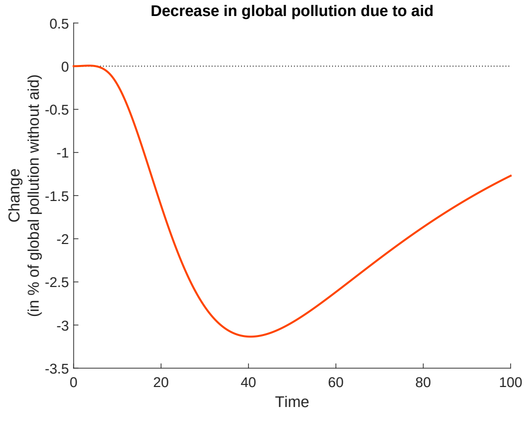
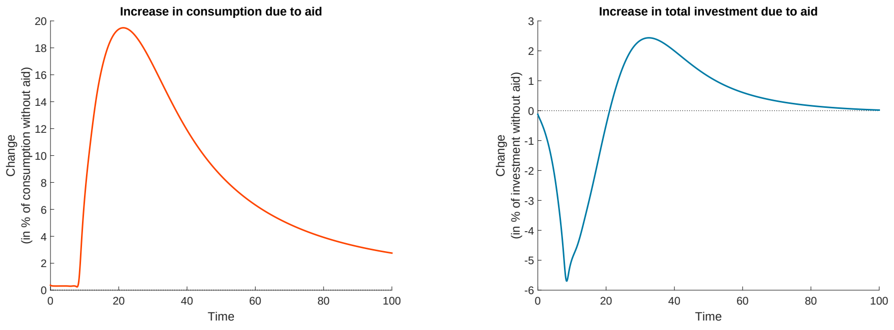


Figure 2.4: Effect of aid on global pollution

As mentioned in Section 2.5.1, in the benchmark situation North starts giving aid when the environmental conditions become critical from its prespective. Figure 2.4 shows the relative change of global pollution level from the benchmark without aid. Giving aid decreases the pollution stock, mainly by shifting brown capital levels downwards. The latter effect become clearer when we study the effect of aid on brown investments.

Figure 2.5a depicts the relative increase of South's consumption when receiving aid compared to the situation where no aid is received; Figure 2.5b gives the corresponding increase in total investments.

The figures show that it is optimal for South to use most of the aid to smooth out its consumption schedule. This is clear from panel 2.5a as investments are postponed, consumption increases a little before aid is received. However, as South starts receiving aid, the rise in consumption takes



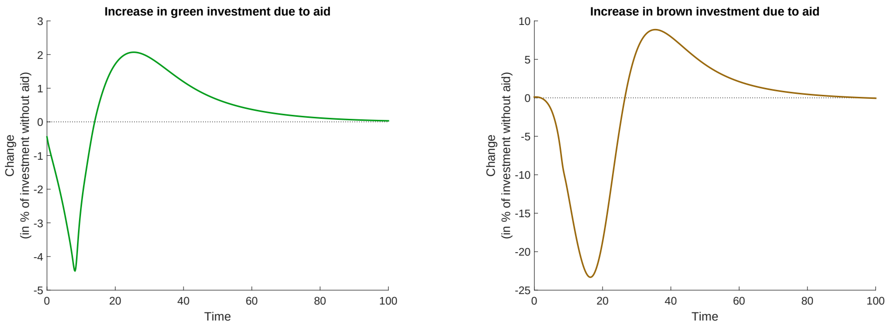
(a) Effect of aid on consumption

(b) Effect of aid on investments

Figure 2.5: South's allocation of aid between consumption and investments

a hump shaped similar to that of the aid profile. This seem at first sight to agree to the findings of Boone (1996), who concludes that aid primarily goes to consumption and that there is no relationship between aid and growth. Figure 2.5b depicts how South's total investments change over time with aid: it shows that investments fall steadily relative to the situation where no aid is expected, until the moment aid starts to arrive. Investments increase again and are then for a substantial period of time over the no-aid levels. Therefore we argue that the conclusion of Boone (1996) about the relationship between aid and growth is imprecise: in our situation aid has a positive effect on growth, but this is modest and lower than what the Harrod and Domar model would predict. These findings are in line with Chatterjee et al. (2003) who find that a temporary pure transfer has only modest short-run growth effects compared to a transfer tied to investment in public infrastructure. We note that a second effect of aid is to push investments into the future.

Figure 2.6 depicts the change of South's investment schedule due to aid for, respectively, brown and green capital. There is a decrease of investments before the aid period begins. The maximal decrease of green investments respective to the case that no aid is received tops out at about 4.5%, before it starts to increase again and ends up at its highest about 2.3% higher than in the no-aid situation. Investments in brown capital fall much more strongly, to a minimum of 26% of investments in the no-aid regime. Also here we see that later on, investments in brown capital pick



(a) Effect of aid on green investments

(b) South's allocation of aid between brown and green investments

Figure 2.6: South's allocation of aid between brown and green investments

up again, topping out at an increase of 9% over the no-aid levels. Note however that these effects are small in absolute terms, as the brown capital level is much lower than the green capital levels. Moreover, since pollution stock is proportional to South's brown capital, figure 2.4 illustrates that aid is effective in lessening brown capital.

We summarise these findings by noting that aid has two effects on investments: it modestly increases total eventual growth, in the benchmark situation mainly for green capital, and it pushes growth farther into the future, by enabling South to increase consumption earlier.

2.5.3 Time consistency

The Stackelberg equilibria we have investigated so far are open-loop equilibria: that is, at time $t = 0$ North announces an aid schedule a_t, and South subsequently makes its plans taking this schedule for granted. At any given point in time, North may reconsider its decision, which then can result in a change in the announced aid policy.

To model South's reaction to such a policy change, we extend the original differential game by introducing a binary state variable, *trust*, which can take the values 0 and 1. At the beginning of the game, *trust* is assumed to take the value 1, which is interpreted as South trusting North to stick to its announced aid schedule. When, at some time $t > 0$, North deviates from the announced schedule — this can be observed by South — *trust* switches from 1 to 0, and South falls back to that growth policy which is optimal if it will receive no aid from North. North will then switch to giving no aid at all, as in the 'no trust' regime giving aid will not alter South's behaviour. This is analogous to the trigger strategy mechanism in repeated games.

In order to find out whether North will stick to its original aid schedule for all time, we have to compare, for each time $t > 0$, North's payoff over the time interval $[t, \infty)$ when sticking to the announced aid schedule versus its payoff when cutting aid at time t. More precisely, let $(E_t, K_{b,t}, K_{g,t})$ be the evolution of pollution level, brown and green capital stock, under the aid schedule a_t announced by North at time $t = 0$, and let

$$W^n(t_0) = \int_{t_0}^{\infty} \mathrm{e}^{-\rho(s-t_0)} (u^n(Y^n - a_s) - D^n(E_s)) \,\mathrm{d}s$$

the corresponding present value of North's welfare at time t_0. If North changes its aid payment at time t_0, South falls back to its optimal growth policy starting at time t_0, with initial values $(E_{t_0}, K_{b,t_0}, K_{g,t_0})$, under the assumption that it will receive no aid. This results, amongst other things, in a different evolution E_t^0 of the pollution stock and a different present value

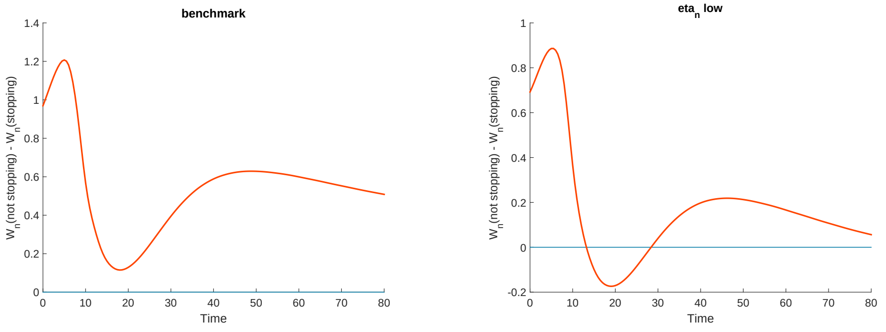
$$W^{n,0}(t_0) = \int_{t_0}^{\infty} \mathrm{e}^{-\rho(s-t_0)} (u^n(Y^n) - D^n(E_s^0)) \,\mathrm{d}s$$

of North's welfare. If the difference

$$\Delta_t = W^n(t) - W^{n,0}(t)$$

is negative for some $t > 0$, North has an incentive to reconsider its aid policy at that date, and the announced policy is not time-consistent.

Figure 2.7a shows the evolution of Δ_t for the benchmark parametrisation. In Section 2.5.2 we saw that in anticipation of the aid transfers, South reduces production, resulting in lower emissions



(a) Benchmark: time consistent

(b) Lower η^n: not time consistent

Figure 2.7: Time consistency of the Stackelberg equilibrium

which benefits North. We conclude that in the benchmark parametrisation, giving aid is a time-consistent policy.

Figure 2.7b illustrates a contrasting situation: if North is less sensitive to pollution damages than in the benchmark parametrisation, giving aid is not time-consistent. Unlike the benchmark parametrisation, here aid is given only temporarily and there is no aid in steady state. Moreover, the Figure shows that this quantity starts taking negative values at the moment where North should be starting making aid payments. In the benchmark situation, the long term gains in pollution reduction in steady state are always more important to North than the short time savings by not sticking to the announced aid transfers.

Accordingly, we conclude that giving unconditional aid in the open loop Stackelberg equilibrium is weakly time consistent if η^n is sufficiently high.

2.5.4 Main effects of giving aid

The discussion in the previous section highlights some of the effects of aid on South's decision over time. We distinguish four effects: the first one is that South chooses to postpone a small amount of its investments until it starts receiving aid, increasing consumption instead. This is coherent with the life-cycle theory of consumption: what is however remarkable is that the intertemporal substitution of consumption is effectively small.

The second effect is that South consumes most of the aid received. This squares with much anecdotal evidence of development aid ‘leaking away’. The present analysis shows however that apart from corruption and mismanagement, which undoubtedly play a role in practice and which are not addressed by our model, there is also the purely economic motivation that the aid is simply better employed elsewhere from South’s point of view.

Thirdly, South stops developing its brown capital when receiving aid. Effectively, giving aid results in a reduction in global emissions.

The fourth effect is that South uses the part of the aid which it allocates to capital investment mainly to increase short term green capital. We think this to be a remarkable finding, the more so as Theorem 1 shows that the steady state level of green capital is never affected by aid.

2.6 Conclusion

This study theoretically identifies the dynamic effects of unconditional aid on the growth and the direction of the growth of a recipient country. We studied a differential Stackelberg game between a leading donor country and a following recipient country. The decision of the donor to give aid in our model is motivated by environmental concerns, and should be classified as mitigation aid. Our model identifies circumstances under which the donor is motivated to give unconditional mitigation aid.

We conclude that if the recipient is sufficiently concerned about environmental quality, there is no incentive for the donor to give aid, as the recipient takes its decisions in a way that preserves the environment whether it receives assistance or not. If the recipient is not concerned about environmental quality at all, again there is no incentive for the donor to give aid, as the behaviour of the recipient will not be influenced by it. In between these two extreme situations, when the recipient is weakly concerned about environmental quality, the donor has an incentive to give aid.

In particular, since we argue that most ‘conditional’ aid is in practice given virtually unconditionally, our study provides an explanation for the empirical evidence that indicates the relative ineffectiveness of aid on growth of the recipient country: our model indicates that it is optimal for the recipient to consume most of the aid and only to allocate a minor part to investments. Still, even giving unconditional aid can be a Pareto-improvement over giving no aid at all.

Our model also shows that unconditional development aid has a modest positive short term effect on growth. This effect seems however much lower than what the Harrod and Domar model predicts. At least for our benchmark case we investigated, we found that most of the increase of growth caused by aid takes place in the green sector.

We propose two possible extensions to our model. The first is to include demographical changes in the recipient country by adding labour as a second input for production. This would help to complete the analysis, to study whether high population growth rate in these countries necessitates a higher growth rate to meet the demographical changes: the possible effect would be that aid is more effectively used to increase growth. The second extension would be to introduce a parameter that captures aid being given under the condition that it is used only for green investments. We expect then to find an intertemporal trade-off between consumption and investments, resulting in a higher consumption ex-ante and consequently a *de facto* failure of conditionality.

As a policy recommendation, results analyzed in this study suggest that even when aid conditionality cannot be fully achieved, a donor country still gives mitigation aid if it can guarantee a sufficient degree of environmental awareness of the recipient country. Note that the effects of aid on green growth might be more than that analyzed here as these effects represent the minimum expected effects, since aid is given unconditionally.

2.7 Appendix

2.7.1 South

South's decision problem

South has to maximize its welfare (2.1), subject to its budget constraint (2.2) and the capital and pollution stock evolution equations (2.3) and (2.4). From the binding budget constraint, we solve

$$c_t = F_b(K_{b,t}) + F_g(K_{g,t}) + a_t - \frac{\beta_b}{2} I_{b,t}^2 - \frac{\beta_g}{2} I_{g,t}^2. \tag{2.27}$$

The current value Hamiltonian for maximization problem is

$$\begin{aligned} H = u\left(F_b(K_{b,t}) + F_g(K_{g,t}) + a_t - \frac{\beta_b}{2} I_{b,t}^2 - \frac{\beta_g}{2} I_{g,t}^2\right) - D(E_t) \\ + \mu_t(\alpha K_{b,t} - \vartheta E_t) + \nu_{b,t}(I_{b,t} - \delta K_{b,t}) + \nu_{g,t}(I_{g,t} - \delta K_{g,t}). \end{aligned}$$

Note that we have written out the argument c_t of u. Maximizing over the remaining decision variables $I_{b,t}$ and $I_{g,t}$ yields

$$\nu_{i,t} = \beta_i I_{i,t} u'(c_t), \qquad i \in \{b, g\}. \tag{2.28}$$

The equations for the shadow prices are given in the main text (equations (2.6)–(2.5)). We have moreover the initial states $K_{b,0}, K_{g,0}, E_0$ and the transversality conditions

$$\lim_{t\to\infty} e^{-\rho t} E_t = 0, \quad \lim_{t\to\infty} e^{-\rho t} K_{i,t} = 0, \qquad i \in \{b, g\}, \tag{2.29}$$

which hold for paths that are uniformly bounded away from 0.

South's steady state

Here, we compute and analyse the steady state of South's decision problem under the assumption that the aid schedule $a_t = a$ is constant in time. To denote a steady state value of a dynamic quantity, we drop the subscript t.

Green capital

First, we derive the steady state level of green capital. At steady state, we obtain from (2.3)

$$I_i = \delta K_i, \qquad \text{for} \quad i \in \{b, g\}. \tag{2.30}$$

Equation (2.28) implies at steady state

$$u'(c) = \frac{\nu_g}{\beta_g I_g}$$

Substituting in (2.7) yields

$$\left(\rho + \delta - \frac{1}{\beta_g I_g} F_g'(K_g)\right) \nu_g = 0.$$

The alternative $\nu_g = 0$ implies, by the previous expression, that $u'(c) = 0$, which is impossible. Hence the term in brackets vanishes, which yields

$$F_g'(K_g) = (\rho + \delta)\beta_g I_g.$$

Eliminating I_g using (2.30) yields finally

$$F_g'(K_g) = (\rho + \delta)\delta\beta_g K_g. \tag{2.31}$$

This equation determines the steady state level K_g of green capital as a function of the system's parameters; K_g in turn determines the steady state level I_g of green investments. Note in particular that green capital and green investments at steady state do not depend on aid.

Brown capital

We turn to brown capital. From the budget constraint (2.2), we write steady state consumption c as a function of aid a and brown capital K_b

$$c = F_b(K_b) + F_g(K_g) + a - \frac{\beta_b \delta^2}{2} K_b^2 - \frac{\beta_g \delta^2}{2} K_g^2. \tag{2.32}$$

From (2.4) and (2.5) it follows that

$$E = \frac{\alpha}{\vartheta} K_b \tag{2.33}$$

and

$$\mu = -\frac{D'(E)}{(\rho + \vartheta)} = -\frac{D'(\frac{\alpha}{\vartheta} K_b)}{(\rho + \vartheta)}. \tag{2.34}$$

This yields E and μ as functions of K_b.

Eliminating μ from (2.6) using (2.34) yields

$$(\rho + \delta)\nu_b = u'(c) F_b'(K_b) - \frac{\alpha}{\rho + \vartheta} D' \left(\frac{\alpha}{\vartheta} K_b \right).$$

Using (2.28) and (2.30), we obtain a second expression

$$\nu_b = \beta_b \delta u'(c) K_b$$

for ν_b. After elimination, we finally obtain

$$F_b'(K_b) = (\rho + \delta)\delta \beta_b K_b + \frac{\alpha}{(\rho + \vartheta)} \frac{D' \left(\frac{\alpha}{\vartheta} K_b \right)}{u'(c)}. \tag{2.35}$$

This equation determines the steady state brown capital level K_b, which in turn determines the steady state brown investments level I_b.

Proofs of theorem 1–3

We first prove theorem 1.

Proof.

It follows from (2.31) that aid does not affect the steady state level of green capital, and hence that $\frac{\partial K_g}{\partial a} = 0$. Consumption c and brown capital K_b are jointly determined by (2.32) and (2.35), which can be written as

$$G_1 = c + \frac{\beta_b \delta^2}{2} K_b^2 + \frac{\beta_g \delta^2}{2} K_g^2 - F_b(K_b) - F_g(K_g) - a = 0,$$
$$G_2 = (\rho + \delta)\delta \beta_b K_b - F_b'(K_b) + \frac{\alpha}{(\rho + \vartheta)} \frac{D'\left(\frac{\alpha}{\vartheta} K_b\right)}{u'(c)} = 0.$$

Introduce the vector-valued functions $G = (G_1, G_2)$ and $X = (c, K_b)$, and the derivative

$$D_X G = \begin{pmatrix} \frac{\partial G_1}{\partial c} & \frac{\partial G_1}{\partial K_b} \\ \frac{\partial G_2}{\partial c} & \frac{\partial G_2}{\partial K_b} \end{pmatrix}.$$

We shall need the elements of the matrix $D_X G$ and its inverse. Compute first

$$\frac{\partial G_1}{\partial c} = 1,$$
$$\frac{\partial G_1}{\partial K_b} = \beta_b \delta^2 K_b - F_b'(K_b),$$
$$\frac{\partial G_2}{\partial c} = \frac{\alpha}{\rho + \vartheta} D'\left(\frac{\alpha}{\theta} K_b\right) \frac{(-u''(c))}{u'(c)^2}$$
$$\frac{\partial G_2}{\partial K_b} = (\rho + \delta)\delta \beta_b - F_b''(K_b) + \frac{\alpha^2}{(\rho + \vartheta)\vartheta} \frac{D''(\frac{\alpha}{\vartheta} K_b)}{u'(c)}$$

It follows from the assumptions of F_b, u and D that $\frac{\partial G_1}{\partial c} > 0$, $\frac{\partial G_2}{\partial c} > 0$ and $\frac{\partial G_2}{\partial K_b} > 0$. Using (2.35) to eliminate $F_b'(K_b)$, we find that

$$\frac{\partial G_1}{\partial K_b} = \beta_b \delta^2 K_b - F_b'(K_b) = -\rho \delta \beta_b K_b - \frac{\alpha}{(\rho + \vartheta)} \frac{D'\left(\frac{\alpha}{\vartheta} K_b\right)}{u'(c)} < 0.$$

This implies that the determinant $\Delta = \det D_X G$ is positive. Setting

$$-(D_X G)^{-1} = B = \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}$$

these results imply that $B_{11} < 0$, $B_{12} < 0$ and $B_{22} < 0$, while $B_{21} > 0$.

Since

$$D_a X = -(D_X G)^{-1} D_a G, \tag{2.36}$$

we also have to compute the elements $D_a G$:

$$\frac{\partial G_1}{\partial a} = -1, \qquad \frac{\partial G_2}{\partial a} = 0.$$

Equation (2.36) implies that

$$\frac{\partial c}{\partial a} = -B_{11} > 0, \quad \frac{\partial K_b}{\partial a} = -B_{21} < 0.$$

This shows the results about consumption and dirty and green capital. The results about investments and the pollution stock follow from equations (2.30) and (2.33). ∎

The proof of the other theorems is now straightforward. We continue with the proof of theorem 2.

Proof.

Retaining the notations from the previous proof, we note that

$$\begin{pmatrix} \frac{\partial c}{\partial \beta_i} \\ \frac{\partial K_b}{\partial \beta_i} \end{pmatrix} = B\, D_{\beta_i} G = B \begin{pmatrix} \frac{\partial G_1}{\partial \beta_i} \\ \frac{\partial G_2}{\partial \beta_i} \end{pmatrix} \qquad \text{for} \quad i \in \{b, g\}.$$

For green investment costs, we have

$$\frac{\partial G_1}{\partial \beta_g} = \frac{\delta^2}{2} K_g^2 > 0, \quad \frac{\partial G_2}{\partial \beta_g} = 0,$$

hence

$$\frac{\partial c}{\partial \beta_g} = B_{11} \frac{\delta^2}{2} K_g^2 < 0, \qquad \frac{\partial K_b}{\partial \beta_g} = B_{21} \frac{\delta^2}{2} K_g^2 > 0.$$

Then, for brown investment costs

$$\frac{\partial G_1}{\partial \beta_b} = \frac{\delta^2}{2} K_b^2 > 0, \quad \frac{\partial G_2}{\partial \beta_b} = (\rho + \delta)\delta K_b > 0,$$

which implies

$$\frac{\partial c}{\partial \beta_b} = B_{11} \frac{\delta^2}{2} K_b^2 + B_{21}(\rho + \delta)\delta K_b < 0,$$

and

$$\frac{\partial K_b}{\partial \beta_b} = B_{21} \frac{\delta^2}{2} K_g^2 + B_{22}(\rho + \delta)\delta K_b.$$

In the last expression, the two terms on the right hand side have opposite signs. However, if the emission intensity $\alpha = 0$, then $B_{21} = 0$ and

$$\frac{\partial K_b}{\partial \beta_b} \Big|_{\alpha=0} < 0,$$

which implies, by continuity, that $\frac{\partial K_b}{\partial \beta_b} < 0$ for values of α close to 0.

Finally, for the capital depreciation rate

$$\frac{\partial G_1}{\partial \delta} = \beta_g \delta K_g^2 + \beta_b \delta K_b^2 > 0, \quad \frac{\partial G_2}{\partial \delta} = (\rho + 2\delta)\beta_b K_b > 0.$$

Analogously to the situation of brown investment costs, this implies

$$\frac{\partial c}{\partial \delta} < 0$$

whereas the sign of $\frac{\partial K_b}{\partial \delta}$ is undetermined in general, but for α taking values close to 0, we have that $\frac{\partial K_b}{\partial \delta} < 0$.

∎

Next, the proof of theorem 3.

Proof.

Again retaining the notations of the proof of theorem 1, we note that

$$D_\vartheta G = -\left(\frac{\alpha}{(\rho+\vartheta)^2}\frac{D'(\frac{\alpha}{\vartheta}K_b)}{u'(c)} + \frac{\alpha^2}{(\rho+\vartheta)\vartheta}\frac{D''(\frac{\alpha}{\vartheta}K_b)}{u'(c)}K_b\right)\begin{pmatrix}0\\1\end{pmatrix} = -C\begin{pmatrix}0\\1\end{pmatrix}$$

with $C > 0$. It follows that

$$\frac{\partial c}{\partial \vartheta} = -B_{12}C > 0, \qquad \frac{\partial K_b}{\partial \vartheta} = -B_{22}C > 0.$$

From

$$D_\alpha G = \left(\frac{1}{\rho+\vartheta}\frac{D'(\frac{\alpha}{\vartheta}K_b)}{u'(c)} + \frac{\alpha}{(\rho+\vartheta)\vartheta}\frac{D''(\frac{\alpha}{\vartheta}K_b)}{u'(c)}K_b\right)\begin{pmatrix}0\\1\end{pmatrix},$$

the factor in brackets being positive, it follows in the same manner that

$$\frac{\partial c}{\partial \alpha} < 0, \qquad \frac{\partial K_b}{\partial \alpha} < 0.$$

Using the functional form $D(E) = \eta E^2/2$, we find

$$D_\eta G = \left(\frac{\alpha}{\rho+\vartheta}\frac{\frac{\alpha}{\vartheta}K_b}{u'(c)}\right)\begin{pmatrix}0\\1\end{pmatrix}.$$

In the same manner as before, we obtain

$$\frac{\partial c}{\partial \eta} < 0, \qquad \frac{\partial K_b}{\partial \eta} < 0.$$

∎

2.7.2 North

North's decision problem

North maximizes its welfare (2.9) subject to: its budget constraint (2.10); the aid positivity constraint (2.11); the evolution equations of South's capital stocks (2.3) and that of the global pollution stock (2.4); the evolution equations of South's shadow prices for capital and pollution (2.5)–(2.7); and South's transversality conditions (2.29).

Since we need take into account of aid positivity $a_t \geq 0$, we need to compute a Lagrangian for North, with ξ_t as the multiplier of the positivity constraint:

$$\begin{aligned} L = {} & u^n(F_g^n(K_{g,t}^n) - a_t) - D^n(E_t) + \xi_t a_t \\ & + \kappa_{b,t}\left(\frac{\nu_{b,t}}{\beta_b u'(c_t)} - \delta K_{b,t}\right) + \kappa_{g,t}\left(\frac{\nu_{g,t}}{\beta_g u'(c_t)} - \delta K_{g,t}\right) \\ & + \lambda_{b,t}\Big((\rho+\delta)\nu_{b,t} - u'(c_t)F_b{}'(K_{b,t}) - \alpha\mu_t\Big) \\ & + \lambda_{g,t}\Big((\rho+\delta)\nu_{g,t} - u'(c_t)F_g{}'(K_{g,t})\Big) \\ & + \psi_t(\alpha K_{b,t} - \vartheta E_t) + \tau_t\big(D'(E_t) + (\rho+\vartheta)\mu_t\big). \end{aligned}$$

Here c_t is given by (2.27).

The multiplier ξ_t has to satisfy the positivity condition $\xi_t \geq 0$, the complementary slackness condition

$$\xi_t a_t = 0,$$

as well as the condition

$$\xi_t = (u^n)'(c_t^n) + \frac{u''(c_t)}{u'(c_t)^2}\Big(\frac{\kappa_{b,t}\nu_{b,t}}{\beta_b} + \frac{\kappa_{g,t}\nu_{g,t}}{\beta_g}\Big) + u''(c_t)\Big(\lambda_{b,t}F_b'(K_{b,t}) + \lambda_{g,t}F_g'(K_{g,t})\Big).$$

The equations for North's shadow prices read as

$$\dot{\kappa}_{b,t} = (\rho+\delta)\kappa_{b,t} + \lambda_{b,t}u'(c_t)F_b''(K_{b,t}) - \alpha\psi_t + F_b'(K_{b,t})\left[\frac{u''(c_t)}{u'(c_t)^2}\Big(\frac{\kappa_{b,t}\nu_{b,t}}{\beta_b} + \frac{\kappa_{g,t}\nu_{g,t}}{\beta_g}\Big) + u''(c_t)\Big(\lambda_{b,t}F_b'(K_{b,t}) + \lambda_{g,t}F_g'(K_{g,t})\Big)\right],$$

$$\dot{\kappa}_{g,t} = (\rho+\delta)\kappa_{g,t} + \lambda_{g,t}u'(c_t)F_g''(K_{g,t}) + F_g'(K_{g,t})\left[\frac{u''(c_t)}{u'(c_t)^2}\left(\frac{\kappa_{b,t}\nu_{b,t}}{\beta_b} + \frac{\kappa_{g,t}\nu_{g,t}}{\beta_g}\right) + u''(c_t)\Big(\lambda_{b,t}F_b'(K_{b,t}) + \lambda_{g,t}F_g'(K_{g,t})\Big)\right],$$

$$\dot{\lambda}_{b,t} = -\delta\lambda_{b,t} - \frac{\kappa_{b,t}}{\beta_b u'(c_t)}, \qquad \dot{\lambda}_{g,t} = -\delta\lambda_{g,t} - \frac{\kappa_{g,t}}{\beta_g u'(c_t)},$$

$$\dot{\psi}_t = (\rho+\vartheta)\psi_t + (D^n)'(E_t) - \tau_t D''(E_t),$$
$$\dot{\tau}_t = -\vartheta\tau_t + \alpha\lambda_{b,t}.$$

The transversality conditions are:

$$\lim_{t\to\infty} e^{-\rho t}K_{b,t} = 0, \quad \lim_{t\to\infty} e^{-\rho t}K_{g,t} = 0, \quad \lim_{t\to\infty} e^{-\rho t}E_t = 0,$$
$$\lim_{t\to\infty} e^{-\rho t}\nu_{b,t} = 0, \quad \lim_{t\to\infty} e^{-\rho t}\nu_{g,t} = 0, \quad \lim_{t\to\infty} e^{-\rho t}\mu_t = 0,$$

as usual holding for solution paths where the associated variable is bounded away from 0. These are complemented by the initial conditions for the states $K_{b,0}$, $K_{g,0}$, and E_0, and the following initial conditions for North's co-states: $\tau_0 = 0$, $\lambda_{b,0} = 0$, $\lambda_{g,0} = 0$.

Solving for North's steady state

In the analysis of South's steady state, aid a was treated as an external parameter. From the steady state conditions of North's co-state equations, we derive an equation that links North's steady state aid level to South's consumption level c and South's brown capital level K_b.

From equation (2.17), we obtain

$$\tau = \frac{\alpha}{\vartheta}\lambda.$$

Equation (2.14) then yields

$$\psi = \frac{\frac{\alpha}{\vartheta}\lambda_b D''(E) - (D^n)'(E)}{\rho + \vartheta};$$

we write here and later E instead of $(\alpha/\vartheta)K_b$ for the sake of legibility. Equations (2.15) and (2.16) allow us to eliminate κ_b and κ_g, as

$$\kappa_i = -\delta\beta_i u'(c)\lambda_i, \qquad i \in \{b, g\}.$$

Using this and equations (2.30) and (2.28), we obtain an expression for the multiplier

$$\xi = (u^n)'(c^n) + u''(c)\Big(\lambda_g(F_g'(K_g) - \delta^2\beta_g K_g) + \lambda_b(F_b'(K_b) - \delta^2\beta_b K_b)\Big). \tag{2.37}$$

We investigate the situation that aid is given, which occurs if $\xi = 0$. Equations (2.12) and (2.13) then yield

$$\begin{aligned} 0 = \lambda_b u'(c)\left(F_b''(K_b) - (\rho+\delta)\delta\beta_b - \frac{\alpha^2}{(\rho+\vartheta)\vartheta}\frac{D''(E)}{u'(c)}\right) \\ - F_b'(K_b)(u^n)'(c^n) + \frac{\alpha}{\rho+\vartheta}(D^n)'(E) \end{aligned}$$

and

$$0 = \lambda_g u'(c)\Big(F_g''(K_g) - (\rho+\delta)\delta\beta_g\Big) - F_g'(K_g)(u^n)'(c^n).$$

From these, we obtain

$$\lambda_b = -\frac{\frac{(u^n)'(c^n)}{u'(c)}F_b'(K_b) - \frac{\alpha}{\rho+\vartheta}\frac{(D^n)'(E)}{u'(c)}}{(\rho+\delta)\delta\beta_b - F_b''(K_b) + \frac{\alpha^2}{(\rho+\vartheta)\vartheta}\frac{D''(E)}{u'(c)}} \tag{2.38}$$

and

$$\lambda_g = -\frac{(u^n)'(c^n)}{u'(c)}\frac{F_g'(K_g)}{(\rho+\delta)\delta\beta_g - F_g''(K_g)}. \tag{2.39}$$

Substituting (2.38) and (2.39) in (2.37), for $\xi = 0$, and recalling North's budget constraint (2.10), yields

$$(u^n)'(Y^n - a) = \frac{A_2}{A_1}, \tag{2.40}$$

where

$$A_1 = 1 - \frac{u''(c)}{u'(c)}\Bigg(\frac{(F_g'(K_g) - \delta^2\beta_g K_g)F_g'(K_g)}{(\rho+\delta)\delta\beta_g - F_g''(K_g)} + \frac{(F_b'(K_b) - \delta^2\beta_b K_b)F_b'(K_b)}{(\rho+\delta)\delta\beta_b - F_b''(K_b) + \frac{\alpha^2}{(\rho+\vartheta)\vartheta}\frac{D''(E)}{u'(c)}}\Bigg),$$

and

$$A_2 = \frac{\alpha}{\rho+\vartheta}\frac{(-u''(c))}{u'(c)}\frac{F_b'(K_b) - \delta^2\beta_b K_b}{(\rho+\delta)\delta\beta_b - F_b''(K_b) + \frac{\alpha^2}{(\rho+\vartheta)\vartheta}\frac{D''(E)}{u'(c)}}(D^n)'(E).$$

It follows from equations (2.31) and (2.35) that the factors $F_i'(K_i) - \delta^2\beta_i K_i$ are positive for $i \in \{b, g\}$. This, together with the standard assumptions put on F_i, u and D, implies that $A_1, A_2 > 0$.

Note that the right hand side of equation (2.40) depends only on K_g, K_b and c, which are differentiable functions of a, determined by equations (2.31), (2.32) and (2.35); hence $A_1 = A_1(a)$

and $A_2 = A_2(a)$ are also differentiable functions of a. Note moreover that $A_2(a)$ is bounded away from 0.

Theorem 5 *If* $(u^n)'(Y^n) < A_2(0)/A_1(0)$*, then there is a steady state with positive aid flow a.*

Proof.

This follows immediately from the intermediate value theorem, as

$$\lim_{a \uparrow Y^n} (u^n)'(Y^n - a) = \infty$$

by the Inada condition on u^n, whereas the expression $A_2(a)/A_1(a)$ is continuous for all $a > 0$. ∎

2.7.3 Benchmark parametrization

Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
$K_{b,0}$	1	δ	0.025	γ	0.75	α	0.05
$K_{g,0}$	1	T	300	ρ	0.05	ϑ	0.016
E_0	15	Ω	0.6	β_b	0.05	η	0.0006
ε	0.5	σ	0.5	β_g	0.125	η^n	0.023
Y^n	12.123						

Chapter 3

Climate Policy and Carbon Leakage with Firm Heterogeneity

3.1 Introduction

Climate change is a global phenomena affecting all countries regardless of their development level. The international community has recognized the necessity of international agreements that limit Green House Gases (GHG) emissions through Paris Climate Agreement of 2015. Asymmetry in the views towards climate change and in the implemented policies across countries, create distortions in international competitiveness, making these policies both less efficient and less acceptable to firms and citizens. Firms in countries that implement a carbon tax or emissions permits face additional production costs, which their international competitors do not bear. The demand for their products decreases, leading to a reduction in output and a loss in profits and market shares. At the same time, emissions in countries with a lax climate policy increase, inducing so-called carbon leakage.

Several instruments have been proposed to tackle carbon leakage and distortions in international competitiveness. A Border Tax Adjustment (BTA) is simply a tariff on imported goods, while a A Border Carbon Adjustment (BCA) is a differential tax on the carbon content of imports.

These two instruments may strengthen climate policy and limit undue competition from firms located in countries with a lax environmental regulation. A priory, they face the possibility to be contested within the framework of the World Trade Organization (WTO), which aims at eliminating trade barriers between member countries. They may be found acceptable, however, if their levels are in line with their goals. Introducing a BCA also faces practical difficulties related mainly to the accurate determination of the carbon content of imports. As firms are heterogeneous in reality, it is necessary to study the impact of carbon taxes and border adjustments on the firm level, and, more precisely, to study how firms with different productivity levels are affected by these policies. This is what we do in this paper.

The Melitz (2003) model with heterogeneous firms provides a rich framework to assess the impact of climate policies on firms' competitiveness, and therefore on their production and emission levels. The model incorporates dynamic forward entry decisions for firms facing sunk market entry costs, and it introduces heterogeneity in firm-specific productivity levels. This mechanism allows to track the reallocation of resources across firms after policy shocks, and to study how firms with different productivity level are affected by the same shock. Such policy effects cannot be explained by representative firm models where the average productivity level is exogenously given (Krugman (1980)).

In this paper, we extend the Melitz model by introducing environmental damages, climate policies, and border adjustments. In the extended model, each country is assumed to be able to implement a carbon tax, a BCA, or a BTA. We study the competitiveness-driven channel of carbon leakage and analyze the national and international aspects of this channel. We identify the impact of these policies on firms across countries; moreover, we investigate the role of the strength of the link between firm-specific emission intensity and its productivity level for policy impacts across the productivity spectrum.

A number of counter-intuitive results are obtained. Climate policy remains effective but may result in more polluting firms entering the market. The leakage phenomena may not materialize or may remain very weak. Finally, a complicated but consistent form of competitiveness between firms facing a climate policy will emerge. When firm-specific emission intensity is weakly decreasing with its productivity level, more productive firms are the ones hardest hit by the tax and we identify an unexpected effect of introducing a climate tax: even though the tax decreases profits in the targeted markets, it increases at the same time the probability of successful entry, inducing less productive firms to enter the market. Furthermore, a unilateral carbon tax decreases the international competitiveness of the implementing country, while the inter-firm profitability decreases only if emission intensity is weakly decreasing with the productivity level.

As with the carbon tax, the impact of a BCA across firms in the targeted market depends on the correlation between firm-specific emission intensity and its productivity level, which is not the case for a BTA. Therefore, a BCA induces a distortion in competitiveness across firms in that market, while a BTA effects no such distortion. Both adjustments are effective tools to mitigate carbon leakage and restore competitiveness. A normative statement on which adjustment is more efficient depends on the objectives of the implementing country. In general, a BCA is a better instrument to mitigate the leakage in emissions than a BTA, as it targets directly carbon contents of imports; a BTA represents a more credible threat to induce cooperation however.

There are a number of studies that employ different frameworks to address carbon leakage and the competitiveness distortions. The possibility of leakage has been documented theoretically and empirically (Carraro and Siniscalco (1998), Copeland and Taylor (2005), Elliott et al. (2010), and Aichele and Felbermayr (2015)). Monjon and Quirion (2010) discuss possible choices for the design of border adjustments to complement the EU Emission Trading System. In Monjon and Quirion (2009) they develop a computational partial equilibrium model to compare different policy combinations to limit carbon leakage and reduce production loss due to the unilateral implementation of EU emission trading system. They conclude that the most efficient way to tackle leakage is auctioning with border adjustments, which even induces a negative leakage (or a spillover). Both Jakob et al. (2013) and Kuik and Hofkes (2010) doubted the effectiveness of BTA to tackle the leakage, Kuik and Hofkes (2010) noted however that BTAs would strengthen sectoral competitiveness. Sanctuary (2014) investigates how a BCA affects government incentives to regulate emissions. He identifies the tariff weakness as a measure to strengthen the climate policy in the country with a lax environmental regulation, which is not the case for a BCA. Böhringer et al. (2012) summarize the results of an Energy Modeling Forum study (EMF 29) on the efficiency and distributional impacts of a BCA. They find that a BCA could effectively affect leakage negatively and that the main effect of a BCA is to shift the economic responsibility of emission reduction to countries with no or lax climate policies through changes in relative prices. Böhringer et al. (2015) analyze the efficiency of carbon tariffs to tackle the leakage in a Computable General Equilibrium (CGE) model. They conclude that a carbon tariff on the firm level provides an incentive for firms to reduce their emission intensity, and therefore, these tariffs are much more efficient in reducing the leakage than those implemented on the industry level[1]. Other studies relying on CGE models give important insights into the interactions of regulating emissions and potential effects from international markets to quantify the leakage ratio (Felder and Rutherford (1993), Elliott et al. (2010), and Burniaux and Oliveira Martins (2012)).

Some studies adopt the Melitz framework to address environmental and trade aspects on the firm level. Kreickemeier and Richter (2014) study the effects of trade liberalization on the environment assuming a negative relationship between firm-specific emission intensity and its productivity level. They conclude that opening the economy to trade will be beneficial to the environment if and only if firm-specific pollution intensity is strongly decreasing with firm productivity level. Empirically, Batrakova and Davies (2012) use the Melitz model to study the impact of exporting status on energy use. They find that most productive firms with a high energy intensity tend to decrease this intensity by adopting new technologies when exporting, which suggest a lower emission intensity as energy production is strongly correlated to GHG emissions. In line with Batrakova and Davies (2012), there are several empirical papers that find, broadly, the same result: more productive firms tend to be cleaner (Cole et al. (2005), Elliott et al. (2008), Mazzanti and Zoboli (2009), Holladay (2010), and Cui et al. (2012)). There are a number of interpretations for the negative relationship between firm-specific emission intensity and its productivity level: it can

[1] Branger and Quirion (2014) provide an overview of a relevant literature on BCAs.

be due to the larger production scale by more productive firms which induces more fixed investments in abatement technology, and therefore, lower emissions per unit of output. This mechanism was introduced and investigated by Forslid et al. (2014) in an extension to the Melitz model. Their empirical results strongly confirm the theoretical model. Another intuition for the negative relationship can be that large more productive firms tend to implement the latest technology, which is, generally, more environmentally friendly. Baldwin and Ravetti (2014) describe the relationship between firms' emissions and their productivity level as a matching process between the best firms with the cleanest irreversible technologies they can afford, as a way for them to avoid future costs related to replacing their technology if environmental regulation becomes tighter.

Throughout this paper, we assume a negative relationship between emission intensity and productivity level. We focus on the distribution of policy burdens depending on the strength of this relationship. Unlike Kreickemeier and Richter (2014) we introduce environmental regulation to the Melitz model in order to address carbon leakage on the firm level, associating policy effects to the link between firm-specific emission intensity and its productivity level. Furthermore, we contrast the effects of BCAs and BTAs on the firm level.

The rest of this study is organized as follows: Section 2 presents an extension of theMelitz (2003) model, Section 3 introduces the methodology and the calibration of model parameters. Section 4 addresses the results. In Section 5, we conclude.

3.2 An extension of Melitz model

We follow Kreickemeier and Richter (2014) and introduce Green House Gases (GHG) emissions to Melitz (2003), assuming that the firm-specific emission intensity depends on its productivity level ϕ (Forslid et al. (2014)). We assume a world of two countries, Home h and Foreign f. We adopt the entry mechanism described by Melitz where potential entrants face a random productivity that is distributed according to a cumulative distribution $G(\phi)$ with a density $g(\phi)$. We only describe relations for Home; relations for Foreign are analogous.

Potential entrant firms have to pay a fixed sunk entry cost and enter only if their expected profit covers this cost. In presence of production fixed costs, an entrant firm may make negative profits: in that case it remains inactive. Before entering, firms are assumed to have no information about their productivity level. This productivity is drawn randomly from a country-specific distribution after entering. Only firms with productivity level higher than an endogenous threshold value ϕ^*_{hh} become active and sell to their domestic market. In order to export, an active firm has to pay a supplementary fixed access cost. Exporting is only profitable for firms with a productivity level higher than a second threshold level ϕ^*_{hf}. The first and second subscript denote respectively the country where the goods are produced and consumed.

The probability of successful entry into the domestic market by a firm located at Home is $(1 - G(\phi^*_{hh}))$, while the probability of entering the export market is $(1 - G(\phi^*_{hf}))$. Therefore, the probability for an active firm to export, the export participation rate, reads

$$m_{hf} = \frac{1 - G(\phi^*_{hf})}{1 - G(\phi^*_{hh})}.$$

The numbers of active firms M_h, and of exporting firms M_{hf}, are related to the number of entrant firms M^e_h. These quantities read

$$M_h = (1 - G(\phi^*_{hh}))M^e_h, \qquad M_{hf} = m_{hf} M_h. \tag{3.1}$$

A representative consumer at Home is assumed to gain utility from the consumption of a continuum of locally produced and imported goods. The utility function is assumed to have a CES form (Dixit and Stiglitz (1977)). Utility U_h of the representative consumer at Home reads

$$U_h = \left[M_{hh} \int_{\phi^*_{hh}}^{\infty} q_{hh}(\phi)^{\frac{\sigma-1}{\sigma}} \frac{g(\phi)}{1 - G(\phi^*_{hh})} d\phi + M_{fh} \int_{\phi^*_{fh}}^{\infty} q_{fh}(\phi)^{\frac{\sigma-1}{\sigma}} \frac{g(\phi)}{1 - G(\phi^*_{fh})} d\phi \right]^{\frac{\sigma}{\sigma-1}}. \tag{3.2}$$

Here $q_{hh}(\phi)$ and $q_{fh}(\phi)$ represent, respectively, the consumption of domestic and imported goods produced by a firm with productivity level ϕ. The elasticity of substitution σ satisfies $\sigma > 1$. Let $\rho = 1 - 1/\sigma$.

Pollution is assumed transboundary such that emissions from one country affect consumers in both countries. Therefore, the representative consumer has a disutility from global pollution E_w. Home's net welfare reads

$$W_h = U_h - D(E_w) = U_h - \frac{\eta(E_w)^\epsilon}{\epsilon}. \tag{3.3}$$

The damage function D is assumed to be increasing and convex with a constant elasticity $\epsilon > 1$; the parameter $\eta \geq 0$ governs the degree of environmental awareness, or equivalently, the sensitivity towards global pollution, in the country.

Production only requires one input, namely labor. Total labor supply L_h in the country is exogenously given. The quantities $q_{hh}(\phi)$ and $q_{hf}(\phi)$ represent also the respective production of Home's firms for domestic and foreign markets. We describe production for the foreign market; production for the domestic market follows easily.

The technology of a firm is represented by a cost function that exhibit constant marginal cost along with a fixed overhead cost f_{hh}, which is paid by the firm in order to be able to produce for the domestic market. The use of labor is therefore a linear function of output q_{hf} augmented by the iceberg trade cost τ for exporters: exporting q_{hf} requires producing τq_{hf}, with $\tau > 1$. Total and variable labor inputs, l_{hf} and l^v_{hf}, are related by

$$l_{hf}(\phi) = l^v_{hf}(\phi) + f_{hf} = \frac{\tau q_{hf}}{\phi} + f_{hf}. \tag{3.4}$$

As mentioned earlier, the fixed access cost to the export market f_{hf}, is added to the production fixed cost f_{hh}. Both fixed costs are measured in terms of labor.

As in Kreickemeier and Richter (2014), production creates emissions as an additional output besides the final consumption goods[2], and we assume, realistically, that international transportation

[2] Equivalently, we can assume a Leontieff production function where emissions are treated as an input beside labor: $q_{hf}(\phi) = \frac{1}{\tau} \min \left\{ l^v_{hf}\phi, \frac{e_{hf}}{\delta(\phi)} \right\}$.

generates emissions as well. Emissions e_{hf} from export production read

$$e_{hf}(\phi) = \delta_h(\phi)\tau q_{hf}(\phi). \tag{3.5}$$

Here $\delta_h(\phi)$ is the emission intensity of a firm with productivity level ϕ. We follow Kreickemeier and Richter (2014) and assume that emission intensity is linked to the firm's productivity level

$$\delta_h(\phi) = \delta_h \phi^{-\alpha}. \qquad \alpha > 0$$

The positive parameter $\delta_h > 0$ represents the degree of technology cleanliness at Home. The parameter α describes the strength of the link between productivity and emission intensity. In line with the empirical findings of Batrakova and Davies (2012) and Forslid et al. (2014), we assume throughout this paper that more productive firms are more environmentally friendly than less productive ones: they use their emissions more efficiently. Therefore, we restrict our analysis to positive values of $\alpha > 0$. Kreickemeier and Richter (2014) noted that in the special case of $\alpha = \sigma$, the reduction in emission intensity for more productive firms is strong enough to compensate their higher output entirely, and the total emissions of a firm do not depend on its productivity level.

3.2.1 Taxation and pricing

We assume that the Home and Foreign governments can introduce per emission unit carbon taxes Z_h and Z_f respectively. If one country does not implement a carbon tax, or introduces a very low one, carbon leakage and distortions in international competitiveness may emerge due to the asymmetry in the implemented tax rates across countries. In such a situation, the country with a stricter carbon tax may impose a Border Carbon Adjustment (BCA) or a Border Tax Adjustment (BTA) to mitigate the leakage and the distortion partially or entirely. A BCA of level X_h imposed by Home is a specific tax on the carbon content of imports designed to complement the Foreign carbon tax Z_f, or to be a substitute for it if it is absent[3]. A BTA of level t_h by Home is a tariff levied on the border price of Foreign's exports. The proceeds from a tax or border adjustments are paid back to consumers as a lump sum transfers.

Let p^c_{hf} and p_{hf} be, respectively, the consumer and producer prices of a good produced at Home and sold at Foreign.

Under monopolistic competition, the profit maximizing consumer price is a mark-up on the unit cost,

$$p^c_{hf} = \left(\frac{\tau}{\rho} c_{hf}\right).$$

The unit production cost c_{hf} reads

$$c_{hf}(\phi) = \begin{cases} \frac{w_h}{\phi} + (Z_h + X_f)\delta_h \phi^{-\alpha}, & \text{if BCA,} \\ (1 + t_f)\left[\frac{w_h}{\phi} + Z_h \delta_h \phi^{-\alpha}\right], & \text{if BTA.} \end{cases} \tag{3.6}$$

Here w_h denotes Home's wage. Resulting profits π_{hf} for a firm with productivity ϕ are proportional to the expenditures r^c_{hf} on that good

$$\pi_{hf}(\phi) = \begin{cases} (\frac{1}{\sigma}) r^c_{hf}(\phi) - w_h f_{hf}, & \text{if BCA,} \\ \frac{1}{\sigma(1+t_f)} r^c_{hf}(\phi) - w_h f_{hf}, & \text{if BTA.} \end{cases} \tag{3.7}$$

The cutoff productivity ϕ^*_{fh} below which an exporting firm makes a negative profit, and therefore it prefers not to export, satisfies the following relation:

$$r^c_{hf}(\phi^*_{hf}) = \begin{cases} \sigma w_h f_{hf}, & \text{if BCA,} \\ \sigma(1 + t_f) w_h f_{hf}, & \text{if BTA.} \end{cases} \tag{3.8}$$

Here $r^c_{hf}(\phi^*_{hf})$ denotes consumer's expenditures on a good produced by the marginal exporting firm at Home with productivity level ϕ^*_{hf}.

[3] We assume that the emission intensity of production across countries is common knowledge.

3.2.2 Equilibrium conditions

In this subsection we derive and describe the conditions that determine the equilibrium in this model. Regarding demand, standard Dixit-Stiglitz homogeneity properties lead to the following equalities:

$$\left(\frac{q_{hf}(\phi)}{q_{hf}(\phi^*_{hf})}\right)^{1-1/\sigma} = \frac{r^c_{hf}(\phi)}{r^c_{hf}(\phi^*_{hf})} = \left(\frac{p^c_{hf}(\phi)}{p^c_{hf}(\phi^*_{hf})}\right)^{1-\sigma} = \left(\frac{c_{hf}(\phi)}{c_{hf}(\phi^*_{hf})}\right)^{1-\sigma} \stackrel{def}{=} \theta_{hf}(\phi). \tag{3.9}$$

Here $\theta_{hf}(\phi)$ denotes a profitability index of a firm with productivity level ϕ, as compared to the cutoff marginal firm with productivity ϕ^*_{hf}. As stressed by Melitz, a more productive firm has lower production costs and charges a lower price, along with having higher output and revenue.

We turn now to describe average quantities. In the Melitz case, without taxes, we have $\theta_{hf}(\phi) = \left(\frac{\phi}{\phi^*_{hf}}\right)^{\sigma-1}$ and we need only to calculate the average $\bar{\theta}_{hf}$ which, moreover, is constant when the productivity distribution takes a Pareto form. In our case however, things are more complicated and for each trade pattern, such as from Home to Foreign, we have to calculate two averages numerically. The average unit cost $\bar{c}_{hf}$ reads

$$\bar{c}_{hf} \stackrel{def}{=} \left[\int_{\phi^*_{hf}}^{\infty} c_{hf}(\phi)^{1-\sigma}\frac{g(\phi)}{1-G(\phi^*_{hf})}d\phi\right]^{1/(1-\sigma)}. \tag{3.10}$$

It determines the average relative profitability $\bar{\theta}_{hf}$, which reads

$$\bar{\theta}_{hf} \stackrel{def}{=} \int_{\phi^*_{hf}}^{\infty} \theta_{hf}(\phi)\frac{g(\phi)}{1-G\left(\phi^*_{hf}\right)}d\phi. \tag{3.11}$$

We also define the share of environmental taxes in the unit cost:

$$\lambda_{hf}(\phi) = \begin{cases} \frac{(Z_h+X_f)\delta_h\phi^{-\alpha}}{\left[\frac{w_h}{\phi}+(Z_h+X_f)\delta_h\phi^{-\alpha}\right]}, & \text{if BCA,} \\ \frac{Z_h\delta_h\phi^{-\alpha}}{\left[\frac{w_h}{\phi}+Z_h\delta_h\phi^{-\alpha}\right]}, & \text{if BTA.} \end{cases}$$

and its corresponding average $\bar{\lambda}_{hf}$ reads

$$\bar{\lambda}_{hf} \stackrel{def}{=} \int_{\phi^*_{hf}}^{\infty} \lambda_{hf}(\phi) \frac{\theta_{hf}(\phi)}{\bar{\theta}_{hf}} \frac{g(\phi)}{1 - G\left(\phi^*_{hf}\right)} d\phi.$$

From (3.9), we get the following relations between averages:

$$\left(\frac{\bar{q}_{hf}}{q_{hf}(\phi^*_{hf})}\right)^{1-1/\sigma} = \frac{\bar{r}^c_{hf}}{r^c_{hf}(\phi^*_{hf})} = \left(\frac{\bar{p}^c_{hf}}{p^c_{hf}(\phi^*_{hf})}\right)^{1-\sigma} = \left(\frac{\bar{c}_{hf}}{c_{hf}(\phi^*_{hf})}\right)^{1-\sigma} = \bar{\theta}_{hf}. \tag{3.12}$$

The cutoff condition (3.8) then yields

$$\bar{r}^c_{hf} = \sigma \bar{\theta}_{hf} w_h f_{hf}, \qquad \bar{r}^c_{hh} = \sigma \bar{\theta}_{hh} w_h f_{hh}. \tag{3.13}$$

Average emissions $\bar{e}_{hf}$ and the average variable labor input $\bar{l^v_{hf}}$, as well as the average firm revenue $\bar{r}_{hf}$, read

$$\left(Z_h + X_f\right) \bar{e}_{hf} = \rho \bar{\lambda}_{hf} \bar{r}^c_{hf}, \quad w_h \bar{l}^v_{hf} = \rho \left(1 - \bar{\lambda}_{hf}\right) \bar{r}^c_{hf}, \quad \bar{r}_{hf} = \left(1 - \rho \bar{\lambda}_{hf}\right) \bar{r}^c_{hf}, \tag{3.14}$$

in the BCA case, and

$$(1+t_f) Z_h \bar{e}_{hf} = \rho \bar{\lambda}_{hf} \bar{r}^c_{hf}, \quad (1+t_f) w_h \bar{l}^v_{hf} = \rho \left(1 - \bar{\lambda}_{hf}\right) \bar{r}^c_{hf}, \quad \bar{r}_{hf} = \left(1 - \rho \bar{\lambda}_{hf}\right) \frac{\bar{r}^c_{hf}}{1+t_f}, \tag{3.15}$$

in the BTA case.

Utility maximization leads to the following demand functions for average quantities $\bar{q}$:

$$\bar{q}_{hh} = \frac{R^c_h}{\left(M_h + M_{fh}\right) P^c_h} \left(\frac{\bar{p}^c_{hh}}{P^c_h}\right)^{-\sigma}, \qquad \bar{q}_{fh} = \frac{R^c_h}{\left(M_h + M_{fh}\right) P^c_h} \left(\frac{\bar{p}^c_{fh}}{P^c_h}\right)^{-\sigma}.$$

Here R_h^c represents the income of the representative consumer at Home, including the redistributed tax revenue, while P_h^c denotes the aggregate price index at Home:

$$R_h^c = M_h \bar{r}_{hh}^c + M_{fh} \bar{r}_{fh}^c,$$

$$\left(P_h^c\right)^{1-\sigma} = \frac{M_h \left(\bar{p}_{hh}^c\right)^{1-\sigma} + M_{fh}(\bar{p}_{fh}^c)^{1-\sigma}}{M_h + M_{fh}}.$$

The resulting utility from consumption, that is, the non-green component of welfare, can be rewritten as:

$$U_h = M_h^v \left(\frac{R_h^c}{P_h^c}\right).$$

It is proportional to the consumer's real income $I_h = \left(\frac{R_h^c}{P_h^c}\right)$ and it reflects the utility benefits from product variety represented by the total number $M_h^v = \left(M_h + M_{fh}\right)^{1/(\sigma-1)}$ of goods, both domestic and imported, to which the consumer has access.

The demand choice between imported and domestically produced goods is expressed by the following condition:

$$\frac{\bar{r}_{fh}^c}{\bar{r}_{hh}^c} = \left(\frac{\tau \bar{c}_{fh}}{\bar{c}_{hh}}\right)^{1-\sigma}. \tag{3.16}$$

As average values are proportional to cutoff values, a similar condition holds for cutoff levels:

$$\frac{w_f f_{fh}}{w_h f_{hh}} = \left(\frac{\tau c_{fh}(\phi_{fh}^*)}{c_{hh}(\phi_{hh}^*)}\right)^{1-\sigma}. \tag{3.17}$$

From (3.7), (3.13), and (3.12) profits can be rewritten as: $\pi_{hf} = \left[\bar{\theta}_{hh} - 1\right] f_{hf}$. Free-entry condition requires that expected profit, including the entry cost f^e (measured in units of labor), should equal zero, that is

$$(1 - G(\phi_{hh}^*)) \left[\bar{\theta}_{hh} - 1\right] f_{hh} + (1 - G(\phi_{hf}^*)) \left[\bar{\theta}_{hf} - 1\right] f_{hf} - f^e = 0. \tag{3.18}$$

Total firm revenue is, therefore, equal to total wages, i.e. $M_h \bar{r}_{hh} + M_{hf} \bar{r}_{hf} = w_h L_h$, that is

$$M_h \sigma \left[(1 - \rho \bar{\lambda}_{hh}) \bar{\theta}_{hh} f_{hh} + m_{hf} (1 - \rho \bar{\lambda}_{hf}) \bar{\theta}_{hf} f_{hf} \right] = L_h. \tag{3.19}$$

Together with the free-entry condition (3.18), condition (3.19) implies equilibrium of the labor-market[4].

Finally, the trade-balance condition states that the values of exports and imports, measured at border prices, are equal

$$M_{hf} \bar{r}^b_{hf} = M_{fh} \bar{r}^b_{fh} \tag{3.20}$$

The border values of exports $\bar{r}^b_{hf}$ and $\bar{r}^b_{fh}$ include taxes paid in the exporting country and excludes the BCA/BTA paid in the importing country. These values read

$$\bar{r}^b_{hf} = \begin{cases} \left(1 - \rho \frac{X f}{Z_h + X_f} \bar{\lambda}_{hf}\right) \bar{r}^c_{hf}, & \text{if BCA,} \\ \frac{\bar{r}^c_{hf}}{(1+t_f)}, & \text{if BTA.} \end{cases} \tag{3.21}$$

The labor market condition (3.19) and its symmetric relation for Foreign, determine the numbers of active firms across countries, M_h and M_f. We are left with a system of five conditions: the *demand condition (3.17)* and the *free-entry condition (3.18)*, along with their analogous conditions for Foreign, and the *trade-balance condition (3.20)*. These five conditions determine the four cutoffs productivity levels (ϕ^*_{hh}, ϕ^*_{ff}, ϕ^*_{hf}, ϕ^*_{fh}) and the relative wage between countries w_h after normalizing the wage in Foreign to $w_f = 1$.

3.3 Methodology

We study several cases of policy configurations across countries to analyze carbon leakage and distortions in international competitiveness. We provide an analytical solution whenever possi-

[4] The labor market condition follows from these two conditions and is

$$M_h \left[\rho\sigma \left(1 - \bar{\lambda}_{hh}\right) \bar{\theta}_{hf} + 1 \right] w_h f_{hh} + M_{hf} \left[\rho\sigma \left(1 - \bar{\lambda}_{hf}\right) \bar{\theta}_{hf} + 1 \right] w_h f_{hf} + M^e_h f^e = L_h$$

ble. Due to the complexity of our model, we resort to numerical analysis in the remaining part. We describe in this section the calibration of the model parameters. Results of different policy configurations are presented in the subsequent section.

3.3.1 Calibration

We present in this subsection the calibration of the key parameters of our model, in order to quantify the importance of firm level heterogeneity on global pollution, international competitiveness, and welfare.

We assume that productivity levels are Pareto distributed, that is $G_h(\phi) = 1 - (\frac{b_h}{\phi})^{\beta}$, where b_h denoting the lowest possible productivity draw, and $\beta > 2$ is a shape parameter. We maintain the Pareto assumption throughout the analysis. We use as a benchmark an equilibrium with symmetric countries, free trade, and no climate policy in any country. Countries are assumed to have the same minimum productivity level $b_h = b_f = 1$, and the same labor endowments $L_h = L_f = 1$.

We follow Felbermayr et al. (2013) and choose a parameterization such that the symmetric model replicates the United States' stylized facts. We match the export participation rate which is reported by Bernard et al. (2003) to average around 20% for the US in the period 1990-2000. As in Felbermayr et al. (2013) and in line with Bernard et al. (2003), we set the elasticity of substitution $\sigma = 3.8$, the shape parameter β to 4, the iceberg trade cost τ (natural barriers to trade) to 1.3, and the fixed cost of serving foreign markets relative to the fixed cost of serving domestic ones $\frac{f_{hf}}{f_{hh}}$ to 1.6. After examining the findings of related studies, Cook et al. (2012) suggest that, in general, in the first year of existence, a range of about 19% to 22% of firms exit the market. Accordingly, we choose the sunk entry cost f^e such that the ratio of the number of active firms relative to the number of potential entrants $\frac{M_h}{M_h^e}$ equals 0.77, which yields $f^e = 2.3$

Following Kreickemeier and Richter (2014), we assume that firm-specific emission intensity decreases with its productivity level. Therefore, we assign a positive value to the parameter α. Forslid et al. (2014) reported empirically that exporting firms emit on average around 12% less per unit of output than firms which only serve domestic markets, active in the same industry. Under the described calibration, average productivity between exporting and non-exporting firms increase by $\frac{\bar{\phi}_{hf}-\bar{\phi}_{hh}}{\bar{\phi}_{hh}} = 53.7\%$, which yields an elasticity $\alpha = \frac{12\%}{53.7\%} = 0.22$. For illustrative purposes and in order to give the reader a complete overview for policy effects, we report also the results for a case when firm-specific emission intensity is strongly decreasing with its productivity level, that is when $\alpha > 1$. In such case, we use $\alpha = 1.3$ in the calibration. Accordingly, we set $\delta_i = 0.28$, where i is a country index $i \in \{h, f\}$, when $\alpha < 1$, and $\delta_i = 1.12$ when $\alpha > 1$, such that we keep the emission to GDP ratio constant between the two cases in the free trade benchmark, which equals 67%[5].

The damage function is assumed to have a quadratic form, that is $\epsilon = 2$. Finally, the weight of environmental quality in welfare is estimated such that the weight of green relative to non green welfare equals 9% , which yields $\eta = 0.05$. The benchmark calibration is summarized in Table 3.1 of Appendix 3.6.1.

3.4 Results

In this section, we introduce the main results of our model. We start by investigating analytically the case of a closed economy which illustrates the effects of a carbon tax in Autarky. When there is trade between countries, we use the case of free trade and no climate policy in any country as a benchmark. We analyze a case of symmetric open economies to study possible leakages when there are symmetric carbon taxes across countries (global carbon tax). We run afterwards numerical simulations to investigate the effect of a unilateral carbon tax at Home on firms across the productivity spectrum. Finally, we analyze the main differences between a BCA and a BTA on tackling carbon leakage and mitigating the distortion in international competitiveness.

[5] This ratio reflects the United States' average CO2 emissions (kg per PPP $ of GDP) for the period 1990-2000 (WorldBank (2017))

3.4.1 Autarky and symmetric open economies

The case of a closed economy (Autarky)

In order to better understand the impact of a carbon tax, we start by considering in this subsection the Autarky case. The equilibrium in this case is determined by the free-entry and labor-market conditions, which read for Home:

$$(1 - G(\phi^*_{hh}))(\bar{\theta}_{hh} - 1) f_{hh} = f^e, \tag{3.22}$$

$$M_h(1 - \rho\bar{\lambda}_{hh})\bar{\theta}_{hh}\sigma f_{hh} = L_h. \tag{3.23}$$

Condition (3.22) determines the cutoff productivity ϕ^*_{hh}. Any decrease in profitability $(\bar{\theta}_{hh} - 1)$, resulting for instance from a higher carbon tax, requires an increase of the probability of successful entry $(1 - G(\phi^*_{hh}))$ in order to maintain expected profit equal to the entry cost: less productive firms enter the market. Condition (3.23) describes the labor market equilibrium and determines the number M^e_h of potential entrants which goes down.

These results may seem surprising and counter-intuitive but they are consistent with the entry dynamics. For a given number M^e_h of potential entrants, labor market equilibrium determines the equilibrium cutoff as an increasing function $\phi^*_{hh} = \Phi^*_{hh}(M^e_h)$: in order to maintain full employment, a lower number of potential entrants has to be compensated by an increase of the probability of successful entry. Average profit is given by the left hand side of (3.22) which we denote by $\Pi(\phi^*_{hh}, Z_h)$. It is decreasing in ϕ^*_{hh} such that a decrease in the cutoff increases the probability of successful entry. It is of course a decreasing function of the carbon tax Z_h.

The entry dynamics may then be represented by the following equation[6], with an adjustment speed μ:

$$\dot{M}^e_h = \mu\Pi(\Phi^*_{hh}(M^e_h), Z_h).$$

[6] As $\bar{\theta}$ depends on Z_h and ϕ^*_{hh}, a more rigorous analysis should be developed.

For an initial equilibrium number of potential entrants, a tax increase affects profits negatively and induces a decrease of the number of potential entrants, accompanied by an increasing probability of successful entry, and therefore, a decrease of the cutoff. This leads to a new equilibrium with lower M_h^e and ϕ_{hh}^*. An increase of the carbon-tax thus induces more polluting firms to enter.

If the parameter α, which captures the strength of the link between productivity and emission intensity, equals 1, then $\theta_{hh} = (\frac{\phi_{hh}}{\phi_{hh}^*})^{\sigma-1}$ does not depend on Z_h. Its average $\bar{\theta}_{hh}$ does not depend on Z_h either, and remains constant when ϕ_{hh}^* changes, when the distribution is Pareto.

When Z_h increases, then from (3.9) we have

$$\theta_{hh}^{1/(1-\sigma)} = \frac{\frac{w_h}{\phi_{hh}} + \frac{\delta_h Z_h}{(\phi_{hh})^\alpha}}{\frac{w_h}{\phi_{hh}^*} + \frac{\delta_h Z_h}{(\phi_{hh}^*)^\alpha}},$$

which increases if $\alpha < 1$, and decreases when $\alpha > 1$, while the average $\overline{\theta}_{hh}$ does the contrary.

The share λ_{hh} of the carbon tax in the unit cost goes up with Z_h. It also does not depend on ϕ_{hh}^* when $\alpha = 1$. However, when ϕ_{hh}^*, the share λ_{hh} increases, if $\alpha < 1$, and decreases when $\alpha > 1$. The average $\bar{\lambda}_{hh}$ therefore always increase with Z_h; it increases with ϕ_{hh}^* , if $\alpha < 1$, and decreases when $\alpha > 1$.

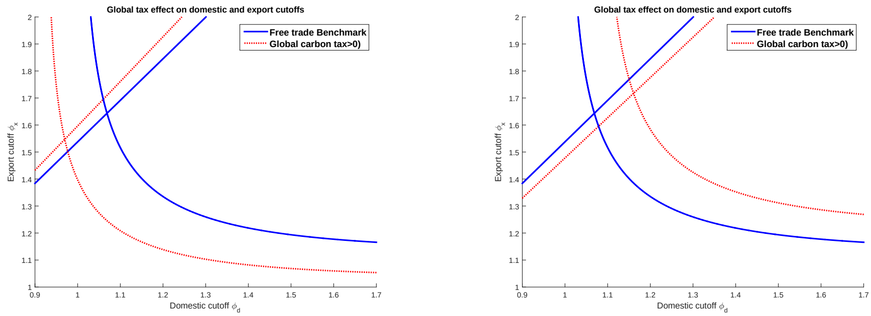
Symmetric open economies

We consider in this subsection two identical economies[7] having the same domestic and export cutoffs, ϕ_d^* and ϕ_x^*. Subscripts d and x denote respectively domestic and export quantities. The equilibrium is characterized by two relations, the free-entry condition (3.18) and the demand condition (3.17), which determine the two cutoffs. Those conditions can be rewritten as:

$$(1 - G(\phi_d^*)) \left[\bar{\theta}_d - 1\right] f_d + (1 - G(\phi_x^*)) \left[\bar{\theta}_x - 1\right] f_x - f^e = 0, \tag{3.24}$$

$$\frac{f_x}{f_d} = \left(\frac{\tau c_x(\phi_x^*)}{c_d(\phi_d^*)}\right)^{1-\sigma}. \tag{3.25}$$

[7] The logic is the same as in Melitz (2003) who considers a given number of identical countries.



(a) $\alpha < 1$ (b) $\alpha > 1$

Figure 3.1: Effect of global carbon tax on domestic and export cutoffs

Figure (3.1) pictures the determination of the equilibrium and the effects of a global increase of the carbon-tax ($Z_h = Z_f = Z > 0$) , under the benchmark calibration, for the cases $\alpha < 1$ and $\alpha > 1$ respectively. The horizontal axes depicts the domestic cutoff productivity level, while the exporting cutoff productivity level is plotted on the vertical axes.

When firm specific emission intensity is weakly decreasing with its productivity level, i.e. $\alpha < 1$, a higher global carbon tax induces the entry of less productive firms, both in domestic and export markets: the downward sloping free entry curve shifts toward the origin. But the demand effects play against exports: the upward sloping demand curve shifts up and left. An increase of the global carbon tax rate leads therefore to a decrease of both ϕ_d^* and ϕ_x^*. The equilibrium in Panel 3.1a of Figure shifts from the intersection of the solid curves to a new equilibrium where the dotted curves intersect.

The reason for this bias is that more productive firms are more sensitive to the tax when $\alpha < 1$. This is a little surprising, as more productive firms pollute less. But the *relative* impact of the carbon tax on the unit cost increases[8] with ϕ if $\alpha < 0$. The cost ratio $\frac{c_x}{c_d}$ therefore increases when

[8] We have:

$$c = \frac{w}{\phi} + Z\delta_0\phi^{-\alpha} = (\frac{w}{\phi})\left(1 + Z\delta_0\phi^{1-\alpha}\right)$$

which implies:

$$\frac{dc}{c} = \frac{\delta_0}{\phi^{\alpha-1} + \delta_0 Z}dZ$$

the tax Z increases. The higher α, the lower is this effect. It disappears in the case $\alpha = 1$, when the relative cost is not affected by the tax.

The $\alpha = 1$ case is indeed very special. In the absence of BCAs and BTAs across countries, the unit cost for an exporting firm is $c_{hf}(\phi) = [w_h + Z_h\delta_h]\,\phi^{-1}$, for all firms, regardless of their productivity level. An increase of the carbon tax has the same effect as an increase of the wage. At the world market equilibrium, the only effect of an increase of the carbon tax in one country is a decrease of the local wage rate, leaving unchanged unit costs and therefore also production, exports and emissions levels. In this Ricardian world, where all goods are produced with a given labor endowment, production remains the same and climate policy has no impact on emissions.

When emission intensity is strongly decreasing with productivity level, that is when $\alpha > 1$, a higher global carbon tax induces the exit of least productive firms in the domestic and export markets. This is illustrated in Panel 3.1b; the free entry curve shifts outwards; the demand curve shifts downwards and to the right. The global carbon tax rate induces an increase of both cutoffs, ϕ_d^* and ϕ_x^*. In this case, the tax hit less productive firms harder and the *relative* impact of the carbon tax on the unit cost decreases with ϕ.

Regardless of the value of α, a global carbon tax has a symmetric negative effect on non green welfare across countries mainly through a decrease in real income. The net effect on welfare is however positive as the gain in welfare from a lower pollution levels outweighs the utility loss.

3.4.2 A unilateral carbon tax at Home and possible leakages

In this subsection, we analyze the effect of a unilateral carbon tax at Home on the main variables and we investigate the possibility of carbon leakage. Therefore, we focus on how Foreign emissions are affected when Home implements a unilateral carbon tax.

Let the cost ratio $\kappa_f = \frac{\bar{c}_{hh}}{\tau\bar{c}_{fh}}$ be a measure of the external competitiveness of Foreign. The internal competitiveness of Foreign is the inverse of Home's external competitiveness. The unilateral carbon tax at Home increases these two cost ratios. From (3.16), the relative country average

which increases with ϕ, as $\alpha - 1$ is negative when $\alpha < 1$.

expenditures and production in its domestic and export markets read:

$$\frac{\overline{r}^c_{fh}}{\overline{r}^c_{hh}} = \left(\kappa_f\right)^{\sigma-1}, \qquad \frac{\bar{q}_{fh}}{\bar{q}_{hh}} = \left(\kappa_f\right)^{\sigma},$$

$$\frac{\overline{r}^c_{ff}}{\overline{r}^c_{hf}} = (\kappa_h)^{1-\sigma}, \qquad \frac{\bar{q}_{fh}}{\bar{q}_{hh}} = (\kappa_h)^{-\sigma}.$$

These properties suggest the possibility of leakage as Home's carbon tax increases Foreign's competitiveness and induces this country to produce more. A more precise analysis is required, however.

When Foreign does not face any tax, i.e. when $Z_f = X_h = t_h = 0$, its producer costs are simply $\frac{w_f}{\phi}$ and we are back to Melitz's analysis. For the description of Foreign's behavior, we may then examine analytically how it reacts to given changes in the cutoffs. These cutoffs are of course endogenous and have to be determined by solving for the complete equilibrium, but examining their impact provides useful information.

The average cost is $\bar{c}_{fh} = \frac{w_f}{\bar{\phi}_{fh}}$, where average labor productivity reads:

$$\bar{\phi}_{fh} = \left[\int_{\phi^*_{hf}}^{\infty} \phi^{\sigma-1} \frac{g(\phi)}{1-G\left(\phi^*_{fh}\right)} d\phi\right]^{1/(\sigma-1)}.$$

Assuming a Pareto distribution with a shape parameter β, we are back to the Melitz formula[9]:

$$\bar{\phi}_{fh} = (\theta_0)^{1/(\sigma-1)} \phi^*_{hf}, \qquad \text{with} \qquad \theta_0 = \frac{\beta}{(\beta-\sigma+1)}. \tag{3.26}$$

Average emissions at Foreign are:

$$\bar{e}_{ff} = \rho \bar{\lambda}^s_{ff} \overline{r}^c_{ff}, \qquad \bar{e}_{fh} = \rho \bar{\lambda}^s_{fh} \overline{r}^c_{fh}.$$

[9] We prove in Appendix 3.6.2 that $\bar{\phi}_{fh}$ is equal to the technical coefficient $\tilde{\phi}_{fh}$, giving the labor input.

Here $\bar{\lambda}^s_{ff}$ and $\bar{\lambda}^s_{fh}$ follow from $\bar{\lambda}_{ff}$ and $\bar{\lambda}_{fh}$. After simplifying by $Z_f = 0$ in domestic market or by $Z_f + X_h = 0$ in Foreign's exporting market, we obtain

$$\bar{r}^c_{ff} = \sigma\theta_0 w_f f_{ff}, \qquad \bar{r}^c_{fh} = \sigma\theta_0 w_f f_{fh},$$

$$\bar{\lambda}^s_{ff} = \left(\frac{\delta_f}{w_f}\right)\left(\frac{\theta_a}{\theta_0}\right)\phi^{*(1-\alpha)}_{ff}, \qquad \bar{\lambda}^s_{fh} = \left(\frac{\delta_f}{w_f}\right)\left(\frac{\theta_a}{\theta_0}\right)\phi^{*(1-\alpha)}_{fh},$$

with $\theta_a = \beta/\left(\alpha + \beta - \sigma\right)$.

Average consumer expenditures $\bar{r}^c_{ff}$ and $\bar{r}^c_{fh}$ do not change when the cutoffs change[10]. On the other hand, both $\bar{\lambda}^s_{ff}$ and $\bar{\lambda}^s_{fh}$ are increasing functions of the relevant cutoff when $\alpha < 1$, and become decreasing functions if $\alpha > 1$.

The simulated model shows that Home's unilateral carbon tax induces a decrease in Foreign's domestic cutoff ϕ^*_{ff} and an increase in it export cutoff $\phi^*_{fh}$when $\alpha < 1$. In the case of $\alpha > 1$, we find that ϕ^*_{ff} goes up and ϕ^*_{fh} becomes lower. Therefore, average domestic emissions $\bar{e}_{ff}$ decrease, while $\bar{e}_{fh}$ increase, which again suggest a leakage in emissions in the exporting market, regardless of the value of α.

Taking into account the masses of active firms, Foreign's aggregate emissions read:

$$E_{ff} = M_f\bar{e}_{ff}, \qquad E_{fh} = M_{fh}\bar{e}_{fh},$$

with:

$$M_f = \frac{L_f}{\sigma\left[f_{ff} + m_{fh}f_{fh}\right]\theta_0}, \qquad M_{fh} = m_{fh}M_f.$$

Foreign's export participation rate $m_{fh}(\phi^*_{fh}, \phi^*_{ff})$ decreases when $\alpha < 1$, which implies that the total number M_f of active firms increases, but the number M_{fh} of exporting firms decreases. Therefore, in this case, the evolution of aggregate emissions from Foreign's domestic and export markets, and thus its total emissions, is ambiguous.

[10] This result is obtained because we normalize w_f to 1, so that Z_h is actually $\frac{Z_h}{wf}$. However $\frac{Z_f}{w_h}$ also increases and we may consider that we study an increase, of a different amount, of $\frac{Z_f}{w_h}$.

When $\alpha > 1$, we have an increase in m_{fh}, a decrease in M_f , and an increase in M_{fh} . In this case, there is a leakage in Foreign's export market, as E_{fh} increase, but the evolution of emissions from its domestic market E_{ff} is negative. The overall net effect on Foreign emissions depends on the magnitude of these effects. The leakage may vanish, and Foreign's emissions may as well decrease.

Effects of Home's unilateral carbon tax across the productivity spectrum

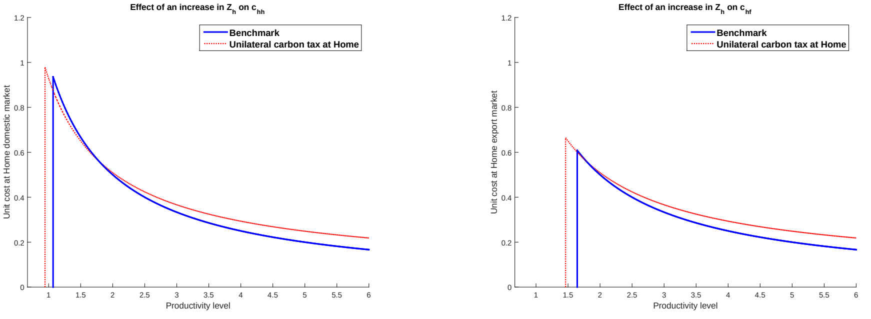
In this subsection we analyze the impacts of a unilateral carbon tax across productivity level. More precisely, we track how firms along the productivity spectrum are affected by a carbon tax. We differentiate in our model between four markets, a domestic and export market for each country. A carbon tax or a border adjustment implemented by any country would have an impact on firms operating in these markets. We shall see that these policies may induce different effects on operating firms depending on the strength of the link between firm-specific emission intensity and its productivity level.

Unit cost

We start by describing the effects of Home's unilateral carbon tax Z_h on the unit cost of firms across countries, starting from a free trade benchmark with no climate policy in any country. Panel 3.2a of Figure 3.2 depicts changes in the unit cost for Home domestic market across the productivity spectrum when α is assumed to be smaller than 1. Panel 3.2b shows the effect on Home's exporting firms. In this Figure, the unit cost is depicted on the vertical axes and the productivity level ϕ on the horizontal one. The solid curve represents the benchmark, while the dotted curve plots the case of Home's unilateral carbon tax $Z_h > 0$.

In the absence of border adjustments, the unit cost of an exporting firm at Home with productivity level ϕ become

$$c_{hf}(\phi) = \frac{w_h}{\phi} + \frac{Z_h \delta_h}{\phi^\alpha}$$



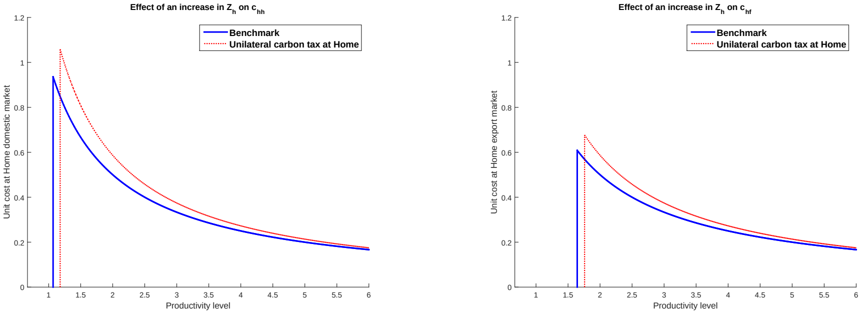
(a) Domestic unit cost

(b) Exporting unit cost

Figure 3.2: Effect of Home's unilateral carbon tax on its unit cost when ($\alpha < 1$)

Following an increase in Z_h, we can differentiate two effects on this unit cost: a direct positive tax effect and a indirect negative wage effect. A carbon tax at Home reduces, in average, labor demand and induces the relative wage w_h between countries to go down. As mentioned in subsection (3.4.1), as long as firm-specific emission intensity decreases weakly with its productivity level ($\alpha < 1$), the *relative* effect of the tax is higher for most productive firms, and the share of the carbon tax in the unit cost λ_{hh} is an increasing function of ϕ. Accordingly, the net tax-wage effect on the unit cost becomes asymmetric across firms with different productivity levels, such that for more productive firms the tax effect dominates and the unit cost increases. This is reflected by the upward shift in the unit cost curve on the right hand side of Panel 3.2a, while for least productive firms the wage effect dominates inducing a reduction in the unit cost, which is reflected by downward shift in the unit cost curve for least productive firms close to the marginal firm. At the same time, Figure 3.2 illustrates the downward shift of the cutoff productivity levels in both markets, and the entrance of less productive, more polluting, firms to domestic and export markets as discussed in the previous subsection.

As mentioned in section (3.4.1), the unit cost of Foreign's operating firms is not affected by the unilateral carbon tax introduced at Home. Wages at Foreign do not change because w_f is normalized to 1 in our benchmark. The only effect of Home's unilateral carbon tax is on Foreign's



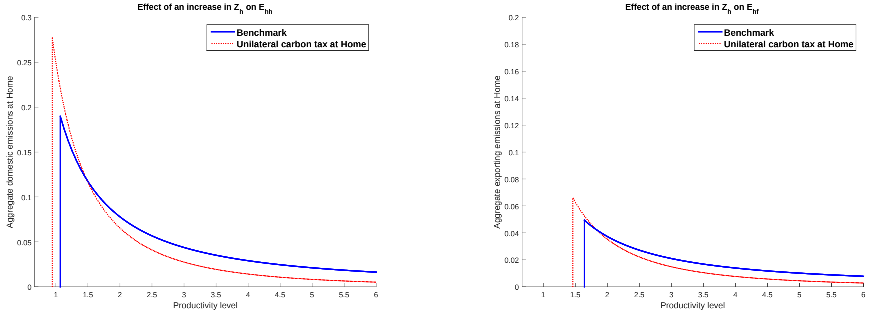
(a) Domestic unit cost (b) Exporting unit cost

Figure 3.3: Effect of Home's unilateral carbon tax on its unit cost when ($\alpha > 1$)

cutoff productivity levels. These cutoffs go up in the export market and down in the domestic one, allowing more firms to enter Foreign's domestic market, while the least productive among Foreign's exporting firms stop exporting.

Figure 3.3 illustrates the case when firm specific emission intensity is strongly decreasing with its productivity level, i.e. $\alpha > 1$. In this case, the tax effect on the unit cost dominates the wage effect for all firms. Moreover, less productive firms are the ones more strongly hit by the tax, since the share of the carbon tax in the unit cost λ_{hh} becomes a decreasing function of ϕ. Therefore, both cutoffs at Home increase which lead least productive firms to exit both markets. Panels 3.3a and 3.3b show these effects across the productivity spectrum in, respectively, Home's domestic and export markets. The tax effect becomes weaker for more productive firms as we move from the left to the right. Foreign's cutoffs increase in domestic markets and decrease in exporting ones, decreasing the number of active firms while some firms start exporting.

The aforementioned results suggest that, depending on the value of α, the carbon tax induces a reallocation of resources (labor) between firms across productivity spectrum. That is when $\alpha < 1$, resources are reallocated towards less productive firms after the increase in the carbon tax, as more productive firms are the ones hardly hit by the tax. The opposite happens when $\alpha > 1$, where the tax reallocates resources towards more productive firms.



(a) Domestic market (b) Exporting market

Figure 3.4: Effect of Home's unilateral carbon tax on its aggregate emissions ($\alpha < 1$)

Output and emissions

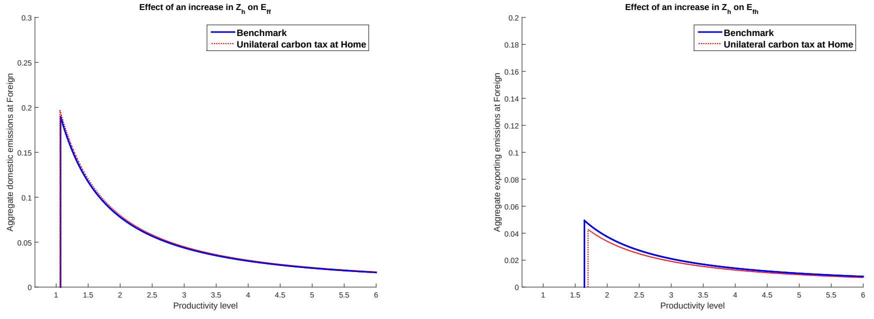
We are also interested in the distribution of produced and consumed quantities. The total quantities of goods produced by firms with productivity ϕ for the local and export markets, Q_{hh} and Q_{hf} respectively, read

$$Q_{hh}(\phi) = M_h \frac{g(\phi)}{(1 - G(\phi_{hh})} q_{hh}(\phi),$$

$$Q_{hf}(\phi) = M_{hf} \frac{g(\phi)}{(1 - G(\phi_{hf})} q_{hf}(\phi).$$

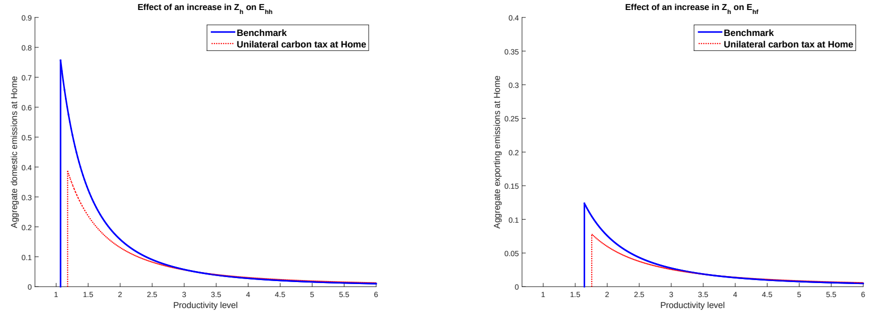
The distributions of emissions follow, as firms with the same productivity have the same emission coefficient.

Figure 3.4 depicts the effects of Home's unilateral carbon tax on its aggregate emissions across the productivity spectrum when $\alpha < 1$. Once again these effects are asymmetric across firms and follow from the aforementioned tax-wage impacts on the unit cost. Home's least productive firms raise their emissions relative to the new marginal firm, while firms at a high productivity level decrease their emissions, and this decrease is larger for more productive firms, since the relative effect of the tax is higher for these firms. This trend continues for Home's aggregate emissions $E_h = E_{hh} + E_{hf}$.



(a) Domestic market (b) Exporting market

Figure 3.5: Effect of Home's unilateral carbon tax on Foreign's aggregate emissions ($\alpha < 1$)



(a) Domestic market (b) Exporting market

Figure 3.6: Effect of Home's unilateral carbon tax on its aggregate emissions ($\alpha > 1$)

Panel 3.5a of Figure 3.5 shows that Foreign's domestic emissions increase for all firms across the productivity level, suggesting a leakage in this market. Panel 3.5b however, illustrates that Foreign's exporting firms decrease their emissions. The final net effect on Foreign's aggregate emissions across productivity level is almost null suggesting a very small leakage or even surplus depending on the quantitative effect on the emissions of Foreign's exporting firms.

When $\alpha > 1$, Home's emissions decrease for less productive firms. As resources are reallocated towards more productive firms, emissions from these firms may very well increase. Panels 3.6a and 3.6b show respectively in Home's domestic and export markets that the decrease in emissions of less productive firms is relatively higher than that of more productive firms. Foreign's emissions go down domestically and up from exporting production. Accordingly, the net effect on Foreign's aggregate emissions, and thus on the possible leakage, depends on the quantitative magnitudes of these effects.

Competitiveness

We analyze in this subsection the effects of a unilateral carbon tax on competitiveness. We distinguish between the inter-firm competitiveness in each market and international competitiveness across countries.

Profitability indices ($\bar{\theta}_{hh}$, $\bar{\theta}_{hf}$, $\bar{\theta}_{ff}$, and $\bar{\theta}_{fh}$) reflect the tax effect on inter-firm competitiveness in the corresponding market. A decrease in one of these indices following some policy shock, means that firms, on average, become less profitable relative to the marginal firm (the firm that has a productivity equals the cutoff productivity level ϕ^*), conversely, an increase in one of these indices reflects an increase in average profitability in the corresponding market. The impacts of a unilateral carbon tax on profitability across the productivity spectrum follows from the effects on the unit cost discussed in subsection (3.4.2). Accordingly, when $\alpha < 1$, firms at a low productivity level witness a rise in profitability relative to the new cutoff firm, following an increase in the carbon tax. On the other hand, more productive firms witness a downward shift in the relative profitability curve. This effect is stronger for the most productive firms. The net effect on average profitability index $\bar{\theta}$ is negative. When $\alpha > 1$, the profitability of all firm goes down, with a higher decrease for less productive firms, inducing a rise in $\bar{\theta}$.

As mentioned in subsection (3.4.2), the policy (a carbon tax or a border adjustment) effects across countries on Home's external competitiveness is captured by the ratio κ_h, and by κ_f for its internal competitiveness. The aforementioned asymmetric tax-wage effect on the unit cost when $\alpha < 1$, makes Home's least productive firms more competitive following the decrease in relative wages. Therefore, Foreign's less productive exporting firms lose in terms of international competitiveness, while its more productive firms gain. This may partially explain why some least productive exporting firms at Foreign exit the exporting market. However, the main explanation is that Foreign's exporting firms can take advantage of the increase in import prices from Home to set higher prices domestically, and thus to gain higher profits from this market. Accordingly, some of Foreign's exporting firms choose to stop exporting and to produce only for the domestic market.

The third column of Table 3.4 of Appendix 3.6.3 summarizes, for $\alpha < 1$, the relative change in the main variables due to a unilateral carbon tax at Home. These simulations show that the inter-firm profitability indices, $\bar{\theta}_{hh}$ and $\bar{\theta}_{hf}$, decrease in both markets with a higher quantitative decrease in the exporting market, as the most productive firms are the ones strongly hit by the tax in this case. The effect on Home's international competitiveness is negative as shown by the decrease in its external competitiveness index $\bar{\kappa}_h$ and the increase in $\bar{\kappa}_f$.

The third column of Table 3.6 in Appendix 3.6.3 reports these effects when $\alpha > 1$. It shows that the inter-firm profitability increases in both markets for Home following the exit of least productive firms. Home's international competitiveness decreases here as well as $\bar{\kappa}_h$ decreases and $\bar{\kappa}_f$ increases.

Note here that a global carbon tax shifts production from exporting markets towards domestic ones. The international competitiveness increases in domestic markets and decreases in exporting ones, while the effect on inter-firm competitiveness is negative in all markets when $\alpha < 1$ and becomes positive if $\alpha > 1$.

Welfare

In this subsection, we analyze the effects of Home's unilateral carbon tax on welfare across countries. The relative change in welfare components following the implementation of Home's optimal unilateral carbon tax are reported in the second column of Tables 3.5 and 3.7 of Appendix 3.6.3 respectively for the cases $\alpha < 1$ and $\alpha > 1$.

Consumers at Home enjoy higher utility from the rise in the number of varieties available for their consumption M_h^v when $\alpha < 1$, mainly because of an increase in the number of domestically produced goods M_h, as the carbon tax induces the entry of new firms to this market. When $\alpha > 1$,

M_h^v decreases as the increase in imported varieties from Foreign M_{fh} compensates for the decrease in domestic ones. Real income for Home's consumers goes down following the rise in price levels for both values of α. The net effect on non green welfare U_h is therefore negative.

When $\alpha < 1$, Foreign witnesses a rise in the number of available varieties M_f^v through domestic and imported varieties alike. When $\alpha > 1$, Foreign's consumers enjoy lower number of available varieties mainly driven by the decrease in its domestically produced varieties. Foreign's real income decreases when $\alpha < 1$ and increases when $\alpha > 1$. Accordingly, the net effect of Home's unilateral carbon tax on Foreign's utility is negative when when $\alpha < 1$ and positive when $\alpha > 1$.

Global pollution decreases in both values of α inducing a rise of green welfare that is high enough to offset any decrease in utility across countries, and therefore, both countries have a higher total welfare. Note that this increase in welfare is quantitatively higher for Foreign.

3.4.3 BTA and BCA comparison

The WTO's General Agreement on Tariffs and Trade (GATT) aims to eliminate trade barriers between members countries. However, paragraph (b) of Article XX states that WTO members can adopt policy measures inconsistent with GATT disciplines if they are necessary to protect human, plant life or animals or health. The national treatment principle of the WTO requires all members to guarantee that imports, once they have passed customs, be treated no less favourably than the similar goods produced domestically. Some economists like Cosbey (2009) argue that in order for a border adjustment to be accepted under the exception rule of the WTO, it should equal the carbon price imposed on national producers.

We mainly focused in previous subsections on analyzing the effect of a global and unilateral carbon tax. In this subsection, we analyze and compare the impacts of implementing either a BTA or a BCA on leakage, competitiveness, and welfare. Any country that opts to implement a carbon tax or a border adjustment is assumed to be able to calculate and implement the rates that maximizes its welfare. Therefore, we use these optimal rates to run simulations for different scenarios of policy mix across countries. We compare scenarios of a unilateral carbon tax at

Home complemented by a BCA with a scenario where it is complemented by a BTA, in order to investigate and compare the main effects of these adjustments on key variables. The optimal rates under different scenarios can be found in Tables 3.2 and 3.3 of Appendix 3.6.3 for $\alpha < 1$ and $\alpha > 1$ respectively.

Difference between BCA and BTA effects

We analyze in this subsection the difference between BCA and BTA effects on cutoffs, averages, aggregates and welfare. Tables 3.4 – 3.7 of Appendix 3.6.3 report the relative change of these quantities for $\alpha < 1$ and $\alpha > 1$. In all scenarios, Foreign is assumed to remain passive. The fourth column of these tables summarizes the case when Home implements a unilateral carbon tax complemented by a BCA rate equals to the implemented tax rate. The fifth column reports relative changes when Home implements the optimal tax-BCA combination that maximizes Home's welfare. The cases of a unilateral carbon tax with an equal BTA rate and an optimal tax-BTA combination are addressed respectively in the sixth and seventh columns of these tables.

Foreign's export market is the main market that is affected by a BCA or BTA imposed by Home. Therefore, we focus on the effects of these border adjustments on this market. Since the impact of border adjustments on key variables follows from their effect on firms' unit cost, we concentrate our analysis on the impacts a BCA or a BTA have on the unit cost of Foreign's exporting firms.

As a BCA is implemented on the carbon content of imports, its effect on the unit cost of Foreign's exporting firms is the similar to the analyzed effect of the unilateral carbon tax, and therefore its impact across productivity level depends on the assumption of the strength of the link between firm specific emission intensity and its productivity level, captured by the parameter α. Whenever $\alpha < 1$, a BCA has a higher relative impact on the cost of Foreign's more productive exporting firms, these firms are the ones strongly hit by the BCA, while Foreign's less productive firms are the ones hit more hardly by the BCA if $\alpha > 1$. In the special case of $\alpha = 1$, the BCA effect becomes symmetric across the productivity spectrum. On the other hand, a BTA is practically an ad-valorem tariff. It affects the unit cost proportionally, hence its impacts do not depend on α.

It has a similar effect on all firms regardless of their productivity level. Accordingly, the inter-firm profitability index in Foreign's exporting markets $\bar{\theta}_{fh}$ is only affected by a BCA. This index decreases when $\alpha < 1$ and increases if $\alpha > 1$. The effect of a BTA on $\bar{\theta}_{fh}$ is almost null.

When the firm specific emission intensity is weakly (strongly) decreasing with its productivity level, Foreign's exporting cutoff ϕ^*_{fh} decreases (increases) inducing an increase (a decrease) in the export participation rate m_{fh}. This rate goes down under a BTA following an increase in ϕ^*_{fh}.

As far as international competitiveness is concerned, we compare BCA and BTA effects on Home's average external and internal competitiveness indices, $\bar{\kappa}_h$ and $\bar{\kappa}_f$. We use the case of a unilateral optimal carbon tax as a benchmark. Results show that a BCA induces an increase in $\bar{\kappa}_h$ and a decrease in $\bar{\kappa}_f$ when $\alpha < 1$, while both indices increase if $\alpha > 1$. In the latter case, a BCA only mitigates the loss in external competitiveness while it deepens the loss in the internal one. The BTA is efficient to mitigate both the external and internal competitiveness loss regardless of the value of α.

Both adjustments have a positive effect on Foreign's aggregate domestic emissions E_{ff} and a negative effect on its exporting emissions E_{fh}. The net effect on total emissions E_f depends on which of these effects dominates. The magnitudes of these effects in turn depends on the level (the rate) of the implemented adjustment.

For any value of α, both adjustments turn to be effective in mitigating the loss in Home's non-green welfare U_h, while having a negative effect on Foreign's non-green welfare U_f, with a higher quantitative effect under a BTA.

To summarize

The main difference between the two adjustments is that the BCA may induce a distortion in competitiveness among Foreign's exporting firms, since its effect across firms depends on the strength of the link between firm specific emission intensity and its productivity level. Accordingly, a BCA induces a reallocation of resources towards Foreign's less productive exporting firms when $\alpha < 1$, and towards its more productive ones when $\alpha < 1$. On the other hand, a BTA has no such distorting effects. Regardless of the assumption about α, the effect of the two adjustments is to induce the least productive exporting firms at Home to stop exporting and to produce only for domestic markets, mainly because these firms can set higher prices and get more profits domestically. From a non-green welfare point of view, the implementing country is better off under a BTA, at the expense of the other country, and therefore, a BTA represents a more credible threat to induce countries to strengthen their climate regulation or to comply with international agreements than a BCA. For the same reason, a BTA has a higher probability to be contested before the WTO's dispute settlement body, while a BCA has a higher probability to be accepted under paragraph (g) of the GATT since it targets the carbon content of imports. However, from a practical point of view a BCA is harder to implement compared to a BTA, due to technical difficulties in calculating the carbon content of imports. As the implementing country may impose a higher rate than needed to tackle carbon leakage and restore competitiveness, We stress here the importance of implementing a BCA rate that maximizes global rather than national welfare.

3.5 Conclusion

We introduced in this paper environmental damages to the Melitz (2003) trade model in order to analyze theoretically the effects of a unilateral carbon tax on the firm level and to study the competitiveness-driven channel of carbon leakage. We investigated as well the efficiency of border adjustments to restore international competitiveness across countries with asymmetric climate policies.

Our results show that the effects of a carbon tax or a BCA across firm-specific productivity spectrum depend on the strength of the link between firm-specific emission intensity and its productivity level. We distinguish between two effects on the unit cost of firms in the targeted markets, a direct policy effect and an indirect wage effect. If emission intensity is strongly decreasing with productivity level, the increase in the policy (a carbon tax or a BCA) dominates the wage decrease for all firms in the targeted markets. Less productive firms are the ones mostly affected by the policy and least productive firms exit the market. The policy induces a reallocation of resources towards more productive firms. On the other hand, when firm-specific emission intensity is weakly decreasing with productivity level, the relative effect of the policy is higher for more productive firms, this is because the policy increase dominates the wage decrease for these firms. For less productive firms, the wage effect dominates, which makes it profitable for some less productive, more polluting, firms to enter the market and start producing. Resources in this case are reallocate towards less productive firm after a policy shock.

The main difference between the effects of a BCA and a BTA is that a BCA distorts competitiveness across firms in the targeted market, while a BTA introduces no such distortion. Moreover, a BTA represents a more credible threat to induce countries to strengthen their climate regulation or to ratify a global environmental agreement. Even though border adjustments play an important role in mitigating carbon leakage and the distortion in international competitiveness, these instruments cannot replace the implementation of a carbon tax in the exporting country. This is because the carbon tax covers both the export and domestic markets of the implementing country, while a BCA/BTA affects only the exporting market.

As a policy recommendation, results obtained in this paper suggest the before implementing a carbon tax or a BCA in a certain sector, the policy maker should have reliable estimates about the strength of the link between firm-specific emission intensity and its productivity level. This is because such policies may have asymmetric impacts across firms in their targeted market, and therefore, may induce unexpected results regarding the number of operating firms and the average productivity and thus competitiveness in those markets.

3.6 Appendix

3.6.1 Benchmark parametrization

Table 3.1: Benchmark parametrization

Parameter	σ	β	f^e	f_{hh}	f_{fh}	b	L	τ	α	δ_0	ϵ	η
Value ($\alpha < 1$)	3.8	4	2.3	1	1.6	1	1	1.3	0.22	0.28	2	0.05
Value ($\alpha > 1$)	3.8	4	2.3	1	1.6	1	1	1.3	1.3	1.12	2	0.05

3.6.2 Proof that $\bar{\phi}_{fh}$ is equal to the technical coefficient $\tilde{\phi}_{fh}$

Giving the labor input, as $c_{fh} = \frac{w_f}{\phi_{fh}}$,

$$\left(\tilde{\phi}_{fh}\right)^{-1} = \int_{\phi^*_{hf}}^{\infty} \phi^{-1} \left(\frac{\bar{\phi}_{fh}}{\phi}\right)^{-\sigma} \frac{g(\phi)}{1 - G\left(\phi^*_{fh}\right)} d\phi = \left(\bar{\phi}_{fh}\right)^{-\sigma} \int_{\phi^*_{hf}}^{\infty} \phi^{\sigma-1} \frac{g(\phi)}{1 - G\left(\phi^*_{fh}\right)} d\phi =$$

$$= \left(\bar{\phi}_{fh}\right)^{-\sigma} \left(\bar{\phi}_{fh}\right)^{\sigma-1} = \left(\bar{\phi}_{fh}\right)^{-1}.$$

Proof expression of $\bar{\lambda}^s_{fh}$

$$\bar{\lambda}^s_{fh} = \int_{\phi^*_{fh}}^{\infty} \frac{\delta_f(\phi)}{c_{fh}(\phi)} \left(\frac{c_{fh}(\phi)}{\bar{c}_{fh}}\right)^{1-\sigma} \frac{g(\phi)}{1 - G\left(\phi^*_{fh}\right)} d\phi$$

$$= \int_{\phi^*_{hf}}^{\infty} \frac{\delta_f \phi^{1-\alpha}}{w_f} \left(\frac{\phi}{\bar{\phi}_{fh}}\right)^{\sigma-1} \frac{g(\phi)}{1 - G\left(\phi^*_{fh}\right)} d\phi$$

$$= \frac{\delta_f}{w_f} \bar{\phi}_{fh}^{1-\sigma} \int_{\phi^*_{hf}}^{\infty} \phi^{\sigma-\alpha} \frac{g(\phi)}{1 - G\left(\phi^*_{fh}\right)} d\phi,$$

and, substituting $\sigma - \alpha$ in the Melitz formula,

$$= \left(\frac{\delta_f}{w_f}\right) (\theta_0)\, \phi_{fh}^{*1-\sigma} \theta_a \phi^{*(\sigma-\alpha)}, \qquad \text{with} \qquad \theta_0 = \frac{\beta}{(\beta - \sigma + \alpha)},$$

An alternative would be to define average technical coefficients in the following way. From (3.9) and (3.12)

$$\frac{q_{hf}(\phi)}{\bar{q}_{hf}} = \left(\frac{c_{hf}(\phi)}{\bar{c}_{hf}}\right)^{-\sigma}$$

From (3.5) and (3.4)

$$e_{hf}(\phi) = \delta_h(\phi)\left(\frac{c_{hf}(\phi)}{\bar{c}_{hf}}\right)^{-\sigma}\tau\bar{q}_{hf}, \qquad l^v_{hf}(\phi) = \frac{1}{\phi}\left(\frac{c_{hf}(\phi)}{\bar{c}_{hf}}\right)^{-\sigma}\tau\bar{q}_{hf},$$

Average emissions and labor inputs are:

$$\bar{e}_{hf} = \left[\int_{\phi^*_{hf}}^{\infty}\delta_h(\phi)\left(\frac{c_{hf}(\phi)}{\bar{c}_{hf}}\right)^{-\sigma}\frac{g(\phi)}{1-G\left(\phi^*_{hf}\right)}d\phi\right]\tau\bar{q}_{hf} \overset{def}{=} \tilde{\delta}\tau\bar{q}_{hf},$$

$$\bar{l}^v_{hf} = \left[\int_{\phi^*_{hf}}^{\infty}\frac{1}{\phi}\left(\frac{c_{hf}(\phi)}{\bar{c}_{hf}}\right)^{-\sigma}\frac{g(\phi)}{1-G\left(\phi^*_{hf}\right)}d\phi\right]\tau\bar{q}_{hf} \overset{def}{=} (1/\tilde{\phi})\tau\bar{q}_{hf}.$$

As the weights do not sum to one, $\tilde{\delta}$ and $\tilde{\phi}$ are not proper averages of $\delta(\phi)$ and ϕ, as the weights appearing under the integrals do not sum to one. An increase of the cutoff ϕ^*_{hf} may therefore lead, paradoxically, to an increase of $\tilde{\delta}$ or a decrease of $\tilde{\phi}$.

We may however write

$$\frac{\left(Z_h + X_f\right)\bar{e}_{hf}}{\bar{c}_{hf}} = \left[\int_{\phi^*_{hf}}^{\infty}\frac{\left(Z_h + X_f\right)\delta_h(\phi)}{c_{hf}(\phi)}\left(\frac{c_{hf}(\phi)}{\bar{c}_{hf}}\right)^{1-\sigma}\frac{g(\phi)}{1-G\left(\phi^*_{hf}\right)}d\phi\right]\tau\bar{q}_{hf},$$

and thus recover $\bar{\lambda}_{hf}$ which is a true average and obtain

$$\tilde{\delta}_{hf} = \frac{\bar{\lambda}_{hf}\bar{c}_{hf}}{(Z_h + X_f)}.$$

The technical coefficient $\tilde{\delta}_{hf}$ appears as the product of two averages but is not an average. As $\delta_{hf}(\phi)$ decreases with ϕ, we expect the aggregate $\tilde{\delta}_{hf}$ to decrease when the cutoff increases, leaving less polluting firms on the market. This is not sure however: the average cost $\bar{c}_{hf}$ indeed decreases when the cutoff ϕ^*_{hf} increases. But the share $\bar{\lambda}_{hf}$ of environmental costs increases with ϕ: as $\alpha < 1$: the environmental cost decreases more slowly than the labor cost when productivity increases. Paradoxical cases where an increase of the cutoff leads to an increase of the aggregate emission coefficient $\tilde{\delta}_{hf}$ are possible.

3.6.3 Optimal rates and simulation scenarios

Table 3.2: Optimal rates for simulation scenarios when ($\alpha < 1$).

Policy \ Scenario	Z_h opt.	$Z_h + X_h$ equal	$Z_h + X_h$ opt.	$Z_h + t_h$ equal	$Z_h + t_h$ opt.
Z_h	10.75%	10.75%	9.346%	10.75%	9.407%
X_h	-	10.75%	31.88%	-	-
t_h	-	-	-	14.88%	49.07%

Note here that the equal BTA rate is calculated such that $t_h = \frac{Z_h^{opt}\overline{\delta}_{hh}\overline{\phi}_{hh}}{w_h}$ where the values of $\overline{\delta}_{hh} = 0.842$ and $\overline{\phi}_{hh} = 1.643$ are taken under the free trade benchmark.

Table 3.3: Optimal rates for simulation scenarios when ($\alpha > 1$).

Policy \ Scenario	Z_h opt.	$Z_h + X_h$ equal	$Z_h + X_h$ opt.	$Z_h + t_h$ equal	$Z_h + t_h$ opt.
Z_h	7.14%	7.14%	9.36%	7.14%	12.415%
X_h	-	7.14%	19.2%	-	-
t_h	-	-	-	11.04%	41.57%

The equal BTA rate is calculated such that $t_h = \frac{Z_h^{opt}\overline{\delta}_{hh}\overline{\phi}_{hh}}{w_h}$ where the values of $\overline{\delta}_{hh} = 0.941$ and $\overline{\phi}_{hh} = 1.643$ are taken under the free trade benchmark.

Table 3.4: Policy effects on cutoffs and averages when ($\alpha < 1$).

Variable	Benchmark	Z_h opt.	$Z_h + X_h$ equal	$Z_h + X_h$ opt.	$Z_h + t_h$ equal	$Z_h + t_h$ opt.
ϕ^*_{hh}	1.0688	-4.03%	-4.89%	-5.49%	-5.27%	-6.41%
ϕ^*_{ff}	1.0688	-0.26%	-1.10%	-2.12%	-1.47%	-3.12%
ϕ^*_{hf}	1.6434	-3.98%	0.17%	7.37%	2.46%	16.95%
ϕ^*_{fh}	1.6434	0.94%	-0.59%	-1.33%	6.16%	17.34%
w_h	1	-5.90%	-2.31%	4.07%	-0.39%	11.67%
M_h	0.0614	17.53%	21.85%	25.07%	23.85%	30.07%
M_f	0.0614	1.05%	4.44%	8.81%	6.09%	13.52%
M_{hf}	0.0110	17.27%	-0.96%	-24.93%	-9.51%	-46.66%
M_{fh}	0.0110	-3.68%	2.34%	5.34%	-21.27%	-47.24%
m_{hf}	0.1789	-0.22%	-18.72%	-39.98%	-26.94%	-58.99%
m_{fh}	0.1789	-4.68%	-2.01%	-3.19%	-25.79%	-53.53%
$\bar{c}_{hh}$	0.6086	5.12%	9.83%	16.44%	12.29%	25.73%
$\bar{c}_{ff}$	0.6086	0.26%	1.11%	2.17%	1.49%	3.22%
$\bar{c}_{hf}$	0.3958	7.56%	7.01%	5.17%	6.66%	3.63%
$\bar{c}_{fh}$	0.3958	-0.93%	10.13%	26.57%	8.21%	27.05%
$\bar{r}^c_{hh}$	12.6667	-15.30%	-11.74%	-4.51%	-9.85%	2.96%
$\bar{r}^c_{ff}$	12.6667	0%	0%	0%	0%	0%
$\bar{r}^c_{hf}$	20.2667	-17.87%	-14.69%	-7.79%	-13.00%	-1.09%
$\bar{r}^c_{fh}$	20.2667	0.00%	-12.41%	-24.41%	14.88%	49.07%
$\bar{e}^c_{hh}$	7.8644	-43.04%	-42.79%	-40.12%	-42.64%	-39.59%
$\bar{e}^c_{ff}$	7.8644	-0.20%	-0.86%	-1.66%	-1.15%	-2.44%
$\bar{e}^c_{hf}$	17.6004	-48.13%	-46.32%	-40.82%	-45.33%	-36.79%
$\bar{e}^c_{fh}$	17.6004	0.73%	-46.17%	-64.30%	4.77%	13.28%
$\bar{\theta}_{hh}$	3.3333	-9.98%	-9.66%	-8.25%	-9.49%	-7.80%
$\bar{\theta}_{ff}$	3.3333	0%	0%	0%	0%	0%
$\bar{\theta}_{hf}$	3.3333	-12.71%	-12.67%	-11.40%	-12.66%	-11.42%
$\bar{\theta}_{fh}$	3.3333	0%	-12.41%	-24.41%	0%	0%
$\bar{\kappa}_h$	1.1828	-6.79%	-5.52%	-2.86%	-4.85%	-0.39%
$\bar{\kappa}_f$	1.1828	6.11%	-0.27%	-8.01%	3.77%	-1.03%

Table 3.5: Policy effects on aggregate emissions and welfare when ($\alpha < 1$).

Variable	Benchmark	Z_h opt.	$Z_h + X_h$ equal	$Z_h + X_h$ opt.	$Z_h + t_h$ equal	$Z_h + t_h$ opt.
E_{hh}	0.4827	-33.05%	-30.28%	-25.11%	-28.96%	-21.43%
E_{hf}	0.1933	-39.17%	-46.83%	-55.57%	-50.53%	-66.28%
E_{ff}	0.4827	0.85%	3.55%	7.01%	4.87%	10.75%
E_{fh}	0.1933	-2.97%	-44.91%	-62.40%	-17.51%	-40.24%
E_h	0.6760	-34.80%	-35.02%	-33.82%	-35.13%	-34.26%
E_f	0.6760	-0.25%	-10.31%	-12.84%	-1.53%	-3.83%
E_w	1.3519	-17.52%	-22.66%	-23.33%	-18.33%	-19.04%
M_h^v	0.3914	5.93%	6.21%	5.92%	6.34%	6.22%
M_f^v	0.3914	0.12%	1.45%	2.88%	0.69%	1.52%
I_h	1.2489	-5.29%	-6.15%	-6.81%	-5.15%	-5.00%
I_f	1.2489	-1.48%	-2.34%	-3.38%	-2.74%	-4.60%
U_h	0.4889	-0.65%	-0.17%	0.07%	0.32%	0.89%
U_f	0.4889	-0.26%	-1.10%	-2.12%	-1.47%	-3.12%
D_w	0.0457	-31.98%	-40.19%	-41.21%	-33.30%	-34.46%
W_h	0.4432	2.58%	3.96%	4.32%	3.79%	4.53%
W_f	0.4432	3.01%	2.93%	1.91%	1.81%	0.11%

Table 3.6: Policy effects on cutoffs and averages when ($\alpha > 1$).

Variable	Benchmark	Z_h opt.	$Z_h + X_h$ equal	$Z_h + X_h$ opt.	$Z_h + t_h$ equal	$Z_h + t_h$ opt.
ϕ^*_{hh}	1.0688	1.73%	0.85%	0.20%	0.46%	-0.63%
ϕ^*_{ff}	1.0688	0.10%	-0.27%	-0.79%	-0.86%	-2.54%
ϕ^*_{hf}	1.6434	1.19%	4.34%	9.83%	5.93%	19.28%
ϕ^*_{fh}	1.6434	-0.34%	2.40%	6.60%	3.31%	12.62%
w_h	1.0000	-4.56%	-1.93%	0.93%	-0.30%	7.21%
M_h	0.0614	-0.24%	3.16%	7.66%	4.69%	13.47%
M_f	0.0614	-0.39%	2.33%	5.99%	3.50%	10.83%
M_{hf}	0.0110	1.92%	-9.97%	-25.41%	-15.32%	-45.36%
M_{fh}	0.0110	1.35%	-7.93%	-20.48%	-12.22%	-37.84%
m_{hf}	0.1789	2.16%	-12.73%	-30.71%	-19.11%	-51.85%
m_{fh}	0.1789	1.75%	-10.03%	-24.98%	-15.19%	-43.92%
$\bar{c}_{hh}$	0.6086	0.35%	3.85%	9.46%	5.89%	19.58%
$\bar{c}_{ff}$	0.6086	-0.10%	0.27%	0.80%	0.86%	2.60%
$\bar{c}_{hf}$	0.3958	0.10%	-0.45%	-1.29%	-0.42%	-2.01%
$\bar{c}_{fh}$	0.3958	0.34%	3.36%	8.26%	7.48%	25.71%
$\bar{r}^c_{hh}$	12.6667	-0.03%	2.62%	6.86%	4.26%	15.02%
$\bar{r}^c_{ff}$	12.6667	0%	0%	0%	0%	0%
$\bar{r}^c_{hf}$	20.2667	-0.55%	2.04%	6.02%	3.66%	13.76%
$\bar{r}^c_{fh}$	20.2667	0%	4%	10.19%	11.04%	41.57%
$\bar{e}^c_{hh}$	8.7829	-3.59%	-3.26%	-3.87%	-3.10%	-4.53%
$\bar{e}^c_{ff}$	8.7829	-0.03%	0.08%	0.24%	0.26%	0.77%
$\bar{e}^c_{hf}$	12.3511	-3.08%	-3.87%	-5.96%	-4.25%	-8.91%
$\bar{e}^c_{fh}$	12.3511	0.10%	-3.29%	-8.34%	-0.97%	-3.50%
$\bar{\theta}_{hh}$	3.3333	4.75%	4.64%	5.87%	4.57%	7.28%
$\bar{\theta}_{ff}$	3.3333	0%	0%	0%	0%	0%
$\bar{\theta}_{hf}$	3.3333	4.20%	4.05%	5.05%	3.97%	6.11%
$\bar{\theta}_{fh}$	3.3333	0%	4%	10.19%	0%	0%
$\bar{\kappa}_h$	1.1828	-0.20%	0.73%	2.11%	1.29%	4.71%
$\bar{\kappa}_f$	1.1828	0.01%	0.48%	1.10%	-1.48%	-4.87%

Table 3.7: Policy effects on aggregate emissions and welfare when ($\alpha > 1$).

Variable	Benchmark	Z_h opt.	$Z_h + X_h$ equal	$Z_h + X_h$ opt.	$Z_h + t_h$ equal	$Z_h + t_h$ opt.
E_{hh}	0.5391	-3.81%	-0.20%	3.50%	1.44%	8.33%
E_{hf}	0.1356	-1.21%	-13.45%	-29.85%	-18.92%	-50.23%
E_{ff}	0.5391	-0.42%	2.41%	6.24%	3.76%	11.69%
E_{fh}	0.1356	1.46%	-10.96%	-27.11%	-13.07%	-40.02%
E_h	0.6747	-3.29%	-2.87%	-3.20%	-2.65%	-3.44%
E_f	0.6747	-0.04%	-0.28%	-0.47%	0.38%	1.30%
E_w	1.3494	-1.67%	-1.57%	-1.84%	-1.14%	-1.07%
M_h^v	0.3914	0.03%	0.42%	0.94%	0.59%	1.60%
M_f^v	0.3914	-0.04%	0.27%	0.70%	0.40%	1.22%
I_h	1.2489	-0.21%	-0.41%	-0.97%	-0.09%	-0.66%
I_f	1.2489	0.11%	-0.44%	-1.22%	-1.08%	-3.33%
U_h	0.4889	-0.20%	0.11%	0.22%	0.66%	1.32%
U_f	0.4889	0.10%	-0.27%	-0.79%	-0.86%	-2.54%
D_w	0.0455	-3.30%	-3.12%	-3.64%	-2.26%	-2.13%
W_h	0.4434	0.11%	0.44%	0.61%	0.97%	1.67%
W_f	0.4434	0.45%	0.02%	-0.50%	-0.71%	-2.58%

Chapter 4

Dynamic Border Carbon Taxes to Enhance Green growth

4.1 Introduction

Climate change and transboundary pollution affect all countries regardless of their development level. In order to address these global issues, international coordination is required, which has been acknowledged through the Paris Climate Agreement of 2015. Nevertheless, there is still asymmetry in the views and in policies implemented across countries, resulting in a decrease of the efficiency of the climate agreement and even its potential failure due to problems such as carbon leakage and distortions in international competitiveness. Recall that carbon leakage defines the situation that emission savings by one country are offset by the rise in emissions of other countries with a lax climate policy.

One suggestion to tackle both the leakage and the competitiveness concerns is to apply differential taxation on the carbon content of imported goods: this tax is referred to as Border Carbon Tax (BCT). When dealing with carbon leakage, a BCT is often referred to as Border Carbon Adjustment (BCA). Many studies have analyzed the effectiveness of BCTs to tackle carbon leakage and to restore competitiveness among countries (Monjon and Quirion (2009), Cosbey (2009), Elliott et al. (2010), Böhringer et al. (2012), Cosbey et al. (2013), Condon and Ignaciuk (2013), and Böhringer et al. (2015))[1]. However, most of these studies are done in a static context that does not allow either for studying the dynamic impacts of BCTs on the growth of trading partners, nor for analyzing the effect of the asymmetry in initial development levels across countries. The present paper fills this gap by incorporating dynamic aspects.[2]

This paper also contributes to the sustainable development literature. Growing in a sustainable way that achieves economic growth and global environmental objectives, such as keeping the increase in the world temperature below 2 degrees, imposes additional costs on growing economies. These costs can be due to more expensive environmentally friendly investments relative to traditional ones as highlighted by Hynes and Wang (2012). Since climate change is a global rather than a national problem, it is in the interest of all countries to direct the growth of developing countries towards a sustainable path. One way to achieve this is through international aid from developed countries. We studied in chapter 2 the impact of unconditional mitigation aid from a developed donor country to a poor recipient country where countries only interact through global pollution. We found that if the lesser developed country is also less hardly hit by environmental damage, unconditionally given aid may be given in a non-cooperative equilibrium. Though the aid enables the recipient country to grow green capital faster, its main effect is to enable consumption in the receiving country and thereby to postpone the development of, cheaper, polluting industries.

Reducing trade barriers to markets of developed countries is another way to help developing countries grow. Nevertheless, in order to achieve a sustainable growth path, this paper argues that opening markets should be selective in terms of goods produced using "green" nonpolluting capital while keeping restrictions on the goods produced using "brown" polluting capital. Helm et al. (2012) argue that the absence of a carbon price implicitly involves a subsidy to dirty production in non-regulated markets and therefore a BCT should not be considered as a dirty trade barrier. Furthermore, in order to investigate whether future trade opportunities with greener markets form an

[1] Branger and Quirion (2014) furnish a useful overview on the effectiveness of BCTs.

[2] Cosbey et al. (2013) discuss different approaches to estimate the embodied carbon content of imports. I will not address this issue in this paper, rather, I will focus on analyzing the BCT impacts assuming the applicability of BCTs across countries on the actual carbon content of imports.

incentive to shift investments in newly exporting countries towards more environmentally friendly ones, I analyze in this paper how imposing a BCT affects the direction of growth across trading countries, and especially if it enhances green growth in the country whose exports are affected by the BCT. I find that such restrictions are effective instruments to shift the investment decisions in this country towards green "nonpolluting" capital.

The OECD defines green growth as: "... Green growth is about fostering economic growth and development while ensuring that the natural assets continue to provide the resources and environmental services on which our well-being relies ...." (OECD (2011)). In this paper, transboundary pollution is considered as a natural asset. Keeping global pollution under tolerable levels is necessary to achieve green growth in the short and long run. Accordingly, investing in non-polluting capital means that these investments are not taking place in the polluting sector, and therefore, lower pollution stock.

There have been an extensive number of studies analyzing the environmental effects of trade liberalization, both theoretically and empirically (Grossman and Krueger (1991), Copeland and Taylor (1994), Antweiler et al. (2001), Frankel and Rose (2005), and Cherniwchan (2017)). Cherniwchan et al. (2016) provide a comprehensive review of new measurement tools and methods in this literature focusing on the evidence from heterogeneous firms models of international trade. Studying the growth aspect of this relationship however completes the picture as climate change and transboundary pollution are dynamic global phenomena. Cui et al. (2011) contribute to the growth, trade, and environment literature by investigating the role of trade variable cost on different inputs to motivate firms to engage in technical innovation. Copeland and Taylor (2004) investigate the link between income growth and the environment and study the impact of trade liberalization. They emphasize the need for economic theory to play a much larger role in guiding empirical investigation.

This paper contributes to that literature as well. It provides a theoretical analysis of the effects of dynamic endogenous BCTs on the growth direction across trading countries, and studies the efficiency of this instrument from both a trade and an environmental perspective. Using a Ramsey framework over an infinite time horizon, I introduce dynamic investment decisions in a trade model. Trade in this model occurs between two substitutable varieties of a final consumption good (Armington type) and is driven by differences in production costs whenever there is asymmetry in the endogenous capital stock across countries. Accordingly, I incorporate in the model two channels of strategic interaction between countries, a trade channel and an environmental externality through a stock of global pollution. I analyze the growth and welfare effects of different BCT configurations across countries. Moreover, I study the impacts of a BCT on carbon leakage, and I assess its effectiveness to direct the growth path in the exporting country towards a sustainable path. I deviate from existing literature by not explicitly introducing climate policies across countries. In this model, these policies are implicitly determined by the shadow price of global pollution across countries and thus through the centralized dynamic investments in "green" non-polluting capital and "brown" polluting capital. A government that is more concerned about the environment, or equivalently more sensitive to pollution damage, invests less in brown capital and more in green and vice versa. Accordingly, investment decisions, including the implicit climate policies, and the optimal BCT rate are endogenously determined. This distinction between green and brown capital provides two possible types for growth paths in each country, a conventional and a sustainable path, which to my knowledge has not been addressed within a trade model before. In addition, the dynamic aspect of the model allows me to investigate what I call "growth leakage", which I define as a shift in the growth path across countries due to the asymmetry in their views towards the environment, such that a country that is less concerned about the environment converges towards higher balanced growth path. From a technical point of view, this model is a differential game between two countries, featuring five state variables: brown and green capital stocks in each country, and a stock for global pollution.

Results show that a unilateral BCT is welfare enhancing for the applying country, primarily through terms of trade, and is an effective tool to shift the growth of the other country towards a greener path, even when neither country does care about the environment. When countries are environmentally conscious, the implementing country takes advantage of the unilateral BCT to increase its stock of brown capital and shift the cost of reducing global pollution to the other country. However, these incentives decrease if the implementing country becomes more concerned about the environment. Furthermore, the country that cares more about the environment witnesses a slower growth and a lower development level in the long run. The other country free rides on this fact to converge to a higher steady state level of capital stock and output inducing growth leakage. Results also indicate that as long as there is symmetry between countries, the optimal unilateral social BCT, chosen by a trade regulator to maximize global welfare, is zero. However, if the implementing country is poorer or more concerned about the environment, the unilateral social BCT becomes positive. Moreover, the social BCT is an effective instrument to mitigate both carbon and growth leakages. Additionally, results indicate that the asymmetry in initial development levels across countries induces a slower growth for the initially poorer country only if the other country is initially richer in brown capital.

A "tariff war" refers to a situation where imposing a border tariff by one country induces the other country to retaliate by implementing a tariff as well. Using a trade model with firm heterogeneity Felbermayr et al. (2013) conclude that tariff wars decrease the total world welfare. Kemp et al. (2001) build a differential game trade model to study tariff wars. They emphasized the role of the time discount rates across countries in the welfare comparison between free trade equilibrium and a bilateral optimum tariff equilibrium in each country. In this paper, I examine a "BCT war" between countries. As in the tariff war, I find in the steady state that a "BCT war" is welfare decreasing when countries are not concerned about the environment. Nevertheless, the model shows that if governments take the environmental quality of their consumers into account to a sufficient degree, a bilateral BCT becomes welfare enhancing as the welfare loss from higher global prices is compensated by the benefits from lower pollution levels.

The model introduced in this paper allows me to contribute to other research questions beyond the purpose of this paper. For instance whether trade openness is good for countries at a low development levels. As in Devereux (1997), I find that opening trade should be done gradually along the development path of poor countries. The intuition is that high initial BCT protects infant industries from international competition and allows countries to build their capital faster.

This paper is closely related to Hémous (2016) who extends the Acemoglu et al. (2012) model to a two-country framework in order to study the optimal policy combination that achieves sustainable growth. He shows that a unilateral climate policy combining clean research subsidies and a trade tax can ensure sustainable growth. Trade in his model occurs in a Ricardo-Heckscher-Ohlin type between the two countries and the trade tax takes a form of a tariff and then an export subsidy which affects also terms of trade when the social planner values consumption across countries differently. In a related model, van den Bijgaart (2017) emphasizes that the relative size and innovativeness across trading countries are relevant factors in determining whether unilateral policies can implement sustainable growth. Unlike Hémous (2016) and van den Bijgaart (2017) who assume exogenous capital endowments and focus on the dynamic aspects of environmental quality and innovation to achieve sustainable growth, I focus on growth in physical capital by employing Ramsey framework to model growth with endogenous investment decisions.

The rest of this paper is organized as follows: Section 2 presents the model and describes the instantaneous equilibrium. Section 3 introduces the dynamics of the model and the government problem. The methodology of solving the model numerically is presented in Section 4. Section 5 addresses the results of the model in the short and long run. In Section 6, I introduce a new game with a trade regulator as a third party in the game between countries, and I analyze the effectiveness of a social BCT to tackle carbon and growth leakages. Finally, in section 7, I conclude.

4.2 The Model

I assume a world of two countries, North and South, with one traded good, c, that has different varieties differentiated by its origin. I only describe relations for South; those for North are analogous.

Pollution is assumed to be transboundary, affecting consumers in both countries regardless of its source. Accordingly, the welfare of the representative consumer is composed of the utility from consumption U_t^s and a negative welfare impact from global pollution P_t, represented by a damage function D^s. The discounted welfare of South's representative consumer reads:

$$W_t^s = \int_0^\infty (U_t^s - D^s(P_t))e^{-\rho t}dt, \tag{4.1}$$

with ρ representing the time preference rate. The damage function is assumed to be increasing and convex. I introduce the terms "non-green" welfare to refer to the utility from consumption and "green welfare" to refer to the damage from global pollution, that is, higher green welfare reflects lower damage from global pollution.

4.2.1 Consumption

The representative consumer at South gains utility from the consumption of domestic, c_t^{ss}, and imported, c_t^{ns}, varieties of the generic good. The first superscript indicates the country where the good is produced while the second indicates where the good is consumed:

$$U_t^s = u_t^s(c_t^{ss}, c_t^{ns}). \tag{4.2}$$

The utility function is assumed to be increasing and concave. Each individual is assumed to provide one unit of labor at a wage ω_t^s. The total labor available in the economy at time t is L_t^s. Firms in the economy are assumed to be owned by consumers. The consumer budget constraint reads

$$\Pi_t^s + \omega_t^s L_t^s + p_t^{ss} S_t^s \geq p_t^{ss} c_t^{ss} + p_t^{ns} c_t^{ns}. \tag{4.3}$$

Profits Π_t^s enter as another source of income besides wages on the left hand side of this constraint. Consumers in each country may also receive a lump sum subsidy from the government S_t^s in real terms, which is endogenously determined and is financed from the proceeds of selling energy that is not used in investments. The role of the subsidy in this model is explained further when I describe the government problem. The right hand side of this constraint represents consumption expenditures. Let p_t^{ss} be the consumer price of the domestically produced good, while the price of imports from North is denoted p_t^{ns}.

The representative consumer in South chooses c_t^{ss} and c_t^{ns} to maximize instantaneous utility (4.2) subject to her budget constraint (4.3). Solving the first order conditions of this instantaneous problem yields that the marginal rate of substitution (MRS) of imported and domestic varieties is equal to the relative consumer prices

$$\frac{u^{s\prime}_{c_t^{ns}}}{u^{s\prime}_{c_t^{ss}}} = \frac{p_t^{ns}}{p_t^{ss}}. \tag{4.4}$$

A prime superscript of a function denotes the first order partial derivative of that function with respect to the variable in the subscript.

4.2.2 Production

I assume that there are a large number of identical firms in each country producing the final consumption good. Their behavior can be described by one representative firm. The firm's location is assumed to be fixed: there is no relocation of firms across countries. The final good is produced using two principal production factors, energy – or any other input that can be produced in a clean or a dirty way – and labor. Production factors are assumed to be country specific and not mobile across countries. Energy can be of two types: green, $E^s_{g,t}$, or brown, $E^s_{b,t}$, depending on the type of capital that is used to generate it. Firms produce the final consumption good, while governments are assumed to be responsible for energy production.

Firms buy energy from the government at prices $r^s_{b,t}$ and $r^s_{g,t}$, for brown and green energy respectively. They take energy prices as given. The degree of substitution between the two kinds of energy is specified in the production technology of the firms, which is described by the production function $F(L_t^s, E^s_{b,t}, E^s_{g,t})$. This function is assumed to be increasing and concave between labor and energy. Accordingly the profit of the representative firm is given by

$$\Pi_t^s = p_{p,t}^s Y_t^s - \omega_t^s L_t^s - r_{b,t}^s E_{b,t}^s - r_{g,t}^s E_{g,t}^s, \tag{4.5}$$

where Y_t^s denotes total output in South. The problem of the representative firm is to choose the optimal factor demands that maximize its profit (4.5), for a given producer price $p_{p,t}^s$, subject to:

$$F(L_t^s, E_{b,t}^s, E_{g,t}^s) \geq Y_t^s.$$

The first order conditions of this problem yields that factor prices – in real terms – equal marginal factor productivity:

$$\omega_t^s = F'_{L_t^s},\ r_{b,t}^s = F'_{E_{b,t}^s},\ r_{g,t}^s = F'_{E_{g,t}^s}. \tag{4.6}$$

Available production factors are fully employed by the representative firm at every point of time.

4.2.3 Energy production

The government in each country is assumed to invest in two kinds of capital stock, non-polluting green capital $K_{g,t}^s$ and polluting brown capital $K_{b,t}^s$. These capital stocks can be thought of as the infrastructure needed to produce energy, or equivalently, as green and brown power plants. The stocks are assumed to be owned by the government, who rents them out to an operator through a bidding mechanism. I assume further that there are an infinite number of potential bidders and that the bidding market is perfectly competitive. The winning bidder pays the government rental prices. Energy production in the country is also an instantaneous decision which is proportional to the available capital stock in every period:

$$a_g^s E_{g,t}^s = K_{g,t}^s,\ a_b^s E_{b,t}^s = K_{b,t}^s. \tag{4.7}$$

The positive parameters $a_g^s > 0$ and $a_b^s > 0$ represent energy intensities of installed green and brown capital respectively, assuming full capacity of installed capital at each point in time. Full employment conditions for capital stocks yield:

$$K_{b,t}^s = a_b^s e_{b,t}^s Y_t^s, \; K_{g,t}^s = a_g^s e_{g,t}^s Y_t^s,$$

where $e_{b,t}^s$, and $e_{g,t}^s$ are the respective unit factor demand for brown and green energy per unit of output. Labor in the country is assumed to grow over time at a rate n, which is exogenously determined. The total labor available at time t is

$$L_t^s = e^{nt} L_0^s.$$

L_t^s in this model reflects the country size at time t. For simplicity, throughout the analysis, I assume a zero labor growth rate across countries ($n = 0$). Moreover, both countries are assumed to have the same initial size ($L_0^n = L_0^s$), normalized to 1.

4.2.4 Taxation and Pricing

With no domestic taxation consumer price for domestic varieties is equal to the producer price $p_{p,t}^s$:

$$p_t^{ss} = p_{p,t}^s. \tag{4.8}$$

Depending on the BCT configuration that is assumed across countries, governments may implement a Border Carbon Tax (BCT), τ_t^s, on the carbon content of their imports. If such a BCT is imposed, then the consumer price of South's imported varieties equals North's producer price $p_{p,t}^n$ augmented by the BCT implemented by South's government:

$$p_t^{ns} = (1 + \tau_t^s z_t^n) p_{p,t}^n. \tag{4.9}$$

Here $z_t^n = \alpha^n a_b^n e_{b,t}^n$ represents the carbon content used to produce one unit of output at North with emission intensity α^n of installed brown capital. If the country does not apply a BCT ($\tau_t^s = 0$), then the consumer price of imports is equal to the producer price of the exporter, $p_t^{ns} = p_{p,t}^n$.

4.2.5 Instantaneous equilibrium

There are three main groups of actors in this economy: consumers, producers, and the government. In this model, the consumers and producers are assumed to be myopic while the government is forward looking; thus the problem of consumers and firms is static while that of the government is dynamic. As production factors are assumed to be immobile across countries and since investments decision, and thus saving decisions, are taken directly by the government, the government is assumed to act dynamically on behalf of consumers. At each point in time, for given levels of stocks of capital and pollution, firms produce the final good at a given producer price while consumers decide how much to consume of the domestic and imported varieties. Accordingly, the instantaneous equilibrium conditions can be derived from the First Order Conditions of the consumer and producer problems. After substituting the firm's profits (4.5), factor prices (4.6), energy production (4.7), and consumer prices (4.8) and (4.9) into the consumer budget constraint (4.3), the latter can be rewritten in real terms as:

$$Y_t^s + S_t^s = c_t^{ss} + (1 + \tau_t^s z_t^n)\frac{p_{p,t}^n}{p_{p,t}^s} c_t^{ns} + \frac{F'_{E_{g,t}^s}}{a_g^s} K_{g,t}^s + \frac{F'_{E_{b,t}^s}}{a_b^s} K_{b,t}^s. \qquad (4.10)$$

Note that $\tau_t^s = 0$ when there is no BCT implemented. Recall the marginal rate of substitution relation (4.4):

$$\frac{u^{s'}_{c_t^{ns}}}{u^{s'}_{c_t^{ss}}} = \frac{p_t^{ns}}{p_t^{ss}}. \qquad (4.11)$$

Finally, trade between countries is assumed to be balanced at every point of time: the value of imports is equal to the value of exports expressed in border prices (which excludes the BCTs).

This yields the following trade balance condition:

$$p_{p,t}^{s} c_{t}^{sn} = p_{p,t}^{n} c_{t}^{ns}. \tag{4.12}$$

These relations show that consumption quantities are determined in terms of capital stocks, subsidies, and the BCT rate implemented by each country. At each point of time equations (4.10), (4.11), the analogous relations for North, and the trade balance condition (4.12) determine the consumption of domestic and imported varieties in each country ($c_t^{ss}, c_t^{ns}, c_t^{nn}, c_t^{sn}$) as well as the relative producer price $p_{p,t}^{n}$ after normalizing $p_{p,t}^{s} = 1$. The relative producer price provides a measure for terms of trade between countries. An increase in $p_{p,t}^{n}$ reflect a gain in terms of trade for North and a loss for South and vice-versa.

4.3 Capital and pollution dynamics

As we are interested in analyzing the effect of asymmetry in initial development levels across trading partners on their transitional dynamics towards a steady state, it is essential to have dynamics in the model. I describe in this section these dynamics and the government decision problem. The stocks of brown and green capital increase through brown investments $I_{b,t}^{s}$ and green investments $I_{g,t}^{s}$, and decrease through depreciation, leading to:

$$\dot{K}_b^s = I_{b,t}^s - \delta K_{b,t}^s, \qquad K_{b,0}^s \text{ given,} \tag{4.13}$$

$$\dot{K}_g^s = I_{g,t}^s - \delta K_{g,t}^s, \qquad K_{g,0}^s \text{ given,} \tag{4.14}$$

with δ the uniformed capital depreciation rate. Global pollution is increasing through the emissions generated by brown capital in each country and decreasing through the natural decay (absorption) rate ϑ:

$$\dot{P} = \alpha^s K_{b,t}^s + \alpha^n K_{b,t}^n - \vartheta P_t, \qquad P_0 \text{ given.} \tag{4.15}$$

Here α^s and α^n are the respective emission intensities of brown capital in South and North respectively. Investments in green and brown capital are determined by the government, to which I turn next.

4.3.1 The government problem

I do not explicitly introduce carbon taxes in this model as these taxes are market instruments that are used to direct the decentralized investments. Since investment decisions between brown and green capital in this model are centralized, a country that is more concerned about the environment will invest less in brown capital. Lower levels of brown capital stocks leads to higher prices for brown energy, which is equivalent to a carbon tax on the use of brown energy. Accordingly, carbon taxes in this model are implicitly reflected through the shadow price of global pollution stock across countries.

The government in each country is responsible for building the infrastructure needed to produce brown and green energy. It has to decide on the level of capital investments $I^s_{b,t}$ and $I^s_{g,t}$, along with the BCT rate τ^s_t and the lump sum subsidies given to consumers S^s_t. The government's budget constraint in real terms reads

$$F'_{E^s_{b,t}} E^s_{b,t} + F'_{E^s_{g,t}} E^s_{g,t} + \frac{p^n_{p,t}}{p^s_{p,t}} \tau^s_t z^n_t c^{ns}_t \geq C^s_b(I^s_{b,t}) + C^s_g(I^s_{g,t}) + S^s_t. \tag{4.16}$$

The left hand side of this constraint represents the government revenues from selling brown and green energy and its BCT's revenues, $\frac{p^n_{p,t}}{p^s_{p,t}} \tau^s_t z^n_t c^{ns}_t$, that arise from taxing the carbon content of imports from North. These latter revenues equal zero if the BCT is not implemented. The right hand side shows the government expenditures on brown and green investments as well as the lump sum subsidy to be distributed back to consumers. Investment costs $C^s_j(I^s_{j,t})$ are assumed to be increasing and convex. More precisely, these costs are assumed to have a quadratic form:

$$C^s_j(I^s_{j,t}) = \frac{\beta_j}{2}(I^s_{j,t})^2, \qquad j \in \{b, g\}.$$

Here $\beta_b > 0$ and $\beta_g > 0$ are positive parameters that represent the rate of increase of the marginal investment costs. Brown investments are assumed cheaper than green ones, i.e. $\beta_g \geq \beta_b$. This assumption has a direct implication on international competitiveness across countries: the country that is more abundant in brown capital relative to green has lower marginal production cost and thus is more competitive internationally. Furthermore, investments are assumed to be irreversible: once an investment in one kind of capital has been made, this capital cannot be transformed to another kind of capital.

The subsidy S_t^s guarantees that investments and BCT decisions in each country are taken optimally. That is, if energy proceeds are higher than the optimal investment levels, the difference is distributed to consumers by means of the subsidy.

The problem of the government in each country is to maximize the intertemporal welfare of its representative consumer (4.1) by choosing investments in green and brown capitals, the BCT rate, and the lump sum subsidies in each period, subject to the dynamics of capitals and pollution in (4.13) - (4.15). The current value Hamiltonian of the intertemporal maximization problem for South reads

$$\begin{aligned} H^s = {} & u_t^s(c_t^{ss}, c_t^{ns}) - D(P_t) + \nu_{b,t}^s[I_{b,t}^s - \delta K_{b,t}^s] \\ & + \nu_{g,t}^s[I_{g,t}^s - \delta K_{g,t}^s] + \mu_t^s[\alpha^s K_{b,t}^s + \alpha^n K_{b,t}^n - \vartheta P_t]. \end{aligned}$$

The first order conditions yield

$$\nu_{b,t}^s + u_{c_t^{ss}}^{s'}(c_t^{ss})'_{I_{b,t}^s} + u_{c_t^{ns}}^{s'}(c_t^{ns})'_{I_{b,t}^s} = 0, \tag{4.17}$$

$$\nu_{g,t}^s + u_{c_t^{ss}}^{s'}(c_t^{ss})'_{I_{g,t}^s} + u_{c_t^{ns}}^{s'}(c_t^{ns})'_{I_{g,t}^s} = 0, \tag{4.18}$$

$$u_{c_t^{ss}}^{s'}(c_t^{ss})'_{\tau_t^s} + u_{c_t^{ns}}^{s'}(c_t^{ns})'_{\tau_t^s} = 0. \tag{4.19}$$

Condition (4.19) disappears if the country is assumed not to impose a BCT. The necessary conditions for the co-states μ_t^s, $\nu_{b,t}^s$, and $\nu_{g,t}^s$ of, respectively, the pollution stock, South's brown capital, and South's green capital, read as:

$$\dot{v}^s_{b,t} = (\rho + \delta)v^s_{b,t} - u^{s'}_{c^{ss}_t}(c^{ss}_t)'_{K^s_{b,t}} - u^{s'}_{c^{ns}_t}(c^{ns}_t)'_{K^s_{b,t}} - \alpha^s \mu^s_t, \tag{4.20}$$

$$\dot{v}^s_{g,t} = (\rho + \delta)v^s_{g,t} - u^{s'}_{c^{ss}_t}(c^{ss}_t)'_{K^s_{g,t}} - u^{s'}_{c^{ns}_t}(c^{ns}_t)'_{K^s_{g,t}}, \tag{4.21}$$

$$\dot{\mu}^s_t = (\rho + \vartheta)\mu^s_t + D^{s'}(P_t). \tag{4.22}$$

Conditions (4.20) – (4.22) are differential equations for South's co-states. These conditions are complemented by initial conditions for the states ($K^s_{b,0}$, $K^s_{g,0}$, P_0) and, since there are no terminal conditions on the states, by the transversality conditions

$$\lim_{t\to\infty} e^{-\rho t} K^s_{b,t} = 0, \lim_{t\to\infty} e^{-\rho t} K^s_{g,t} = 0, \lim_{t\to\infty} e^{-\rho t} P_t = 0, \tag{4.23}$$

which hold whenever the state variables are uniformly bounded away from zero (Michel (1982)). North's problem is symmetric to that of South, accordingly North decision problem yields symmetric conditions to (4.17) – (4.23).

If the government decides to decenteralize energy production, then it has to decide on policies that affect incentives of market agents to invest in order to achieve a socially desirable outcome. In this model, as the government chooses investments directly, climate policies are reflected by the shadow price of the global pollution stock μ^s_t. The domestic carbon tax rate x^s_t is implicitly determined by

$$x^s_t = -\mu^s_t. \tag{4.24}$$

In order to compute the partial derivatives of consumption and capital with respect to investments and the BCT, the instantaneous equilibrium conditions are used along with the government budget constraints in each country. This leads to a system of seven equations and seven unknowns, the consumption levels of domestic and imported varieties in each country, the relative producer price, and the lump sum subsidies given to consumers. The partial derivatives are then determined using the implicit function theorem. I elaborate on the computation of these derivatives in Appendix 4.8.1.

4.4 Methodology

Jørgensen and Zaccour (2007) recognize that the complexity of some differential games comes at the cost of using numerical methods rather than obtaining analytical solutions. This model falls under this category. As the model is highly non-linear, it is too complicated to solve it analytically and I have to resort to numerical simulations.

The model is solved for an open loop Nash equilibrium, where each country takes its investment and BCT choices treating the choices of the other country as given. Since this model involves five state variables, a closed loop Nash equilibrium would require the BCT to be conditioned on all these variables. In addition, the instantaneous market equilibrium needs to be solved for in every period. This makes the model highly complex, I restrict the analysis therefore to open loop Nash equilibria.

This section presents the numerical methods that are used to determine the open loop Nash equilibria of the dynamic game between countries, and motivates the calibration of the model parameters.

4.4.1 Numerical Solution

The necessary conditions of South's government decision problem, described in section (4.3.1), along with the identical problem for North, are formulated in the form of a boundary value problem over an infinite time interval, involving eleven non-linear differential equations together with initial and terminal conditions for both countries. Finding an analytical solution is most likely not possible; I therefore adapt a numerical approach introduced by Grass (2012) and described by Altaghlibi and Wagener (2016), by solving for the solution paths as a boundary value problem, after approximating the transversality conditions by asymptotic conditions that hold for a large, but finite, time T.

More explicitly, the boundary value problem of this model consists of differential equations (4.13), (4.14), (4.20), (4.21), (4.22) and their symmetric equations for North, along with the dynamics of pollution (4.15), together with five initial conditions at $t = 0$ for the five states: the initial development levels ($K^s_{b,0}$, $K^s_{g,0}$, $K^n_{b,0}$, $K^n_{g,0}$) of both countries, the initial state of the stock of world pollution P_0, and finally, six terminal conditions: those are the transversality conditions (4.23) and their symmetric conditions for North.

4.4.2 Functional forms

The utility function in both countries is assumed to take a CES form (Dixit and Stiglitz (1977)). It reads for South

$$u^s_t(c^{ss}_t, c^{ns}_t) = [(c^{ss}_t)^\sigma + (c^{ns}_t)^\sigma]^{\frac{1}{\sigma}}.$$

Here $\sigma = \frac{\theta-1}{\theta}$, with θ denotes the elasticity of substitution between domestic and imported varieties. Accordingly, the consumer price index in each country can be represented by an aggregate price

$$p^s_t = [(p^{ss}_t)^{1-\theta} + (p^{ns}_t)^{1-\theta}]^{\frac{1}{1-\theta}}.$$

Technology used for production is assumed to be accessible to both countries. Furthermore, the production function for final goods takes a Cobb-Douglas form between labor and energy and a CES form between green and brown energy

$$F(L^s_t, E^s_{b,t}, E^s_{g,t}) = (L^s_t)^{1-\gamma}[(E^s_{b,t})^\epsilon + (E^s_{g,t})^\epsilon]^{\frac{\gamma}{\epsilon}}.$$

Here $\epsilon = \frac{\varepsilon - 1}{\varepsilon}$, with ε representing the elasticity of substitution between green and brown energy. Throughout the analysis, the two types of energy are assumed substitutes, such that $\varepsilon > 1$. The two kinds of energy become perfect substitutes whenever ε tends to infinity. Finally, γ denotes the elasticity of output with respect to energy.

The damage functions from global pollution are assumed to be quadratic:

$$D^i(P_t) = \frac{\eta^i}{2}(P_t)^2, \qquad i \in \{s, n\},$$

where i is a country index. The parameters $\eta^i \geq 0$ have three related interpretations in this model. Firstly, they govern the weight of the environmental quality in the welfare of each country, equivalently, they represent an index of environmental awareness. Secondly, they capture the stringency of the implicit climate policy across countries. Thirdly, as this model has two channels of strategic interaction between countries, namely international trade and global pollution, these parameters manage the pollution game between countries. Whenever $\eta^i = 0$, countries interact only through international trade. If η^i is positive, the pollution game becomes active and the level of global pollution affect the government decisions across countries.

4.4.3 Calibration

I adopt the calibration provided in chapter 2 for the parameters in this model, by taking a wind energy plant as a model for green industrial capital, and a traditional coal/gas energy plant as a model for brown capital. I obtain a range of values for each parameter as follows: the relative cost ($\frac{\beta_g}{\beta_b}$) of green investments with respect to brown investments ranges between 1 and 2.5, while the investment cost parameter β_b itself ranges between 2% and 8%. Emission intensity α^i with $i \in \{s, n\}$, of brown capital ranges between 5% and 9%. The damage from global pollution stock is likely to be a persistent problem for a long time, and in order to be consistent with the calibration of other parameters, I use a discount factor ρ between 3% and 6%. Higher values of the parameters η^i imply that governments care more about the environmental quality of their consumers when taking decisions. I calibrate this parameter such that the weight of the damage from global pollution relative to the utility from consumption does not exceed 30%. I choose different values of η^i to test different assumptions about environmental concerns across countries. The natural decay rate for the emissions of installed capital is between 1.55% and 2.8%. The uniformed depreciation rate for both types of capital δ ranges between 2.5% and 5%. The elasticity of substitution between domestic and imported goods θ is set equal to 3.8, in line with Felbermayr et al. (2013). Finally, the elasticity of output with respect to energy γ is set such that the average labor elasticity of output is around 66%. The benchmark calibration for all parameters and initial conditions is summarized in Table 4.2 of Appendix 4.8.2.

4.5 Results

I focus in this paper on three possible BCT configurations across countries: a benchmark case, which reflects free trade, where no country is allowed to implement a BCT; an asymmetric case where only one country is assumed to be able to implement a BCT while the other country remains passive, henceforth called a unilateral BCT; finally, a third case where both countries can implement a BCT, which is henceforth called a bilateral BCT. I investigate the investment and BCT decisions in each country among the three cases and under different assumptions between countries. I start by analyzing the steady state of the model and perform a comparative analysis for some key parameters. I turn afterwards to study the optimal paths of the main variables and analyze the effect of asymmetry between countries in initial development level and some key parameters on these paths. Finally, I contrast the impact of a BCT with those of a normal tariff.

4.5.1 Steady state and comparative analysis

This subsection describes the long run results of the three cases under benchmark parameters. I show in Appendix 4.8.3 how I solve for the steady state for each these. I distinguish for each case two sub-cases; first, the "consumption only" case when governments are assumed to not to care about green welfare, meaning $\eta^n = \eta^s = 0$, and, second, the "environmentally conscious" case where governments put a positive weight on the green welfare of their consumers, having $\eta^n = \eta^s > 0$. Finally, I present a comparative parameter analysis for the optimal BCT rates.

Free trade: no BCT in any country

Consumption only

I start the analysis by studying the investment decisions in the benchmark case of free trade between countries, that is $\tau_t^n = \tau_t^s = 0$. Simulations for this case, under the benchmark calibration, are reported in the second column of Table 4.4 of Appendix 4.8.4.

Both countries invest in both kinds of capital even when the two types of electricity are perfect substitutes. The two kinds of capital co-exist; due to the concavity of the production function, investing in green capital is always feasible. Under this configuration, the ratio of brown to green capital in the steady state equals the relative cost between the two kinds of investments ($\frac{\beta_g}{\beta_b}$). Naturally, if green investments become more expensive relative to brown ones, countries invest more in brown rather than in green capital, which result in a decrease of output. If both kinds of capital have the same investment costs, then governments invest equally in both. The representative consumer demands domestic and imported varieties equally since there is no price distortions under free trade. The lump sum subsidy is positive and is quantitatively increasing with higher levels of capital and output in the steady state.

Environmentally conscious

When governments take the environmental quality of their consumers into account, that is, when $\eta^n = \eta^s > 0$, there is a new cost to the economy since pollution has a social value now, leading to lower output and capital stocks in the steady state compared to the consumption only scenario. This is illustrated in the fourth column of Table 4.4 in Appendix 4.8.4. Higher values of η^i result in more investments in green capital and lower investments in brown capital, but the net total stock of capital is lower since green investments are assumed more costly relative to brown ones. The decrease in capital stocks induces a decrease in output, lump sum subsidies, and consumption.

In this case, there is a trade off for investing in brown capital. On one hand, there is a social cost as any additional unit of brown capital results in an increase in the global pollution stock, hence investing in green capital is preferred by governments. On the other hand, as brown investments are relatively cheaper than green ones, the marginal production cost is lower with more brown capital, thus brown capital is preferred.

Unilateral BCT

In this subsection I assume that only one country, namely North, is able to implement a BCT while South remains passive. As a benchmark I use the case of free trade. Even though the main motivation for implementing a BCT is to protect the environment, countries may take advantage of it to protect their own industries or to shift the cost of developing green capital towards the other country. Moreover, a BCT represents a form of an international transfer by providing additional income for the implementing country. In order to isolate the different effects of these incentives for the implementing country, I distinguish also here between a "consumption only" scenario and an "environmentally conscious" one. I analyze the impact on the main variables including both green and non-green welfare.

Consumption only

I find that even if $\eta^n = \eta^s = 0$, North decides to impose a positive BCT, $\tau^n > 0$, in steady state. This BCT represents a form of protectionism, as there are no environmental incentives to implement it. By imposing a BCT, North gains in terms of trade and international competitiveness. The BCT induces price and income effects in both countries. It creates a wedge between the price of imported and domestic varieties at North. The optimal unilateral BCT rate under the benchmark calibration is reported in the second column of Table 4.3 of Appendix 4.8.4. The fifth column of Table 4.4 summarizes the main effects of this BCT on main variables as a percentage change from the free trade benchmark. It shows that as imported varieties become more expensive, consumers switch to domestically produced ones. Consumers in both countries face higher prices. However, the price increase at North is offset by an increase in income, which is financed by the BCT revenues and channeled to consumers through the lump sum subsidies from the government. Meanwhile, South's consumers face a decrease in their real income that lowers their demand of imported varieties. For North, this decrease in export demand is compensated by the increase in domestic demand, leaving total output, capital stocks, and factor prices without a change.

The optimal unilateral BCT rate imposed by North under this case is such that the BCT revenues induce an increase in income by an amount that exactly offsets the welfare loss of higher price levels at North. More precisely, the optimal BCT rate, which maximizes the welfare of North, equalizes the marginal gain from improving the terms of trade and the marginal efficiency costs. At that level, welfare is maximized or North's welfare function reaches a maximum (Krugman et al. (2015)). The steady state level of South's brown capital decreases; the level of its green capital increases inducing a reduction in its output and international competitiveness.

The elasticity of substitution between domestic and imported varieties plays an essential role in the quantitative results analyzed here. More precisely, as long as domestic and imported varieties have some degree of complementarity ($\theta < \infty$), there will be a positive unilateral BCT because there will always be some demand of imported varieties at North.

Environmentally conscious

When countries take the environmental quality of their consumers into account, $\eta^n = \eta^s > 0$, pollution costs enter policy decisions. The third column of Table 4.3 of Appendix 4.8.4 reports the optimal BCT rate, while the sixth column of Table 4.4 reports the percentage change in main variables from the free trade benchmark. In this case, part of the motivation for imposing a BCT is environmental. Since a BCT targets only the carbon content of South's imports, North is able to use it to shift most of the costs that are related to environmental pollution to South. Results show that the BCT rate implemented by North increases with higher values of η^i. Compared to the benchmark case of free trade, South invests less in brown and more in green capital, and witnesses a further decrease in its output. North takes advantage of this reaction by South by investing less in green and more in brown capital, resulting in the net increase of capital stocks at North. North's output and lump sum subsidies increase following an increase in global demand of its varieties. Both countries benefit from lower global pollution after the BCT is implemented. Global welfare goes down as consumers across countries face higher prices. The negative effects of the BCT on South's non-green welfare are however partly mitigated by the rise in green welfare from a lower global pollution stock.

To summarize

Results derived in this subsection suggest that even when countries do not take the environment into account, imposing a unilateral BCT, or a tariff on the carbon content of imports, is an effective tool to direct investments in the exporting country towards green capital, as a BCT affects the investment decisions in South: South can avoid the BCT by investing in green rather than brown capital. Moreover, the more costly global pollution is (higher η^i) the more control the implementing country has, and the more it is able to take advantage of the BCT to shift the cost of reducing pollution to the other country. This increase in the unilateral BCT advantage is noticeable by the increase of North's long run output and brown capital stock when η^i is positive compared to the case when $\eta^i = 0$. The intuition here is that North knows that South cares about the environment and would have to reduce its brown investments to compensate for North's increase of its brown capital stock. Similar results were highlighted by Copeland (2012) and Branger and Quirion (2014) who noted the controversiality of BCT because they can be used by the abating countries to shift a part of the emission reduction costs to non abating countries.

Bilateral BCT (BCT war)

Imposing a unilateral BCT is not directly relevant in practice as it most likely induces the other country to react by imposing a BCT as well. Such situation is known in the international trade literature as a "tariff war", when countries implement tariffs on the value of their imports. I analyze in this subsection what I call a "BCT war", that is a bilateral BCT implemented across countries, distinguishing again between the "consumption only" and "environmentally conscious" scenarios. I describe main effects from the benchmark case of free trade and symmetric countries.

Consumption only

In equilibrium, as we have identical countries, a symmetric positive BCT rate is implemented by both countries. The bilateral BCT induces symmetric effects across countries. The optimal bilateral BCT rate under the benchmark calibration is reported in the fourth column of Table 4.3 of Appendix 4.8.4, and the sixth column of Table 4.4 summarizes the main effects of the bilateral BCT on main equilibrium variables as a percentage change from the free trade benchmark.

A bilateral BCT makes imported varieties more expensive relative to domestic ones, and consumption therefore shifts towards the latter. The bilateral BCT results in a shift towards green investments. Lump sum subsidies increase as the BCTs generate positive revenue. Nevertheless, this income effect does not compensate for the negative price effect: total demand goes down, total capital stock and output in both countries decrease, inducing a negative effect on welfare. This is of course a known result in traditional trade theory: a tariff war between countries induces a negative effect on national and global welfare. A possible interpretation of the bilateral BCT is that countries regain "control" when they implement it even though it has a negative impact on GDP and welfare following a higher prices globally.

Environmentally conscious

When governments start to take the environmental quality of their consumers into account, that is when $\eta^s = \eta^n > 0$, I find the most important result of this paper, namely that bilateral BCT rates become an effective tool to increase national and global welfare. Figure 4.1 makes this point clearer. Let $\triangle$ denotes the gain in consumption due to the bilateral BCT, which is defined as follows:

$$u_t^s(c_{w,t}^{ss}, c_{w,t}^{ns}) - D^s(P_{w,t}) = u_t^s(\triangle c_{f,t}^{ss}, \triangle c_{f,t}^{ns}) - D^s(P_{f,t})$$

Here the subscripts w and f denote consumption and pollution under BCT war and free trade respectively. Assuming a homogenous utility function of degree 1, I obtain

$$\triangle = \frac{u_t^s(c_{w,t}^{ss}, c_{w,t}^{ns}) - D^s(P_{w,t}) + D^s(P_{f,t})}{u_t^s(c_{f,t}^{ss}, c_{f,t}^{ns})}.$$

Accordingly, the vertical axes Figure 4.1 plots the relative gain in consumption due to the bilateral BCT ($\triangle - 1$), while the weight of the environmental quality of consumers (η^i) is plotted on the horizontal axes.

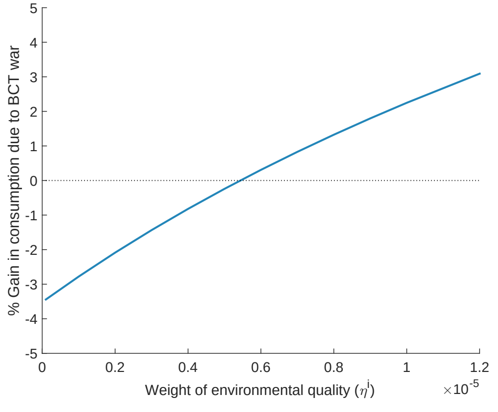


Figure 4.1: Bilateral BCT effects on consumption across η^i

The Figure shows that imposing the bilateral BCT decreases consumption for low values of η^i, which correspond to what traditional trade theory predicts for a "tariff war". However, the negative effect on consumption weakens if η^i increases and becomes a gain as the environmental quality of consumers become more important. This is an important result: a "BCT war" is welfare increasing when countries put sufficient weight on the environmental quality of their consumer. The interpretation for this result is as follows. As damage from global pollution becomes more important the environmental benefits of implementing a bilateral BCT outweigh the loss in consumption, which become relatively small with higher BCT rates. In other words, the bilateral BCT becomes an effective tool to internalize the pollution externality. The fifth column of Table 4.3 of Appendix 4.8.4 reports the optimal bilateral BCT rates, and the seventh column of Table 4.4 summarizes the main effects of the bilateral BCT on main variables as a percentage change from the free trade benchmark.

South \ North	No BCT	BCT
No BCT	$(6.77, 6.77)$	$(6.15, 7.11)$
BCT	$(7.11, 6.15)$	$(6.54, 6.54)$

(a) Payoffs matrix when $\eta^i = 0$

South \ North	No BCT	BCT
No BCT	$(4.42, 4.42)$	$(4.06, 5.07)$
BCT	$(5.07, 4.06)$	$(4.79, 4.79)$

(b) Payoffs matrix when $\eta^n = \eta^s > 0$

South \ North	No BCT	BCT
No BCT	$(6.71, 3.37)$	$(6.11, 3.96)$
BCT	$(7.02, 3.27)$	$(6.49, 3.95)$

(c) Payoff matrix when $\eta^n > 0$ and $\eta^s = 0$

Table 4.1: Payoffs matrices

The aforementioned result can also be illustrated using the matrices in Table 4.1 which summarizes the steady state payoffs (welfare) of North and South under different BCT configurations across the two countries. The strategy of each country is either to implement a BCT or not, and the first component of each cell represents South's payoff. The matrix in Panel 4.1a reflects the "consumption only" case. This is a prisoner dilemma game. The Nash equilibrium in this case is to have a "BCT war" while the social optimum is clearly to play No BCT by both countries. This game supports the WTO argument to promote free trade, as free trade will benefit the importing and exporting countries. However, the "environmentally conscious" case in Panel 4.1b reports the payoffs of the situation when countries care about the environment to a sufficient degree. The Nash equilibrium when both countries set a BCT becomes the social optimum. This result remains valid even when countries have asymmetric weights for the damage from global pollution, as shown in Panel 4.1c.

Note here that the bilateral BCT restores the equivalence of welfare between countries compared to the case of a unilateral BCT, as South's welfare increases while that of North decreases until they become equal. However, global welfare, as measured by the discounted sum of national welfare, is quantitatively lower under the bilateral BCT relative to the unilateral BCT case.

Comparative parameter analysis

In this subsection I analyze how the endogenously determined unilateral and bilateral BCT rates are affected by different parameters in the model. I report in Table 4.5 of Appendix 4.8.4 the elasticity of these rates with respect to different parameters deviating from the benchmark calibration described in Appendix 4.8.2. The effects on the demand, capital stocks, and welfare across countries follow from earlier discussion. First of all, comparing the level of the two BCT rates, the bilateral BCT rate is lower than the unilateral BCT rate. This is expected since South is not passive under the bilateral case and it retaliates by imposing a BCT on North's exports, which breaks North's advantage under the unilateral case inducing North to apply a lower rate.

Both the unilateral and bilateral rates decrease when green investments are more expensive relative to brown ones ($\frac{\beta_g}{\beta_b}$), because countries become more constrained in building their green capital. A higher natural decay rate ϑ affects the stock of global pollution negatively, therefore lower BCT rates are needed. A higher depreciation rate of capital δ results in lower unilateral BCT rate and a higher bilateral rate. This is because higher δ induces lower capital stocks and output in the steady state, and thus a lower unilateral rate is needed to affect South's brown capital. Optimal unilateral and bilateral rates increase as governments become more sensitive to global pollution (higher η^i), because these rates have higher influence in the pollution game between countries with high values of η^i. Furthermore, when one country is assumed to be more concerned about the environment, for example $\eta^n > \eta^s > 0$, the other country implements a higher BCT rate, that is $\tau^s > \tau^n$.[3] The unilateral BCT rate imposed by North becomes higher.

[3] This case is analyzed in detail in subsection (4.5.2).

Higher emission intensity of brown capital in both countries α^i, increases the global pollution and induces a lower BCT rates in the steady state. As the carbon content per unit of imports becomes higher, lower rates are needed to affect brown capital. Moreover, when there is asymmetry in emission intensities of brown capital across countries, due to some technological advancement for example, having a lower emission intensity at North (lower α^n) induces a lower unilateral BCT rate because North has more control on global pollution through its own investments. A lower emission intensity at South (lower α^s) has two effects: it decreases global pollution and the unilateral BCT revenues for North, the latter effect dominates and North implements a higher unilateral BCT rate to compensate for the reduction of its revenues[4]. For the bilateral BCT, the country with dirtier brown capital imposes a higher rate in order to switch the cost of reducing global pollution to the other country.

Furthermore, the easier imported varieties can replace domestic ones (a higher θ), the lower both BCT rates become. This is because the demand of imported varieties becomes more sensitive to changes in prices with higher θ. Finally, a decrease of the degree of substitubililty between green and brown energy in the production process (lower ε) induces a decrease of the unilateral BCT rate implemented. This is because the BCT becomes less effective in shifting the use of energy towards green energy as the two kinds of energy are needed for production.

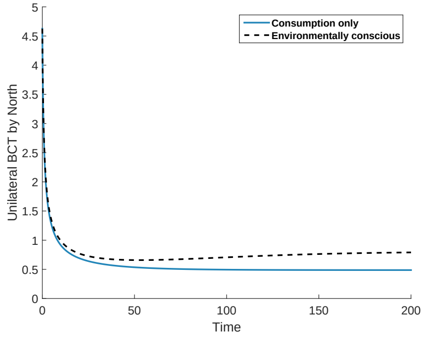
4.5.2 Optimal paths and asymmetry across countries

When there is symmetry in initial conditions and in main parameters across countries, the optimal unilateral BCT rate is not constant over time. More precisely, North starts with almost a prohibitive rate (around 450%) which allows it to build its capital faster. The BCT rate decreases gradually until it stabilizes at its steady state level.

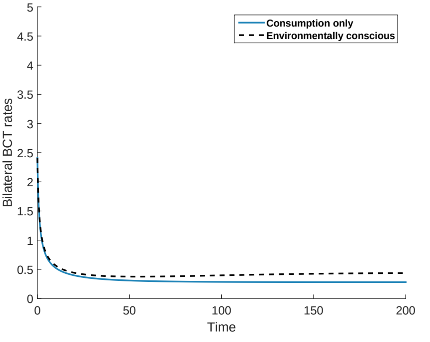
The bilateral BCT rates have similar optimal paths but on a lower level. Panels 4.2a and 4.2b of Figure 4.2 depict the optimal unilateral and bilateral and BCT rates respectively. The solid curve in

[4] Note here that North is better off sharing its clean technology, as a decrease in South's emission intensity would induce a positive effect on North's welfare.

these Panels represents BCT rates under a consumption only case ($\eta^i = 0$), while the dashed curve reflects the case when countries are environmentally conscious ($\eta^i > 0$), under the assumption of symmetric countries.



(a) Unilateral BCT rate by North for $\eta^i = 0$ and $\eta^i > 0$



(b) Bilateral BCT rates for $\eta^i = 0$ and $\eta^i > 0$

Figure 4.2: Optimal profile for unilateral and bilateral BCT rates (symmetric countries)

The BCT profiles in Figure 4.2 suggest that it is optimal for countries at low development levels to open their markets gradually along with their economic development. The interpretation of this result is that countries initially protect their infant industries from global competition until they become sufficiently mature to compete internationally. In addition, the higher initial BCT revenues can be used in new investments to have a faster growth for the implementing country. Moreover, the BCT has a negative effect on the accumulation of capital in the exporting country which gives the implementing country a competitive advantage by having a cheaper products internationally.

A higher initial stock for global pollution induces both countries to shift investments at the beginning of the time horizon towards green capital. Both unilateral and bilateral BCT rates are initially higher as well. National and global discounted welfare decrease as shown in the fourth column of Table 4.6 of Appendix 4.8.4.

I focus in subsequent subsections on analyzing the impact of introducing various forms of asymmetry across countries. More precisely, I start by studying a temporary asymmetry in initial development levels, when one country is assumed initially richer than the other. I turn afterwards to assessing the impacts of asymmetry in the weight governments put to the environmental quality of their consumers. We shall see that the asymmetry in initial development levels across countries plays an important role in determining the direction and the growth path across countries.

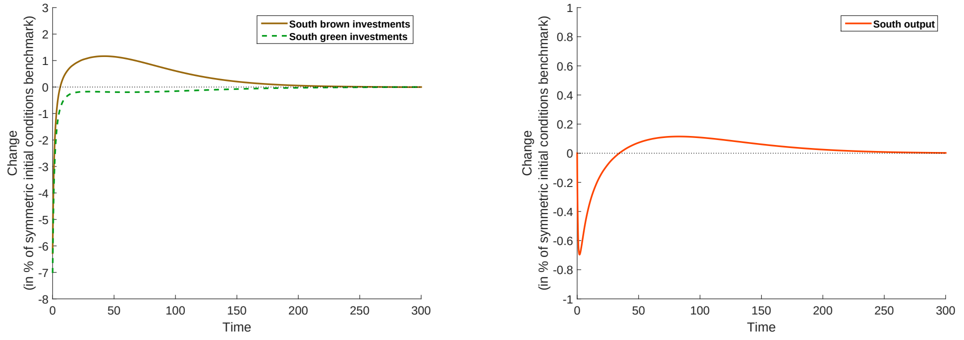
Asymmetry in initial development levels across countries

In this subsection the optimal paths of BCT rates and main variables are analyzed when one country is assumed to be initially richer than the other. This asymmetry is temporary and disappears as the two countries converge to the same steady state in the long run. Countries can be initially richer either in green or brown capital. I shall treat these cases separately. The case of symmetric initial conditions is used as a benchmark. We will see that South witnesses a slower growth only if North is initially richer in brown capital. The asymmetry in initial green capital induces an intertemporal substitution effect between consumption and investments at South.

North initially richer in green capital

In this subsection North is assumed to be initially richer in green capital, that is $K^n_{g,0} > K^s_{g,0}$, while both countries have the same initial level of brown capital $K^n_{b,0} = K^s_{b,0}$. The initial level of green capital $K^n_{g,0}$ is set at the steady state level under free trade.

The main change in the optimal paths is in the transitional period at the beginning of the time interval. When we have free trade between countries, the relative producer price at North $p^n_{p,t}$ decreases, with respect to the benchmark case of symmetric initial development levels, making North's varieties cheaper in domestic and export markets and increasing demand for them globally. Accordingly, South consumes less of domestic varieties and more of imported ones. North's output increases initially and this in turn rises wages following an increase in labor demand for production. North's higher income from rising wages and subsidies increase its consumption of both varieties. As its capital stock is already large, North invests less in both types of capital. Figure 4.3 depicts the relative change in South's green and brown investments along with the relative change in its output under free trade. Panel 4.3a shows that there is a decrease in investments in green capital and an intertemporal effect on investments in brown capital. The latter decrease in early periods and increase afterwards.



(a) Change in South's investments

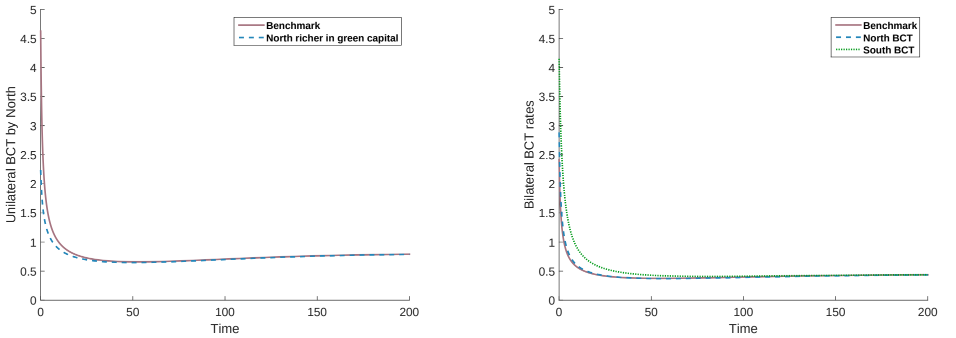
(b) Change in South's output

Figure 4.3: Change in South's output and investments when North is assumed initially richer in green capital

This suggests an inter-temporal substitution effect between consumption and investments at South. This effect arise because higher initial green capital at North brings down energy prices and makes Northern varieties more competitive internationally. South's imports become relatively cheaper than domestic varieties, thus South postpones part its investments towards the future. This intertemporal effect follows for South's output as shown in Panel 4.3b. Furthermore, South takes advantage of lower investments by North to shift its investments towards brown capital, which explains the humped shaped increase in its output as brown capital is relatively cheaper than green one. Transitional global pollution decreases while the discounted welfare in both countries increases. The third column of the Table 4.6 of Appendix 4.8.4 reports the percentage change in countries' discounted welfare under this case.

The analyzed impacts are similar for the cases of unilateral and bilateral BCT rates across countries. The main effects on North's unilateral BCT rate are depicted in Panel 4.4a of Figure 4.4. The solid curve in this Panel represents the BCT rate under a benchmark case of symmetric initial development levels across countries, while the dashed curve represents the scenario when

North is assumed initially richer in green capital. From this graph we can see that the unilateral BCT rate has a similar path but it starts initially at a lower level. This supports our earlier finding that opening trade should be done gradually along the development path of countries. As North becomes initially richer it opens its markets sooner. Conversely, if South is the one assumed to be initially richer in green capital, North implements a higher unilateral BCT rate to close its markets against cheaper imports which allows it to shift investments towards brown capital and grow faster.



(a) Change in the unilateral BCT rate by North

(b) Change in bilateral BCT rates

Figure 4.4: Change in the unilateral and bilateral BCT rates when North is assumed initially richer in green capital

Panel 4.4b shows changes in the bilateral BCT rates across countries. This Panel illustrates that South starts at a higher BCT rate (dotted curve), while North increases its BCT (dashed curve) initially a little. The development advantage of North in green capital makes its varieties greener by having a lower carbon content. Accordingly, these varieties have an easier access to South's markets since South's BCT only covers the carbon content of its imports. Therefore, South has to implement higher BCT rate to close its markets in order to build its capital. The bilateral rates converges to the same rate, as the capital asymmetry between countries diminishes over time.

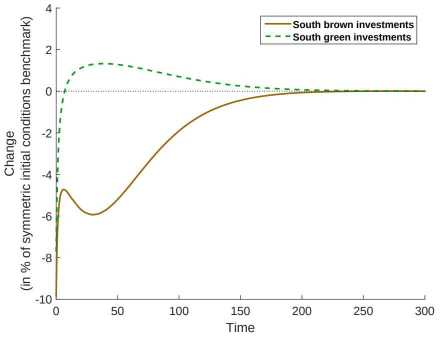
North initially richer in brown capital

I turn to the situation where North is initially richer in brown capital, i.e: $K^n_{b,0} > K^s_{b,0}$, while $K^n_{g,0} = K^s_{g,0}$. Since the level of accumulated brown capital in the developed world is presumed not to be sustainable, initial brown capital $K^n_{b,0}$ is set twice the steady state level of brown capital under free trade[5]. This case is more realistic as most developed countries had achieved their development level by accumulating brown capital. Developing and least developed countries argue that developed countries should be held responsible for the current high levels of pollution, because these pollution levels have a negative effect on their growth. In this subsection I investigate the validity of such claim.

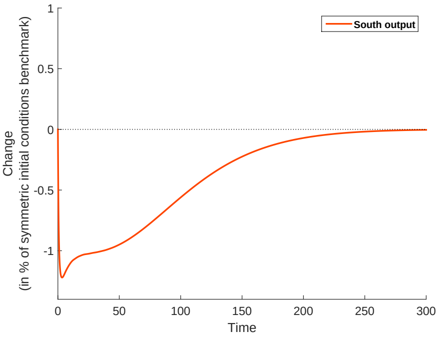
The relative producer price at North decreases initially and Northern varieties become cheaper globally, which induce the same effect on the market as described in the asymmetry in green capital. However, the difference in this case is in the impacts on South's investments, output, and the transitional pollution. Figure 4.5 depicts the relative change in South's investments and output, from the symmetric initial conditions benchmark, under free trade. Panel 4.5a illustrates that South invests less in brown capital and more in green capital. Moreover, the quantitative decrease in brown investments outweighs the increase in green ones, thus South witnesses a decrease in its output level, as shown in Panel 4.5b. This induces a decrease in South's wages following a decrease in labor demand.

This result suggest that South would witness a slower growth as it takes more time to reach its balanced growth path. There are two reasons for the slower growth of South. The first is because of North's development advantage, that is North is abundant in brown capital which makes it more competitive internationally. The second reason is through global pollution. A higher initial brown capital in North induces a higher initial pollution stock, and South has to accommodate for this by investing less in brown capital, this accordingly induces a lower output as green capital is relatively

[5] This yield an initial output ratio between North and South around 113%. This ratio corresponds to the 2015 GDP per capita of United Arab Emirates relative to that of the Central African Republic in PPP.



(a) Change in South's investments



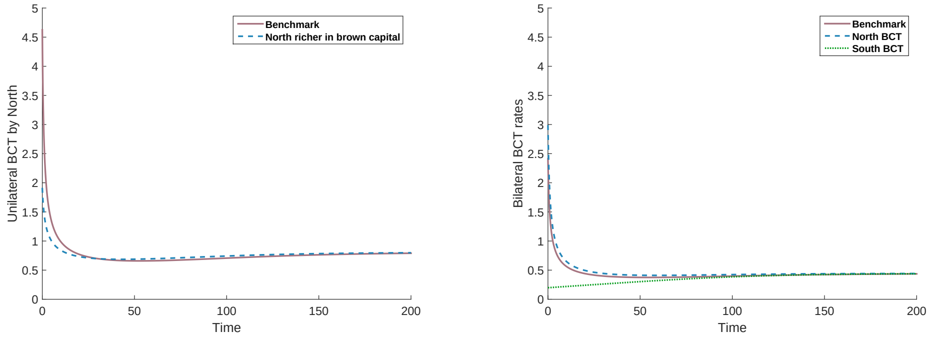
(b) Change in South's output

Figure 4.5: Change in South's output and investments when North is assumed initially richer in brown capital

more expensive relative to the green one. South's discounted welfare decreases as illustrated in the third column of Table 4.6 in Appendix 4.8.4. Note here that South's slower growth is further slowed down in the unilateral and bilateral BCT cases. Figure 4.6 embodies the main changes on the unilateral and bilateral BCT rates in this case.

A unilateral BCT rate in Panel 4.6a has the same effect as the case when North is assumed initially richer in green capital. Conversely, when South is the one that is assumed to be initially richer in brown capital, a lower unilateral BCT rate is imposed by Northern government, as a higher initial global pollution stock forces North to allow for cheaper imported varieties to enter its market more easily, as the degradation of initial environmental conditions prevents North from investing in cheap brown capital.

The bilateral BCT rates act differently here as well. Panel 4.6b clarifies the difference, compared to what we obtained in Panel 4.4b for the initial asymmetry in green capital. The carbon content of South's imports is high in this case. At the same time, South has to adapt to higher initial pollution stock, caused by North's initial brown capital, which induces it to implement a lower BCT rate and to open its markets to cheaper imports.



(a) Unilateral BCT rate by North

(b) Bilateral BCT rates

Figure 4.6: Change in the unilateral and bilateral BCT rates when North is assumed initially richer in brown capital

To summarize

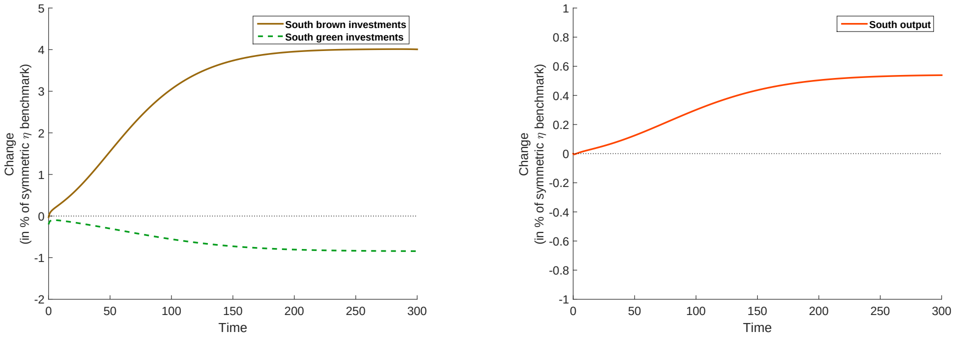
The cases analyzed in this subsection highlight the effect of asymmetric initial development levels on the growth path of an initially poorer country. They show that initially richer country always decrease its investments in both types of capital. The higher capital stock at North decreases the price of its varieties globally, the demand of these varieties follows. When North is initially richer in green capital, there would be an intertemporal substitution effect between consumption and investments at South. South postpones investments to the future and increase its consumption in early periods. If North is initially richer in brown capital, South witnesses a slower growth. North forces South to invest in green capital because of its development advantage. This finding supports the argument of developing countries that developed countries should help financing their green investments to help them grow faster. This was acknowledged by Paris Climate Agreement 2015 where developed countries committed themselves to give climate finance up to $100 billion per year, starting from 2020 onward, to help developing countries face the challenges of climate change (Eyckmans et al. (2016)).

Higher weight for environmental quality at North

The global nature of transboundary pollution provides an incentive for free riding by imposing a lax climate policy in response to reduction in emissions by others (Carraro and Siniscalco (1998), Copeland and Taylor (2005), Elliott et al. (2010)). I investigate in this subsection the phenomena of carbon leakage: emissions savings by one country is offset by the increase in emissions of another country with a lax environmental regulation. I also introduce the concept of "growth leakage". As mentioned earlier the stringency of environmental regulation in this model is captured by the weight governments put for the environmental quality of their consumers (η^i). Further, since emissions are assumed proportional to the installed brown capital stocks, the change in country specific brown capital reflect the change in its emissions. Accordingly, I analyze the effect of the asymmetry in the weight that governments put to the environmental quality of their consumers on investments in brown capital. I use free trade and symmetric environmental weights ($\eta^n = \eta^s > 0$) as a benchmark. I deviate from this benchmark by increasing the weight of environmental quality at North (increase in η^n).

As North becomes more concerned about the environment it invests less in brown capital and more in green capital of its own accord. South free rides on this fact by investing more in brown and less in green capital. This confirms the existence of carbon leakage when one country is more concerned about the environment than the other. Global pollution goes down and stabilizes at a lower level in the long run as the quantitative decrease in North's brown capital outweigh the increase in that of South. Figure 4.7a illustrates the change in South's green and brown capital stocks and the existence of leakage. The solid curve in this Figure represents the relative change in South's brown investments while the dashed curve depicts the change in its green ones, under free trade.

North's relative producer price starts at the same level initially but it increases gradually to stabilize at a higher level in the long run. This is because the net capital stock increases at South and decreases at North, which makes Northern varieties relatively more expensive globally. The global demand of these varieties goes down. North's output decreases which negatively affect



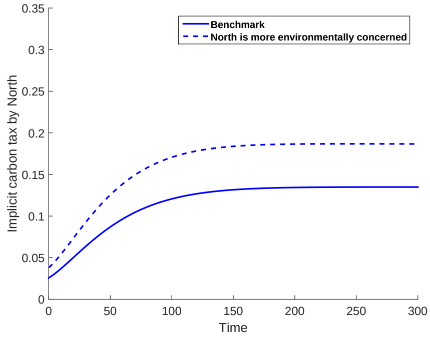
(a) Change in South's green and brown capital stocks

(b) Change in South's output

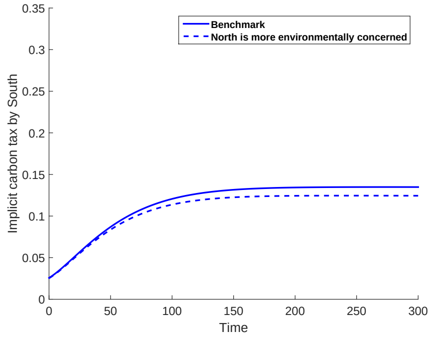
Figure 4.7: Change in South's output and investments when North is more environmentally concerned (higher η^n)

income and induces a fall in North's consumption of both imported and domestic varieties. On the other hand, the demand of Southern varieties increases in domestic markets. This is caused by the increase in South's output which can be seen in Panel 4.7b of Figure 4.7. South's wages increase following the rising labor demand. The fifth column of the Table 4.6 in Appendix 4.8.4 shows that the discounted welfare falls for North and rises for South. The negative effect on North's welfare has two sources. On one hand, global pollution has a higher effect on North's welfare (higher η^n), on the other hand, North's consumption decreases. These results suggest that the country that is more concerned about the environment would be the one to bear most of the cost of decreasing the level of global pollution. Arguably, this country witnesses a slower growth and a lower development level in the long run, while the other country free rides on this fact to increase its long run levels of brown capital and output. I call the latter effect "growth leakage".

Figure 4.8 depicts the implicit carbon tax rates, that are determined by (4.24), on the vertical axes. Panel 4.8a shows that as η^n increases, North increases its tax rate while South does the contrary in Panel 4.8b, reflecting the free riding behavior of South and emphasizing the leakage phenomena.



(a) Change in North's implicit carbon tax



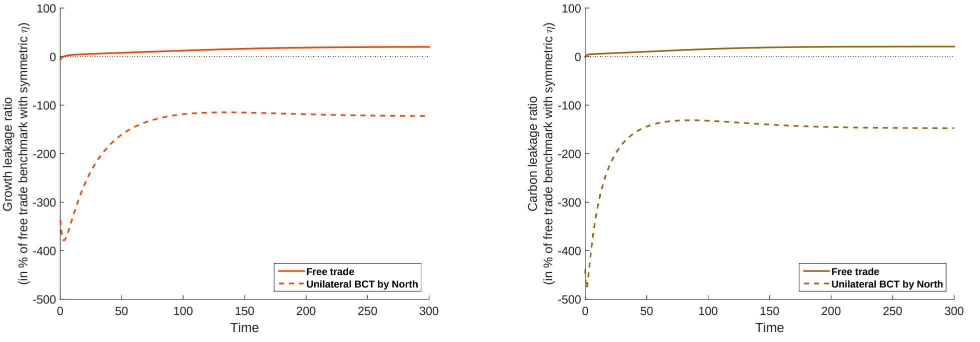
(b) Change in South's implicit carbon tax

Figure 4.8: Change in implicit carbon tax rates across countries when North is more environmentally concerned (higher η^n)

North's unilateral BCT rate does not change at the beginning of the time span, however, it stabilizes at a lower steady state level. This is because the incentives of North to take advantage of the unilateral BCT to shift the cost of reducing global pollution to South decreases when ($\eta^n > \eta^s$). As North controls pollution through its own investments, it opens its markets to relatively cheaper imports. Moreover, in the bilateral BCT case, the rate imposed by South increases while that of North decreases. This is because South knows that North is more concerned about the environment than it does and it uses its BCT to shift the burden of reducing global pollution to North by investing more in brown capital and closing its markets further against Northern imports.

BCT and leakages

Carbon leakage is normally measured, and reported, as a ratio between the emissions increase by countries with a lax environmental regulation relative to emission savings by countries with a tighter regulation. Similarly, I measure growth leakage by the ratio of the increase in output of the country that is less concerned about the environment reltaive to the decrease in output of the country with higher environmental awareness.



(a) BCT effect on growth leakage

(b) BCT effect on carbon leakage

Figure 4.9: BCT effect on leakages when η^n increases from $(\eta_0^n = \eta_0^s)$ to $(\eta^n > \eta_0^s)$

In order to evaluate the effectiveness of a unilateral BCT to mitigate carbon leakage, I keep the assumption of asymmetry in the η^i and I compare the unilateral BCT and the free trade equilibria. Panels 4.9a and 4.9b of Figure 4.9 show, respectively, growth and carbon leakage ratios for the cases of free trade and a unilateral BCT by North when η^n increases from the free trade benchmark of $(\eta_0^n = \eta_0^s > 0)$. The solid curve of Panel 4.9a illustrates the previously described growth leakage expressed by the leakage ratio between the increase in South's output and the decrease in the output of North, the dashed curve shows the effect of unilateral BCT in mitigating this leakage as the growth leakage ratio becomes negative. Similarly, Panel 4.9b depicts the carbon leakage expressed as a ratio between the emission increase in South relative to emission savings by North. This Panel clearly show that the decrease under the unilateral BCT more than enough to offset the leakage under free trade. The discounted welfare goes down for South and up for North due to the BCT. Therefore, I conclude that the BCT is an effective instrument to tackle both growth and carbon leakages. However, as mentioned earlier, it is obvious from the magnitudes of the leakage ratios that North takes advantage of the BCT, to exhaust the terms of trade benefits, by implementing higher rate than is needed to offset the free riding behavior of South, and tackle these leakages. Therefore, I stress here the necessity to implement a unilateral BCT rate that maximizes global rather than only the national welfare of the implementing county. This case is analyzed in the subsequent section.

4.5.3 Tariff effects

I turn in this subsection to briefly analyze the effect of a normal tariff, that is ad-valorem tariff on imports, on the growth direction across countries. I highlight as well the main differences between a BCT and a normal tariff.

For a normal tariff the consumer price of South's imports in (4.9) can be rewritten, excluding the carbon content of imports z^n, as:

$$p_t^{ns} = (1 + \tau_t^s) p_{p,t}^n. \tag{4.25}$$

Accordingly, the instantaneous equilibrium condition (4.10) and the government budget constraint (4.16), respectively, become:

$$Y_t^s + S_t^s = c_t^{ss} + (1 + \tau_t^s) \frac{p_{p,t}^n}{p_{p,t}^s} c_t^{ns} + \frac{F'_{E_{g,t}^s}}{a_g^s} K_{g,t}^s + \frac{F'_{E_{b,t}^s}}{a_b^s} K_{b,t}^s, \tag{4.26}$$

$$F'_{E_{b,t}^s} E_{b,t}^s + F'_{E_{g,t}^s} E_{g,t}^s + \frac{p_{p,t}^n}{p_{p,t}^s} \tau_t^s c_t^{ns} \geq C_b^s(I_{b,t}^s) + C_g^s(I_{g,t}^s) + S_t^s. \tag{4.27}$$

Taking these new conditions into account the model is solved similarly to the BCT case by setting z^i equals to 1. Table 4.7 of Appendix 4.8.5 compiles the optimal unilateral and bilateral tariff rates under the benchmark calibration, while Table 4.8 summarizes the relative change in key variables from a free trade benchmark.

Results indicate that when governments are only concerned about consumption, the optimal unilateral and bilateral tariffs have no effect on the steady state level of capital or output across countries. These tariffs have only a static effect on the instantaneous equilibrium and no dynamic effect since they are imposed on the value of imports exchanged between countries and thus they do not affect the dynamics of the model through capital or pollution. The optimal tariff rate is lower than the optimal BCT rate because the BCT targets the carbon content of imports only and in order for North to exhaust all the terms of trade benefits a higher BCT rate is needed.

When governments become environmentally conscious ($\eta^i > 0$), the optimal unilateral tariff by North decreases a little mainly because the number of varieties exchanged between the two countries goes down, as output falls with higher η^i. The optimal bilateral tariff rate is insensitive to η^i. Similar to the BCT case, when governments are environmentally conscious, the unilateral tariff becomes an instrument that affect the game of emissions between countries. The implementing country gains an advantage to invest more in brown capital and increase its output, and therefore, shifting the cost of decreasing the global pollution damage to the other country. A retaliation by the exporting country (a tariff war) results in a lower output for both countries and induce a decrease in welfare regardless of the value of η^i. This is because the effect of the bilateral tariff on the damage from global pollution, compared to that of a BCT, is very modest to offset the welfare decrease from globally higher prices.

As long as there is symmetry in initial development levels across countries the unilateral tariff rate is constant over time. This is because the optimal tariff rate equalizes the marginal benefits form terms of trade and the marginal cost of consumer and producer distortions, therefore, it is not optimal to implement a higher rate initially. When the implementing country is initially poorer however, it becomes optimal to impose a higher initial tariff rate to protect infant industries. This further confirms that it is optimal for an initially poorer country to open its markets gradually to international products; initially richer country should opens its markets sooner.

The main difference between the tariff and a BCT is that a BCT affects South's incentives to invest: South can avoid the BCT by investing in green capital, which is not the case for the tariff and therefore a BCT is more efficient in tackling the leakage. At the same time, the BCT affect the pollution game between countries directly and gives the implementing country a higher advantage, compared to a tariff, to shift the cost of reducing emissions towards the other country.

4.6 Social BCT

We have seen in subsection (4.5.1) that it is optimal for a country which imposes a unilateral BCT to set a rate that exhausts all the terms of trade benefits. Moreover, when countries care about the environment, the implementing country can take advantage of the BCT to shift the cost of global pollution to the other country. In order to isolate the incentives of the implementing country, I introduce in this subsection a third party to the non-cooperative game between the two countries. In practice, this party can be represented by the World Trade Organization (WTO) or any other regulator of international trade. In the new game, the government in each country chooses how much to invest in green and brown capital, while the trade regulator chooses the BCT rate that can be implemented by any country.

The WTO's General Agreement on Tariffs and Trade (GATT) aims at eliminating trade barriers between member countries. However, paragraph (b) of Article XX allows WTO members to adopt policy measures that are inconsistent with GATT disciplines but necessary to protect human, animal, plant life or health.

The trade regulator chooses a unilateral BCT rate that maximizes global rather than national welfare of the implementing country. Since the BCT rate is chosen by the WTO, it is supposed to reflect a measure that aims to protect the environment, and therefore, it would be justified under paragraph (g).

I assume a utilitarian global welfare W_t^g equals the sum of national welfare across countries. The intertemporal global welfare reads:

$$W_t^g = \int_0^\infty [u_t^n(c_t^{nn}, c_t^{sn}) - D^n(P_t) + u_t^s(c_t^{ss}, c_t^{ns}) - D^s(P_t)]e^{-\rho t}dt. \tag{4.28}$$

The trade regulator chooses the BCT rate τ_t that maximizes (4.28) subject to a positivity constraint:

$$\tau_t \geq 0. \tag{4.29}$$

Condition (4.29) excludes the possibility of using a BCT to subsidize the carbon content of imports. The first order conditions yield:

$$\xi_t = u^{n'}_{c^{nn}_t}(c^{nn}_t)'_{\tau_t} + u^{n'}_{c^{sn}_t}(c^{sn}_t)'_{\tau_t} + u^{s'}_{c^{ss}_t}(c^{ss}_t)'_{\tau_t} + u^{s'}_{c^{ns}_t}(c^{ns}_t)'_{\tau_t} \tag{4.30}$$

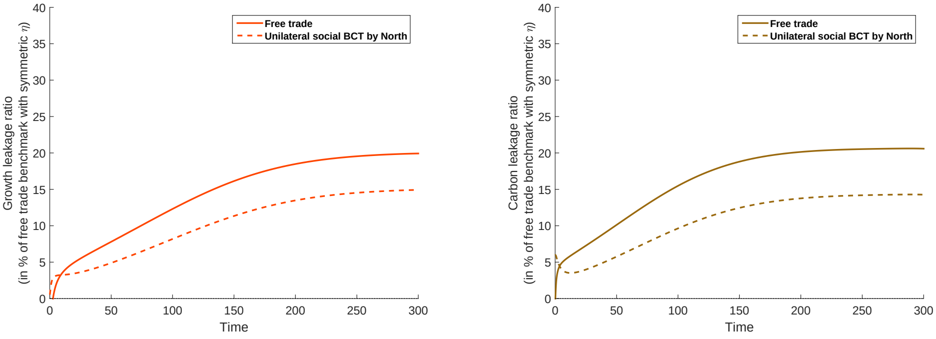
$$\xi_t \tau_t = 0. \tag{4.31}$$

Equation (4.31) is the complementary slackness condition, and (4.30) is the expression for the Lagrange multiplier ξ_t that is associated to the positivity constraint (4.29). This multiplier has also to satisfy the positivity condition $\xi_t \geq 0$ for all $t \geq 0$. The government problem in both countries is almost identical to that described in subsection (4.3.1), with however, conditions (4.30) and (4.31) replacing condition (4.19) for the country that implements a BCT. This rate is henceforth referred to as social BCT rate. It takes into account consumption of both countries, and it is therefore insensitive to the terms of trade benefits for the implementing country.

4.6.1 Unilateral social BCT

Results show that as long as there is symmetry in the country specific sensitivity to global pollution η^i across countries, the optimal unilateral social BCT rate is zero. There is no need to have a BCT as both countries care about the environment in the same manner. The temporary asymmetry in initial development levels induces a positive social BCT only if the implementing country is initially poorer. Furthermore, this country opens its markets sooner if the richer country is richer in brown capital. The social BCT is applied temporarily and it becomes zero once the asymmetry in capital stocks between countries disappears.

Significantly, when North is more concerned about the environment than South ($\eta^n > \eta^s > 0$), North's social unilateral BCT rate becomes positive ($\tau_t > 0$). It is much lower than the regular unilateral BCT rate analyzed in subsection (4.5.1), and its level increase monotonically with the difference between η^n and η^s. In order to illustrate the effect of the social BCT on growth and carbon leakages, Figure 4.10 depicts, respectively, the relative change in South's growth and carbon leakage ratios for two cases, free trade and the social unilateral BCT by North, when η^n increases from $(\eta_0^n = \eta_0^s > 0)$ to $(\eta^n > \eta_0^s)$ from the free trade benchmark of $(\eta_0^n = \eta_0^s > 0)$.



(a) Social BCT effect on growth leakage

(b) Social BCT effect on carbon leakage

Figure 4.10: Social BCT effect on leakages when η^n increases from $(\eta_0^n = \eta_0^s)$ to $(\eta^n > \eta_0^s)$

Panel 4.10a illustrates that the social BCT rate is effective to mitigate the growth leakage only partially as the BCT covers only South's exporting sector and does not affect domestic production. The effect of the social BCT on carbon leakage is similar as the the carbon leakage ratio becomes lower under the social BCT case in Panel 4.10b. Naturally, as the social BCT maximizes global welfare, the discounted global welfare is higher under the social unilateral BCT compared to a unilateral rate chosen by North.

4.7 Conclusion

This paper theoretically analyzed the dynamic impacts of BCTs on the growth and welfare of trading partners. It introduced a trade model between two countries with dynamic investments decisions in two types of capital; polluting brown capital, that is assumed to have an environmentally negative effect by increasing a global transboundary pollution stock, and a nonpolluting green capital. At each point in time, governments decide on how much to invest in each kind of capital, the size of subsidies to consumers, and whether to implement a BCT on the carbon contents of imports or not. I analyzed the investment and welfare effects among three cases: a benchmark case of free trade; a case when a unilateral BCT can be implemented by only one country; and a third case with bilateral BCT when both countries can implement a BCT.

The paper has found the following main results: In the open loop Nash equilibrium a positive unilateral and bilateral BCT rates are implemented. I find that a unilateral BCT is an effective instrument to direct investments in the exporting country towards green capital even when governments do not care about the environment. Nevertheless, as pollution becomes more important, a unilateral BCT rate gives the implementing country more control. This country takes advantage of the BCT to shift the cost of reducing global pollution to the other country.

Furthermore, I find that when a bilateral BCT is implemented across countries (a BCT war), it becomes welfare increasing if governments care about the environmental quality of their consumers sufficiently. This is because the benefits from a lower pollution stock become large enough to outweigh the loss in consumption.

I also find that when there is asymmetry in the initial development levels across countries, the initially poorer country witnesses a slower growth only if the other country is initially richer in brown capital. The model also show that it is optimal for countries at a low development level to open their markets to foreign products gradually along their development path. In case of asymmetry in the weight of environmental quality across countries, growth leakage can arise, as the country that is less concerned about the environment witnesses a faster growth and a higher development level in the long run.

A social unilateral BCT rate, that is determined by an international trade regulator, is only feasible when the implementing country is more concerned about the environment than the other. The optimal social rate imposed is lower than a regular BCT rate. Moreover, it is an effective instrument to mitigate both carbon and growth leakages.

Several extensions can be proposed to the model presented in this paper. A first extension is to solve the model for a closed loop Nash equilibrium. Under this specification, the BCT become a function that depends on state variables rather than only time, which excludes the possibility of time inconsistent BCTs. However, the computations for the closed loop Nash equilibria are expected to be highly complex. A second extension would be to verify whether the obtained results continue to hold when there is more than one trading partner. This would help generalizing the obtained results. However, under this framework new issues, like coalition stability, should be analyzed. A third extension would be to make the relative cost between green and brown investments decreasing rather than keeping it constant over time. This is a more realistic assumption as the technological progress in renewable energy sources is speeding up in recent years inducing a decrease in their relative cost, and thus in the implemented BCT rates and in the growth direction across countries.

4.8 Appendix

4.8.1 Partial derivatives

As mentioned earlier in subsection (4.2.5), consumption is determined instantaneously in terms of capital stocks, subsidies, and the BCT rates. At the same time, the capital dynamics are increasing with investments, therefore, the consumption of domestic and imported varieties are implicitly determined by investments in green and brown capitals. From the adjusted consumer budget constraint in (4.10) for both countries, the demand function (4.11) and its symmetric relation for North, the trade balance condition (4.12), and the government budget constraint (4.16) and its symmetric relation for North I construct a system $M_t = M_t(V_t, D_t^s, K_t^s)$ as the following:

$$M_t = \begin{bmatrix} Y_t^s + S_t^s - c_t^{ss} - \frac{p_{p,t}^n}{p_{p,t}^s} c_t^{ns}(1+\tau_t^s z_t^n) - \frac{F'_{E_{g,t}^s}}{a_g^s} K_{g,t}^s - \frac{F'_{E_{b,t}^s}}{a_b^s} K_{b,t}^s, \\ Y_t^n + S_t^n - c_t^{nn} - \frac{p_{p,t}^s}{p_{p,t}^n} c_t^{sn}(1+\tau_t^n z_t^s) - \frac{F'_{E_{g,t}^n}}{a_g^n} K_{g,t}^n - \frac{F'_{E_{b,t}^n}}{a_b^n} K_{b,t}^n, \\ \frac{u^{s'}_{c_t^{ns}}(c_t^{ss}, c_t^{ns})}{u^{s'}_{c_t^{ss}}(c_t^{ss}, c_t^{ns})} - \frac{(1+\tau_t^s z_t^n) p_{p,t}^n}{p_{p,t}^s}, \\ \frac{u^{n'}_{c_t^{sn}}(c_t^{nn}, c_t^{sn})}{u^{n'}_{c_t^{nn}}(c_t^{nn}, c_t^{sn})} - \frac{(1+\tau_t^n z_t^s) p_{p,t}^s}{p_{p,t}^n}, \\ \frac{p_{p,t}^n}{p_{p,t}^s} - \frac{c_t^{ns}}{c_t^{sn}}, \\ \frac{F'_{E_{g,t}^s}}{a_g^s} K_{g,t}^s + \frac{F'_{E_{b,t}^s}}{a_b^s} K_{b,t}^s + \frac{p_{p,t}^n}{p_{p,t}^s} c_t^{ns} \tau_t^s z_t^n - C_b^s(I_{b,t}^s) - C_g^s(I_{g,t}^s) - S_t^s \\ \frac{F'_{E_{g,t}^n}}{a_g^n} K_{g,t}^n + \frac{F'_{E_{b,t}^n}}{a_b^n} K_{b,t}^n + \frac{p_{p,t}^s}{p_{p,t}^n} c_t^{sn} \tau_t^n z_t^s - C_b^n(I_{b,t}^n) - C_g^n(I_{g,t}^n) - S_t^n \end{bmatrix}. \tag{4.32}$$

I define the vector $V_t = (c_t^{ss}, c_t^{nn}, c_t^{ns}, c_t^{sn}, p_{p,t}^n, S_t^s, S_t^n)$ of instantaneous consumption quantities, relative producer price, and subsidies. Also the control vector $A_t^s = (I_{b,t}^s, I_{g,t}^s, \tau_t^s)$, and the capital vector $K_t^s = (K_{b,t}^s, K_{g,t}^s)$.These vectors are country specific. Accordingly, the system M_t implicitly determines $V_t = V_t(A_t^s, K_t^s)$. I derive matrices for partial derivatives of M_t with respect to vectors V_t, A_t^s, A_t^n, K_t^s, K_t^n as the following:

$$\frac{\partial M_t}{\partial V_t} = \begin{bmatrix} -1 & 0 & -\frac{p_{p,t}^n}{p_{p,t}^s}(1+\tau_t^s z_t^n) & 0 & -\frac{c_t^{ns}}{p_{p,t}^s}(1+\tau_t^s z_t^n) & 1 & 0 \\ 0 & -1 & 0 & -\frac{p_{p,t}^s}{p_{p,t}^n}(1+\tau_t^n z_t^s) & \frac{c_t^{sn} p_{p,t}^s}{(p_{p,t}^n)^2}(1+\tau_t^n z_t^s) & 0 & 1 \\ Z_1 & 0 & Z_3 & 0 & -\frac{1}{p_{p,t}^s}(1+\tau_t^s z_t^n) & 0 & 0 \\ 0 & Z_2 & 0 & Z_4 & \frac{p_{p,t}^s}{(p_{p,t}^n)^2}(1+\tau_t^n z_t^s) & 0 & 0 \\ 0 & 0 & -\frac{1}{c_t^{sn}} & \frac{c_t^{ns}}{(c_t^{sn})^2} & \frac{1}{p_{p,t}^s} & 0 & 0 \\ 0 & 0 & \frac{p_{p,t}^n}{p_{p,t}^s}\tau_t^s z_t^n & 0 & \frac{1}{p_{p,t}^s}\tau_t^s z_t^n c_t^{ns} & -1 & 0 \\ 0 & 0 & 0 & \frac{p_{p,t}^s}{p_{p,t}^n}\tau_t^n z_t^s & -\frac{p_{p,t}^s}{(p_{p,t}^n)^2}\tau_t^n z_t^s c_t^{sn} & 0 & -1 \end{bmatrix}. \tag{4.33}$$

Denoting:

$$
Z_1 = \frac{(u^{s''}_{c^{ns}_t c^{ss}_t} u^{s'}_{c^{ss}_t} - u^{s''}_{c^{ss}_t} u^{s'}_{c^{ns}_t})}{(u^{s'}_{c^{ss}_t})^2}, \quad Z_2 = \frac{(u^{n''}_{c^{sn}_t c^{nn}_t} u^{n'}_{c^{nn}_t} - u^{n''}_{c^{nn}_t} u^{n'}_{c^{sn}_t})}{(u^{n'}_{c^{nn}_t})^2},
$$

$$
Z_3 = \frac{(u^{s''}_{c^{ns}_t} u^{s'}_{c^{ss}_t} - u^{s''}_{c^{ss}_t c^{ns}_t} u^{s'}_{c^{ns}_t})}{(u^{s'}_{c^{ss}_t})^2}, \quad Z_4 = \frac{(u^{n''}_{c^{sn}_t} u^{n'}_{c^{nn}_t} - u^{n''}_{c^{nn}_t c^{sn}_t} u^{n'}_{c^{sn}_t})}{(u^{n'}_{c^{nn}_t})^2}.
$$

The Jacobian matrix $\frac{\partial M_t}{\partial V_t}$ reflect the general case when both countries are assumed to implement a BCT. This matrix will simplify by setting $\tau^s_t = 0$ in the case of unilateral BCT by North, and by setting $\tau^n_t = \tau^s_t = 0$ in the case of free trade.

On the other hand, the matrices $\frac{\partial M_t}{\partial A^s_t}$ and $\frac{\partial M_t}{\partial A^n_t}$, yield:

$$
\frac{\partial M_t}{\partial A^s_t} = \begin{bmatrix} 0 & 0 & -\frac{p^n_{p,t}}{p^s_{p,t}} z^n_t c^{ns}_t \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{p^n_{p,t}}{p^s_{p,t}} z^n_t \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -\beta_b I^s_{b,t} & -\beta_g I^s_{g,t} & \frac{p^n_{p,t}}{p^s_{p,t}} z^n_t c^{ns}_t \\ 0 & 0 & 0 \end{bmatrix}, \quad \frac{\partial M_t}{\partial A^n_t} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -\frac{p^s_{p,t}}{p^n_{p,t}} z^s_t c^{sn}_t \\ 0 & 0 & 0 \\ 0 & 0 & -\frac{p^s_{p,t}}{p^n_{p,t}} z^s_t \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -\beta_b I^n_{b,t} & -\beta_g I^n_{g,t} & \frac{p^s_{p,t}}{p^n_{p,t}} z^s_t c^{sn}_t \end{bmatrix}. \tag{4.34}
$$

The entries of the last column are zeros when the country is assumed not to implement a BCT.

Finally, partial derivatives with respect to the capital vector in matrices $\frac{\partial M_t}{\partial K^s_t}$, $\frac{\partial M_t}{\partial K^n_t}$, read:

$$
\frac{\partial M_t}{\partial K^s_t} = \begin{bmatrix}
-(\frac{F''_{E^s_{g,t}E^s_{b,t}}}{a^s_g a^s_b} K^s_{g,t} + \frac{F''_{E^s_{b,t}}}{(a^s_b)^2} K^s_{b,t}) & -(\frac{F''_{E^s_{b,t}E^s_{g,t}}}{a^s_b a^s_g} K^s_{b,t} + \frac{F''_{E^s_{g,t}}}{(a^s_g)^2} K^s_{g,t}) \\
-\frac{p^s_{p,t}}{p^n_{p,t}} \tau^n_t \alpha^s c^{sn}_t (\frac{Y^s_t - F'_{E^s_{b,t}} K^s_{b,t}}{(Y^s_t)^2}) & \frac{p^s_{p,t}}{p^n_{p,t}} \tau^n_t \alpha^s c^{sn}_t (\frac{F'_{E^s_{g,t}} K^s_{b,t}}{(Y^s_t)^2}) \\
0 & 0 \\
-\frac{p^s_{p,t}}{p^n_{p,t}} \tau^n_t \alpha^s (\frac{Y^s_t - F'_{E^s_{b,t}} K^s_{b,t}}{(Y^s_t)^2}) & \frac{p^s_{p,t}}{p^n_{p,t}} \tau^n_t \alpha^s (\frac{F'_{E^s_{g,t}} K^s_{b,t}}{(Y^s_t)^2}) \\
0 & 0 \\
(\frac{F''_{E^s_{g,t}E^s_{b,t}}}{a^s_g a^s_b} K^s_{g,t} + \frac{F'_{E^s_{b,t}}}{a^s_b} + \frac{F''_{E^s_{b,t}}}{(a^s_b)^2} K^s_{b,t}) & (\frac{F''_{E^s_{b,t}E^s_{g,t}}}{a^s_b a^s_g} K^s_{b,t} + \frac{F'_{E^s_{g,t}}}{a^s_g} + \frac{F''_{E^s_{g,t}}}{(a^s_g)^2} K^s_{g,t}) \\
\frac{p^s_{p,t}}{p^n_{p,t}} \tau^n_t \alpha^s c^{sn}_t (\frac{Y^s_t - F'_{E^s_{b,t}} K^s_{b,t}}{(Y^s_t)^2}) & -\frac{p^s_{p,t}}{p^n_{p,t}} \tau^n_t \alpha^s c^{sn}_t (\frac{F'_{E^s_{g,t}} K^s_{b,t}}{(Y^s_t)^2})
\end{bmatrix}, \tag{4.35}
$$

$$
\frac{\partial M_t}{\partial K^n_t} = \begin{bmatrix}
-\frac{p^n_{p,t}}{p^s_{p,t}} \tau^s_t \alpha^n c^{ns}_t (\frac{Y^n_t - F'_{E^n_{b,t}} K^n_{b,t}}{(Y^n_t)^2}) & \frac{p^n_{p,t}}{p^s_{p,t}} \tau^s_t \alpha^n c^{ns}_t (\frac{F'_{E^n_{g,t}} K^n_{b,t}}{(Y^n_t)^2}) \\
-(\frac{F''_{E^n_{g,t}E^n_{b,t}}}{a^n_g a^n_b} K^n_{g,t} + \frac{F''_{E^n_{b,t}}}{(a^n_b)^2} K^n_{b,t}) & -(\frac{F''_{E^n_{b,t}E^n_{g,t}}}{a^n_b a^n_b} K^n_{b,t} + \frac{F''_{E^n_{g,t}}}{(a^n_g)^2} K^n_{g,t}) \\
-\frac{p^n_{p,t}}{p^s_{p,t}} \tau^s_t \alpha^n (\frac{Y^n_t - F'_{E^n_{b,t}} K^n_{b,t}}{(Y^n_t)^2}) & \frac{p^n_{p,t}}{p^s_{p,t}} \tau^s_t \alpha^n (\frac{F'_{E^n_{g,t}} K^n_{b,t}}{(Y^n_t)^2}) \\
0 & 0 \\
0 & 0 \\
\frac{p^n_{p,t}}{p^s_{p,t}} \tau^s_t \alpha^n c^{ns}_t (\frac{Y^n_t - F'_{E^n_{b,t}} K^n_{b,t}}{(Y^n_t)^2}) & -\frac{p^n_{p,t}}{p^s_{p,t}} \tau^s_t \alpha^n c^{ns}_t (\frac{F'_{E^n_{g,t}} K^n_{b,t}}{(Y^n_t)^2}) \\
(\frac{F''_{E^n_{g,t}E^n_{b,t}}}{a^n_g a^n_b} K^n_{g,t} + \frac{F'_{E^n_{b,t}}}{a^n_b} + \frac{F''_{E^n_{b,t}}}{(a^n_b)^2} K^n_{b,t}) & (\frac{F''_{E^n_{g,t}}}{(a^n_g)^2} K^n_{g,t} + \frac{F'_{E^n_{g,t}}}{a^n_g} + \frac{F''_{E^n_{b,t}E^n_{g,t}}}{a^n_b a^n_g} K^n_{b,t})
\end{bmatrix}, \tag{4.36}
$$

for the case when both countries are assumed to implement a BCT. These matrices simplify by setting $\tau^s_t = 0$ in (4.36) in the case of unilateral BCT implemented by North, and by setting both $\tau^n_t = 0$ in (4.35) and $\tau^s_t = 0$ in (4.36) in the case of free trade.

When considering a normal tariff rather than a BCT, the matrices (4.32), (4.33), and (4.34) simplify by setting the carbon content of imports across countries z^i to 1. Moreover, the matrices of the partial derivatives with respect to capital stocks (4.35) and (4.36) become:

$$
\frac{\partial M_t}{\partial K_t^s} = \begin{bmatrix} -(\frac{F''_{E^s_{g,t}E^s_{b,t}}}{a^s_g a^s_b} K^s_{g,t} + \frac{F''_{E^s_{b,t}}}{(a^s_b)^2} K^s_{b,t}) & -(\frac{F''_{E^s_{b,t}E^s_{g,t}}}{a^s_b a^s_g} K^s_{b,t} + \frac{F''_{E^s_{g,t}}}{(a^s_g)^2} K^s_{g,t}) \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ (\frac{F''_{E^s_{g,t}E^s_{b,t}}}{a^s_g a^s_b} K^s_{g,t} + \frac{F'_{E^s_{b,t}}}{a^s_b} + \frac{F''_{E^s_{b,t}}}{(a^s_b)^2} K^s_{b,t}) & (\frac{F''_{E^s_{b,t}E^s_{g,t}}}{a^s_b a^s_g} K^s_{b,t} + \frac{F'_{E^s_{g,t}}}{a^s_g} + \frac{F''_{E^s_{g,t}}}{(a^s_g)^2} K^s_{g,t}) \\ 0 & 0 \end{bmatrix}, \tag{4.37}
$$

$$
\frac{\partial M_t}{\partial K_t^n} = \begin{bmatrix} 0 & 0 \\ -(\frac{F''_{E^n_{g,t}E^n_{b,t}}}{a^n_g a^n_b} K^n_{g,t} + \frac{F''_{E^n_{b,t}}}{(a^n_b)^2} K^n_{b,t}) & -(\frac{F''_{E^n_{b,t}E^n_{g,t}}}{a^n_b a^n_b} K^n_{b,t} + \frac{F''_{E^n_{g,t}}}{(a^n_g)^2} K^n_{g,t}) \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ (\frac{F''_{E^n_{g,t}E^n_{b,t}}}{a^n_g a^n_b} K^n_{g,t} + \frac{F'_{E^n_{b,t}}}{a^n_b} + \frac{F''_{E^n_{b,t}}}{(a^n_b)^2} K^n_{b,t}) & (\frac{F''_{E^n_{g,t}}}{(a^n_g)^2} K^n_{g,t} + \frac{F'_{E^n_{g,t}}}{a^n_g} + \frac{F''_{E^n_{b,t}E^n_{g,t}}}{a^n_b a^n_g} K^n_{b,t}) \end{bmatrix}. \tag{4.38}
$$

Accordingly, the partial derivatives of consumption with respect to investments and BCTs (or tariffs) are included in a matrix:

$$
\frac{\partial V_t}{\partial A_t^s} = -(\frac{\partial M_t}{\partial V_t})^{-1} \frac{\partial M_t}{\partial A_t^s}.
$$

Here the $(\frac{\partial M_t}{\partial V_t})^{-1}$ denotes the inverse of the matrix $\frac{\partial M_t}{\partial V_t}$. Symmetrically for North I get:

$$
\frac{\partial V_t}{\partial A_t^n} = -(\frac{\partial M_t}{\partial V_t})^{-1} \frac{\partial M_t}{\partial A_t^n}.
$$

The partial derivatives of consumption with respect to capital stocks are given by the following matrix:

$$\frac{\partial V_t}{\partial K_t^s} = -(\frac{\partial M_t}{\partial V_t})^{-1}\frac{\partial M_t}{\partial K_t^s}.$$

Symmetrically for North I have:

$$\frac{\partial V_t}{\partial K_t^n} = -(\frac{\partial M_t}{\partial V_t})^{-1}\frac{\partial M_t}{\partial K_t^n}.$$

4.8.2 Benchmark parametrization

Table 4.2: Benchmark parametrization

Parameter	**Value**	**Parameter**	**Value**	**Parameter**	**Value**	**Parameter**	**Value**
$K^i_{b,0}$	5	ϑ	0.016	ε	10	β_b	0.5
$K^i_{g,0}$	8	θ	3.8	n	0	β_g	1
L^i_0	1	γ	0.33	ρ	0.5	a^i_b	1
P_0	40	α^i	0.05	η^i	0.00002	a^i_g	1
T	300	δ	0.025				

4.8.3 Solving for Steady state

I start by solving the general case of bilateral BCT across countries, I turn afterwards to a free trade case and finally the unilateral BCT case.

Bilateral BCT

In the steady state, the rate of change for any variable Q becomes zero, that is $\dot{Q} = 0$. Therefore, from the laws of motion of capital (4.13) and (4.14), the steady state levels of new investments of each kind of capital equal the depreciated capital for both countries:

$$I_b^s = \delta K_b^s, \tag{4.39}$$

$$I_g^s = \delta K_g^s, \tag{4.40}$$

$$I_b^n = \delta K_b^n, \tag{4.41}$$

$$I_g^n = \delta K_g^n. \tag{4.42}$$

Output is function of capital and labor. Labor is exogenously determined:

$$Y^s = F(L^s, \frac{K_b^s}{a_b^s}, \frac{K_g^s}{a_g^s}),$$

$$Y^n = F(L^n, \frac{K_b^n}{a_b^n}, \frac{K_g^n}{a_g^n}).$$

From the trade balance condition (4.12) I get the relative producer price:

$$p_p^n = p_p^s \frac{c^{sn}}{c^{ns}}. \tag{4.43}$$

From the demand conditions (4.11) and its symmetric relation I define the BCT rate in both countries:

$$\tau^s = \frac{1}{z^n}(\frac{u^{s'}_{c^{ns}}}{u^{s'}_{c^{ss}}} \frac{p_p^s}{p_p^n} - 1), \tag{4.44}$$

$$\tau^n = \frac{1}{z^s}(\frac{u^{s'}_{c^{sn}}}{u^{s'}_{c^{nn}}} \frac{p_p^n}{p_p^s} - 1). \tag{4.45}$$

Here $z^n = \alpha^n a_b^n e_b^n$ is the carbon content used to produce one unit of output at North with emission intensity α^n of installed brown capital. The unit factor demand for brown energy per unit of output at North yield: $e_b^n = \frac{K_b^n}{a_b^n Y^n}$.

From the government budget constraints (4.16) and its symmetric relation for North lump sum transfers to consumers read:

$$S^s = \frac{F'_{E^s_{g,t}}}{a_g^s} K_g^s + \frac{F'_{E^s_{b,t}}}{a_b^s} K_b^s + \frac{p_p^n}{p_p^s} c^{ns} \tau^s z^n - C_b^s(I_b^s) - C_g^s(I_g^s), \tag{4.46}$$

$$S^n = \frac{F^{'}_{E^n_{g,t}}}{a^n_g} K^n_g + \frac{F^{'}_{E^n_{b,t}}}{a^n_b} K^n_b + \frac{p^s_p}{p^n_p} c^{sn} \tau^n z^s - C^n_b(I^n_b) - C^n_g(I^n_g). \tag{4.47}$$

From (4.15) steady state level of global pollution depends on the stock of brown capital in both countries:

$$P = \frac{\alpha^s}{\vartheta} K^s_b + \frac{\alpha^n}{\vartheta} K^n_b. \tag{4.48}$$

From (4.22) and the symmetric relation for North, the co-states for global pollution read:

$$\mu^s = \frac{D^{s'}(P)}{(\rho + \vartheta)}, \tag{4.49}$$

$$\mu^n = \frac{D^{n'}(P)}{(\rho + \vartheta)}. \tag{4.50}$$

Using (4.17) and (4.18) and their symmetric relations for North, shadow prices for brown and green capital in both countries are:

$$\nu^s_b = -(u^{s'}_{c^{ss}}(c^{ss})^{'}_{I^s_b} + u^{s'}_{c^{ns}}(c^{ns})^{'}_{I^s_b}), \tag{4.51}$$

$$\nu^s_g = -(u^{s'}_{c^{ss}}(c^{ss})^{'}_{I^s_g} + u^{s'}_{c^{ns}}(c^{ns})^{'}_{I^s_g}), \tag{4.52}$$

$$\nu^n_b = -(u^{n'}_{c^{nn}}(c^{nn})^{'}_{I^n_b} + u^{n'}_{c^{sn}}(c^{sn})^{'}_{I^n_b}), \tag{4.53}$$

$$\nu^n_g = -(u^{n'}_{c^{nn}}(c^{nn})^{'}_{I^n_g} + u^{n'}_{c^{sn}}(c^{sn})^{'}_{I^n_g}), \tag{4.54}$$

From the consumer budget constraint in (4.10) and the symmetric relation for North I get:

$$Y^s + S^s - c^{ss} - \frac{p^n_p}{p^s_p} c^{ns}(1 + \tau^s z^n) - \frac{F^{'}_{E^s_g}}{a^s_g} K^s_g - \frac{F^{'}_{E^s_b}}{a^s_b} K^s_b = 0, \tag{4.55}$$

$$Y^n + S^n - c^{nn} - \frac{p^s_p}{p^n_p} c^{sn}(1 + \tau^n z^s) - \frac{F^{'}_{E^n_g}}{a^n_g} K^n_g - \frac{F^{'}_{E^n_b}}{a^n_b} K^n_b = 0. \tag{4.56}$$

From (4.21) and its symmetric relation for North I have:

$$(\rho + \delta)\nu_g^s - u_{c^{ss}}^{s'}(c^{ss})_{K_g^s}^{'} - u_{c^{ns}}^{s'}(c^{ns})_{K_g^s}^{'} = 0, \tag{4.57}$$

$$(\rho + \delta)\nu_g^n - u_{c^{nn}}^{n'}(c^{nn})_{K_g^n}^{'} - u_{c^{sn}}^{n'}(c^{sn})_{K_g^n}^{'} = 0. \tag{4.58}$$

Similarly, from (4.20) and analogous relation for North I obtain:

$$(\rho + \delta)\nu_b^s - u_{c^{ss}}^{s'}(c^{ss})_{K_b^s}^{'} - u_{c^{ns}}^{s'}(c^{ns})_{K_b^s}^{'} - \alpha^s \mu^s = 0, \tag{4.59}$$

$$(\rho + \delta)\nu_b^n - u_{c^{nn}}^{n'}(c^{nn})_{K_b^n}^{'} - u_{c^{sn}}^{n'}(c^{sn})_{K_b^n}^{'} - \alpha^n \mu^n = 0. \tag{4.60}$$

Finally, from (4.19) and its symmetric relation in North:

$$u_{c_t^{ss}}^{s'}(c^{ss})_{\tau_t^s}^{'} + u_{c_t^{ns}}^{s'}(c^{ns})_{\tau_t^s}^{'} = 0 \tag{4.61}$$

$$u_{c_t^{nn}}^{n'}(c^{nn})_{\tau_t^n}^{'} + u_{c_t^{sn}}^{n'}(c^{sn})_{\tau_t^n}^{'} = 0 \tag{4.62}$$

Equations (4.55) - (4.62) determine the equilibrium consumption quantities c^{ss},c^{nn},c^{sn},c^{ns} and the levels for brown and green capital in each country K_b^s, K_g^s, K_b^n, K_g^n, which determine the steady state of this economy after normalizing $p_p^s = 1$.

Free trade

I assume in this case that no country is implementing a BCT. Therefore, the instantaneous equilibrium conditions described in subsection (4.2.5), the government budget constraints in (4.16), the symmetric relation for North, along with the F.O.C in (4.17) and (4.18) simplify by setting $\tau_t^s = \tau_t^n = 0$. Having the same laws of motion for states and co-states as in (4.13) - (4.22) and their symmetric relations for North.

Accordingly, the steady state levels of investments in this case are governed by (4.39) - (4.42), along with the relative producer price in (4.43). While the steady state levels of pollution and its shadow prices are determined by (4.48) - (4.50). On the other hand, from the government budget constraint the lump sum subsidies transferred to consumers as become:

$$S^s = \frac{F'_{E^s_g}}{a^s_g} K^s_g + \frac{F'_{E^s_b}}{a^s_b} K^s_b - C^s_b(I^s_b) - C^s_g(I^s_g), \tag{4.63}$$

$$S^n = \frac{F'_{E^n_g}}{a^n_g} K^n_g + \frac{F'_{E^n_b}}{a^n_b} K^n_b - C^n_b(I^n_b) - C^n_g(I^n_g). \tag{4.64}$$

From the consumer budget constraint in (4.10) and its symmetric relation for North I define domestic consumption as:

$$c^{ss} = Y^s + S^s - \frac{p^n_p}{p^s_p} c^{ns} - \frac{F'_{E^s_g}}{a^s_g} K^s_g - \frac{F'_{E^s_b}}{a^s_b} K^s_b, \tag{4.65}$$

$$c^{nn} = Y^n + S^n - \frac{p^s_p}{p^n_p} c^{sn} - \frac{F'_{E^n_g}}{a^n_g} K^n_g - \frac{F'_{E^n_b}}{a^n_b} K^n_b. \tag{4.66}$$

The shadow prices for brown and green capital are determined by (4.51) - (4.54). From the demand conditions in (4.11) and its symmetric relation I get:

$$\frac{u^{s'}_{c^{ns}}}{u^{s'}_{c^{ss}}} - \frac{p^n_p}{p^s_p} = 0, \tag{4.67}$$

$$\frac{u^{n'}_{c^{sn}}}{u^{n'}_{c^{nn}}} - \frac{p^s_p}{p^n_p} = 0. \tag{4.68}$$

Equations (4.57) - (4.60), along with (4.63) and (4.64) determine the equilibrium import quantities c^{ns},c^{sn} and the levels for brown and green capital in each country K^s_b, K^s_g, K^n_b, K^n_g, which determine the steady state of this economy after normalizing $p^s_p = 1$.

Unilateral BCT by North

Since I assume in this case that only North can implement a BCT, the instantaneous equilibrium conditions described in section (4.2.5), and the government budget constraints in (4.16) and the symmetric constraint for North simplify by setting $\tau_t^s = 0$, along with the F.O.C in (4.17), (4.18), and the symmetric relation of (4.19). Having the same laws of motion of states and co-states as in (4.13) - (4.22) and their symmetric relations for North.

As in previous cases, the steady state levels of investments are governed by (4.39) - (4.40). The relative producer price by (4.43). While the steady state levels of pollution and it shadow prices are governed by (4.48) - (4.50). The lamp sum transfers to consumers are determined by (4.63) for South and by (4.47) for North. The shadow prices for brown and green capital are governed by (4.51) - (4.54). While the unilateral BCT rate at North is defined by (4.45).

Finally, the equations (4.57) - (4.60), along with (4.55), (4.56), (4.62) and (4.67) determine the equilibrium consumption quantities c^{ss},c^{nn},c^{sn},c^{ns} and the levels for brown and green capital in each country K_b^s, K_g^s, K_b^n, K_g^n, which determine the steady state of this economy after normalizing $p_p^s = 1$.

4.8.4 BCT effects

Table 4.3: Optimal unilateral and bilateral BCT rates

BCT	**Unilateral BCT** ($\eta^i = 0$)	**Unilateral BCT** ($\eta^i > 0$)	**Bilateral BCT** ($\eta^i = 0$)	**Bilateral BCT** ($\eta^i > 0$)	**Social BCT** ($\eta^n > \eta^s$)
τ^s	0	0	28.06%	44.01%	0
τ^n	48.72%	80.21%	28.06%	44.01%	2.3%

Table 4.4: Steady state benchmark and BCT effect on key variables

Variable	Benchmark ($\eta^i = 0$)	Benchmark ($\eta^i > 0$)	Effect Of η^i	Unilateral BCT ($\eta^i = 0$)	Unilateral BCT ($\eta^i > 0$)	Bilateral BCT ($\eta^i = 0$)	Bilateral BCT ($\eta^i > 0$)
K_g^s	59.71	66.74	11.79%	5,48%	7.58%	6.43%	6.82%
K_g^n	59.71	66.74	11.79%	0%	-1.36%	6.43%	6.82%
K_b^s	112.12	71.19	-36.5%	-10.07%	-22.23%	-11.85%	-17.72%
K_b^n	112.12	71.19	-36.5%	0%	6.48%	-11.85%	-17.72%
P	700.75	444.94	-36.5%	-5.04%	-7.87%	-11.85%	-17.72%
Y^s	5.6	5.21	-6.85%	-1.5%	-2.67%	-1.77%	-1.98%
Y^n	5.6	5.21	-6.85%	0%	0.87%	-1.77%	-1.98%
c^{ss}	2.64	2.50	-5.56%	25.22%	22.33%	38.45%	37.58%
c^{nn}	2.64	2.50	-5.56%	40.30%	41.44%	38.45%	37.58%
c^{sn}	2.64	2.50	-5.56%	-27.45%	-27.53%	-41.1%	-41.48%
c^{ns}	2.64	2.50	-5.56%	-40.30%	-39.89%	-41.1%	-41.48%
p_p^n	1	1	0%	21.52%	20.56%	0%	0%
p_p^s	1	1	0%	0%	0%	0%	0%
S^s	1.54	1.5	-2.41%	-0.17%	-2.43%	25.28%	22.67%
S^n	1.54	1.5	-2.41%	45.70%	44.28%	25.28%	22.67%
r_b^s	0.011	0.012	18.29%	3.74%	7.46%	4.45%	5.56%
r_b^n	0.011	0.012	18.29%	0%	-2.11%	4.45%	5.56%
r_g^s	0.011	0.013	11.79%	2.10%	4.03%	2.5%	2.84%
r_g^n	0.011	0.013	11.79%	0%	-1.36%	2.5%	2.84%
ω^s	3.75	3.49	-6.85%	-1.50%	-2.67%	-1.77%	-1.98%
ω^n	3.75	3.49	-6.85%	0%	0.87%	-1.77%	-1.98%
U^s	6.77	6.4	-5.56%	-9.11%	-10.21%	-3.52%	-4.13%
U^n	6.77	6.4	-5.56%	4.97%	5.46%	-3.52%	-4.13%
D^s	0	1.98	-	-	-15.12%	-	-32.31%
D^n	0	1.98	-	-	-15.12%	-	-32.31%
W^s	6.77	4.42	-34.78%	-9.11%	-8.01%	-3.52%	8.5%
W^n	6.77	4.42	-34.78%	4.97%	14.68%	-3.52%	8.5%

Table 4.5: Elasticity of unilateral and bilateral BCT rates with respect to key parameters

BCT \ Parameter	$\frac{\beta_g}{\beta_b}$	ϑ	δ	η^i	α^i	α^n	α^s	θ	ε
Unilateral τ^n	-0.433	-0.55	-0.068	0.45	-0.089	0.176	-0.268	-1.4	0.0106
Bilateral τ^n	-0.387	-0.453	0.0378	0.369	-0.254	0.017	-0.272	-0.715	-0.002
Bilateral τ^s	-0.387	-0.453	0.0378	0.369	-0.254	-0.291	0.0369	-0.715	-0.002

Table 4.6: Effects on the discounted welfare for a change in initial conditions

Discounted welfare		**Higher $K^n_{g,0}$**	**Higher $K^n_{b,0}$**	**Higher P_0**	**Higher η^n**	$\eta^i = 0$
Free trade	W^s	2.63%	0.89%	-1.68%	0.18%	3.91%
	W^n	17.23%	16.65%	-1.68%	-1.76%	3.91%
Unilateral BCT	W^s	2.55%	0.61%	-1.84%	0.19%	4.30%
	W^n	16.90%	16.46%	-1.55%	-1.52%	3.42%
Bilateral BCT	W^s	1.87%	-0.12%	-1.67%	0.18%	3.67%
	W^n	17.69%	17.65%	-1.67%	-1.66%	3.67%

4.8.5 Tariff effects

Table 4.7: Optimal unilateral and bilateral tariff rates

Tariff	**Unilateral tariff** ($\eta^i = 0$)	**Unilateral tariff** ($\eta^i > 0$)	**Bilateral tariff** ($\eta^i = 0$)	**Bilateral tariff** ($\eta^i > 0$)	**Social tariff** ($\eta^n > \eta^s$)
τ^s	0%	0%	25.22%	25.22%	0
τ^n	44.95%	44.75%	25.22%	25.22%	1.7%

Table 4.8: Steady state benchmark and tariff effect on key variables

Variable	**Benchmark** ($\eta^i = 0$)	**Benchmark** ($\eta^i > 0$)	**Effect Of** η^i	**Unilateral tariff** ($\eta^i = 0$)	**Unilateral tariff** ($\eta^i > 0$)	**Bilateral tariff** ($\eta^i = 0$)	**Bilateral tariff** ($\eta^i > 0$)
K_g^s	59.71	66.74	11.79%	0%	0.46%	0%	0.04%
K_g^n	59.71	66.74	11.79%	0%	-0.53%	0%	0.04%
K_b^s	112.12	71.19	-36.50%	0%	-2.14%	0%	-0.17%
K_b^n	112.12	71.19	-36.50%	0%	2.51%	0%	-0.17%
P	700.75	444.94	-36.50%	0%	0.18%	0%	-0.17%
Y^s	5.60	5.21	-6.85%	0%	-0.29%	0%	-0.02%
Y^n	5.60	5.21	-6.85%	0%	0.34%	0%	-0.02%
c^{ss}	2.64	2.50	-5.56%	27.14%	26.55%	40.31%	40.28%
c^{nn}	2.64	2.50	-5.56%	40.28%	40.71%	40.31%	40.28%
c^{sn}	2.64	2.50	-5.56%	-27.14%	-27.08%	-40.31%	-40.33%
c^{ns}	2.64	2.50	-5.56%	-40.28%	-40.11%	-40.31%	-40.33%
p_p^n	1	1	0%	22%	21.76%	0%	0%
p_p^s	1	1	0%	0%	0%	0%	0%
S^s	1.54	1.50	-2.41%	0%	-0.20%	25.87%	25.01%
S^n	1.54	1.50	-2.41%	46.13%	44.79%	25.87%	25.01%
r_b^s	0.01	0.01	18.29%	0%	0.72%	0%	0.06%
r_b^n	0.01	0.01	18.29%	0%	-0.83%	0%	0.06%
r_g^s	0.01	0.01	11.79%	0%	0.46%	0%	0.04%
r_g^n	0.01	0.01	11.79%	0%	-0.53%	0%	0.04%
ω^s	3.75	3.49	-6.85%	0%	-0.29%	0%	-0.02%
ω^n	3.75	3.49	-6.85%	0%	0.34%	0%	-0.02%
U^s	6.77	6.40	-5.56%	-8.22%	-8.39%	-2.22%	-2.24%
U^n	6.77	6.40	-5.56%	5.13%	5.37%	-2.22%	-2.24%
D^s	0	1.98	-	-	0.37%	-	-0.34%
D^n	0	1.98	-	-	0.37%	-	-0.34%
W^s	6.77	4.42	-34.78%	-8.22%	-12.32%	-2.22%	-3.09%
W^n	6.77	4.42	-34.78%	5.13%	7.61%	-2.22%	-3.09%

Bibliography

Acemoglu, D., P. Aghion, L. Bursztyn, and D. Hemous (2012): "The environment and directed technical change," *The American Economic Review*, 102, 131–166.

Adam, C. S. and S. A. O'Connell (1999): "Aid, Taxation and Development in Sub-Saharan Africa," *Economics and Politics*, 11, 225–253.

Aichele, R. and G. Felbermayr (2015): "Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade," *Review of Economics and Statistics*, 97, 104–115.

Alesina, A. and D. Dollar (2000): "Who Gives Foreign Aid to Whom and Why?" *Journal of Economic Growth*, 5, 33–63.

Altaghlibi, M. and F. O. O. Wagener (2016): "Unconditional Aid and Green Growth," Tinbergen institute discussion paper, Tinbergen Institute.

Antweiler, W., B. R. Copeland, and M. S. Taylor (2001): "Is Free Trade Good for the Environment?" *American Economic Review*, 91, 877–908.

Azam, J.-P. and J.-J. Laffont (2003): "Contracting for aid," *Journal of Development Economics*, 70, 25–58.

Baldwin, R. E. and C. Ravetti (2014): "Emissions, exporters and heterogeneity: asymmetric trade policy and firms' selection," in *Working Paper 2014-2*, Centre for Trade and Economic Integration.

Batrakova, S. and R. B. Davies (2012): "Is there an environmental benefit to being an exporter? Evidence from firm-level data," *Review of World Economics*, 148, 449–474.

Bernard, A. B., J. Eaton, J. B. Jensen, and S. Kortum (2003): "Plants and productivity in international trade," *The American Economic Review*, 93, 1268–1290.

Böhringer, C., E. J. Balistreri, and T. F. Rutherford (2012): "The role of border carbon adjustment in unilateral climate policy: Overview of an Energy Modeling Forum study (EMF 29)," *Energy Economics*, 34, S97–S110.

Böhringer, C., A. Müller, and J. Schneider (2015): "Carbon Tariffs Revisited," *Journal of the Association of Environmental and Resource Economists*, 2, 629–672.

Boone, P. (1996): "Politics and the effectiveness of foreign aid," *European Economic Review*, 40, 289–329.

Bowen, A., S. Cochrane, and S. Fankhauser (2012): "Climate change, adaptation and economic growth," *Climatic Change*, 113, 95–106.

Branger, F. and P. Quirion (2014): "Climate policy and the 'carbon haven' effect," *Wiley Interdisciplinary Reviews: Climate Change*, 5, 53–71.

Burniaux, J.-M. and J. Oliveira Martins (2012): "Carbon leakages: a general equilibrium view," *Economic Theory*, 49, 473–495.

Cabo, F. (2002): "Towards an ecological technology for global growth in a North-South trade model," *Journal of International Trade & Economic Development*, 11, 15–41.

Carraro, C. and D. Siniscalco (1998): "International environmental agreements: Incentives and political economy," *European economic review*, 42, 561–572.

Chatterjee, S., G. Sakoulis, and S. J. Turnovsky (2003): "Unilateral capital transfers, public investment, and economic growth," *European Economic Review*, 47, 1077–1103.

Chenery, H. and A. Strout (1966): "Foreign Assistance and Economic Development," *American Economic Review*, 56, 679–733.

Cherniwchan, J. (2017): "Trade liberalization and the environment: evidence from NAFTA and US manufacturing," *Journal of International Economics*.

Cherniwchan, J., B. R. Copeland, and M. S. Taylor (2016): "Trade and the Environment: New Methods, Measurements, and Results," *Annual Review of Economics*.

Claude, D., C. Figuières, and M. Tidball (2012): "Regulation of Investments in Infrastructure: The Interplay between Strategic Behaviors and Initial Endowments," *Journal of Public Economic Theory*, 14, 35–66.

Cole, M. A., R. J. Elliott, and K. Shimamoto (2005): "Industrial characteristics, environmental regulations and air pollution: an analysis of the UK manufacturing sector," *Journal of environmental economics and management*, 50, 121–143.

Condon, M. and A. Ignaciuk (2013): "Border Carbon Adjustment and International Trade," .

Cook, R., D. Campbell, and C. Kelly (2012): "Survival rates of new firms: An exploratory study," *Small Business Institute Journal*, 8, 35–42.

Copeland, B. R. (2012): "International trade and green growth," World Bank Policy Research Working Paper 6235, The World Bank.

Copeland, B. R. and M. S. Taylor (1994): "North South trade and the environment," *The quarterly journal of Economics*, 109, 755–787.

——— (2004): "Trade, growth, and the environment," *Journal of Economic literature*, 42, 7–71.

——— (2005): "Free trade and global warming: a trade theory view of the Kyoto protocol," *Journal of Environmental Economics and Management*, 49, 205–234.

Cosbey, A. (2009): "Border Carbon Adjustment: Questions and Answers," Background paper produced for the 2009 international trade meeting october 26-27, toronto.

Cosbey, A., S. Droege, C. Fischer, J. Reinaud, J. Stephenson, L. Weischer, and P. Wooders (2013): "A guide for the concerned: guidance on the elaboration and implementation of border carbon adjustment," Policy report, Entwined.

Cui, J., Y. Ji, et al. (2011): "The Environment, Trade and Innovation with Heterogeneous Firms: A Numerical Analysis," in *2011 Annual Meeting, July 24-26, 2011, Pittsburgh, Pennsylvania*, Agricultural and Applied Economics Association, 103478.

Cui, J., H. E. Lapan, and G. Moschini (2012): "Are exporters more environmentally friendly than non-exporters? Theory and evidence," .

Devereux, M. B. (1997): "Growth, specialization, and trade liberalization," *International Economic Review*, 565–585.

Dixit, A., H. McGray, J. Gonzales, and M. Desmond (2012): "Ready or Not: Assessing Institutional Aspects of National Capacity for Climate Change Adaptation," *World Resources Institute*.

Dixit, A. K. and J. E. Stiglitz (1977): "Monopolistic Competition and Optimum Product Diversity," *The American Economic Review*, 67, 297–308.

Doucouliagos, H. and M. Paldam (2008): "Aid effectiveness on growth: a meta study," *European Journal of Political Economy*, 24, 1–24.

Easterly, W. (2003): "Can Foreign Aid Buy Growth?" *Journal of Economic Perspectives*, 17, 23–48.

Edgren, G. (1996): "A challenge to the aid relationship," *Aid Dependency*, 9–21.

Elliott, J., I. Foster, S. Kortum, T. Munson, F. P. Cervantes, and D. Weisbach (2010): "Trade and carbon taxes," *The American Economic Review*, 100, 465–469.

Elliott, R. J., W. Shanshan, et al. (2008): "Industrial activity and the environment in China: an industry-level analysis," *China economic review*, 19, 393–408.

Eyckmans, J., S. Fankhauser, and S. Kverndokk (2016): "Development aid and climate finance," *Environmental and resource economics*, 63, 429–450.

Eyraud, L., C. Zhang, A. A. Wane, and B. J. Clements (2011): "Who's Going Green and Why? Trends and Determinants of Green Investment," IMF Working Papers 11/296, International Monetary Fund.

Felbermayr, G., B. Jung, and M. Larch (2013): "Optimal tariffs, retaliation, and the welfare loss from tariff wars in the Melitz model," *Journal of International Economics*, 89, 13–25.

Felder, S. and T. F. Rutherford (1993): "Unilateral CO2 reductions and carbon leakage: The consequences of international trade in oil and basic materials," *Journal of Environmental Economics and Management*, 25, 162–176.

Forslid, R., T. Okubo, and K. H. Ulltveit-Moe (2014): "Why are firms that export cleaner? International trade and CO2 emissions," .

Frankel, J. A. and A. K. Rose (2005): "Is trade good or bad for the environment? Sorting out the causality," *Review of economics and statistics*, 87, 85–91.

Fredj, K., G. Martín-Herrán, and G. Zaccour (2004): "Slowing deforestation pace through subsidies: a differential game," *Automatica*, 40, 301–309.

Grass, D. (2012): "Numerical computation of the optimal vector field: Exemplified by a fishery model," *Journal of Economic Dynamics and Control*, 36, 1626–1658.

Grossman, G. M. and A. B. Krueger (1991): "Environmental impacts of a North American free trade agreement," Tech. rep., National Bureau of Economic Research.

Hansen, H. and F. Tarp (2000): "Aid effectiveness disputed," *Journal of International Development*, 12, 375–398.

Helm, D., C. Hepburn, and G. Ruta (2012): "Trade, climate change, and the political game theory of border carbon adjustments," *Oxford review of economic policy*, 28, 368–394.

Hémous, D. (2016): "The dynamic impact of unilateral environmental policies," *Journal of International Economics*, 103, 80–95.

Heuson, C., W. Peters, R. Schwarze, and A.-K. Topp (2012): "Which mode of funding developing countries' climate policies under the post-Kyoto framework?" Tech. rep., UFZ-Diskussionspapiere.

Holladay, J. S. (2010): "Are exporters mother nature's best friends?" *New York University School of Law*.

Hynes, W. and S. Wang (2012): "Green Growth and Developing Countries: A Summary for Policymakers," *Document DCD/DAC (2012)*, 27.

Jakob, M., R. Marschinski, and M. Hübler (2013): "Between a rock and a hard place: a trade-theory analysis of leakage under production-and consumption-based policies," *Environmental and Resource Economics*, 56, 47–72.

Jørgensen, S. and G. Zaccour (2007): "Developments in differential game theory and numerical methods: economic and management applications," *Computational Management Science*, 4, 159–181.

Kemp, M. C., N. Van Long, and K. Shimomura (2001): "A differential game model of tariff war," *Japan and the World Economy*, 13, 279–298.

Kreickemeier, U. and P. M. Richter (2014): "Trade and the environment: The role of firm heterogeneity," *Review of International Economics*, 22, 209–225.

Krugman, P. (1980): "Scale economies, product differentiation, and the pattern of trade," *The American Economic Review*, 950–959.

Krugman, P. R., M. Obstfeld, and M. Melitz (2015): *International Economics: Theory and Policy*, Pearson Series in Economics, 10th ed.

Kuik, O. and M. Hofkes (2010): "Border adjustment for European emissions trading: competitiveness and carbon leakage," *Energy policy*, 38, 1741–1748.

Lahiri, S. and P. Raimondos-Moller (2000): "Lobbying by Ethnic Groups and Aid Allocation," *Economic Journal*, 110, C62–79.

Martín-Herrán, G., P. Cartigny, E. Motte, and M. Tidball (2006): "Deforestation and foreign transfers: a Stackelberg differential game approach," *Computers & operations research*, 33, 386–400.

Mazzanti, M. and R. Zoboli (2009): "Environmental efficiency and labour productivity: Trade-off or joint dynamics? A theoretical investigation and empirical evidence from Italy using NAMEA," *Ecological Economics*, 68, 1182–1194.

Mekasha, T. J. and F. Tarp (2013): "Aid and Growth: What Meta-Analysis Reveals," *Journal of Development Studies*, 49, 564–583.

Melitz, M. J. (2003): "The impact of trade on intra-industry reallocations and aggregate industry productivity," *Econometrica*, 71, 1695–1725.

Michel, P. (1982): "On the transversality condition in infinite horizon optimal problems," *Econometrica: Journal of the Econometric Society*, 975–985.

Monjon, S. and P. Quirion (2009): "Addressing leakage in the EU ETS: results from the CASE II model," *Climate Strategies*.

——— (2010): "How to design a border adjustment for the European Union Emissions Trading System?" *Energy policy*, 38, 5199–5207.

Mosley, P. (1986): "Aid-effectiveness: The Micro-Macro Paradox," *IDS Bulletin*, 17, 22–27.

——— (1996): "The failure of aid and adjustment policies in Sub-Saharan Africa: counter-examples and policy proposals," *Journal of African Economies*, 5, 406–443.

Mosley, P., J. Harrigan, and J. F. Toye (1995): *Aid and power: the World Bank and policy-based lending*, Psychology Press.

Nordhaus, W. D. (2014): *A question of balance: Weighing the options on global warming policies*, Yale University Press.

OECD (2011): "Towards green growth: monitoring progress," .

Paldam, M. (1997): "The micro efficiency of Danish development aid," Working paper 1997-13, University of Aarhus.

Pittel, K. and D. T. Rübbelke (2013): "Improving Global Public Goods Supply through Conditional Transfers–The International Adaptation Transfer Riddle," Working paper series, CESifo.

Rajan, R. G. and A. Subramanian (2007): "Does Aid Affect Governance?" *American Economic Review*, 97, 322–327.

——— (2008): "Aid and growth: What does the cross-country evidence really show?" *The Review of Economics and Statistics*, 90, 643–665.

Rosenstein-Rodan, P. N. (1961): "International aid for underdeveloped countries," *The Review of Economics and Statistics*, 107–138.

Rozenberg, J., A. Vogt-Schilb, and S. Hallegatte (2014): "Transition to clean capital, irreversible investment and stranded assets," Policy Research Working Paper Series 6859, The World Bank.

Salvadore, M. S. and J. H. Keppler (2010): "Projected costs of generating electricity: 2010 edition," Tech. rep., Paris Dauphine University.

Sanctuary, M. (2014): "Border carbon adjustments and strategic climate policy," .

Stern, N. H. (2007): *The economics of climate change: the Stern review*, cambridge University press.

Sundquist, E., R. Burruss, S. Faulkner, R. Gleason, J. Harden, Y. Kharaka, L. Tieszen, and M. Waldrop (2008): "Carbon Sequestration to Mitigate Climate Change," Tech. rep., US Geological Survey.

Svensson, J. (2000): "When is foreign aid policy credible? Aid dependence and conditionality," *Journal of Development Economics*, 61, 61–84.

——— (2003): "Why conditional aid does not work and what can be done about it?" *Journal of Development Economics*, 70, 381–402.

Tornell, A. and A. Velasco (1992): "The tragedy of the commons and economic growth: why does capital flow from poor to rich countries?" *Journal of Political Economy*, 1208–1231.

van den Bijgaart, I. (2017): "The unilateral implementation of a sustainable growth path with directed technical change," *European Economic Review*, 91, 305–327.

Van Soest, D. and R. Lensink (2000): "Foreign transfers and tropical deforestation: what terms of conditionality?" *American Journal of Agricultural Economics*, 82, 389–399.

WNA (2011): "Comparison of life cycle GHG emissions of various electricity generation sources," Tech. rep., World Nuclear Association.

WorldBank (2017): "CO2 emissions (kg per PPP $ of GDP)," Data provided by Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, United States, http://data.worldbank.org/indicator/EN.ATM.CO2E.PP.GD?end=2000&locations=US&start=1990&view=chart.

Dutch Summary

In regio's rond de wereld vinden de afgelopen jaren ongekende fenomenen plaats: verschuiving en verandering van habitat (zeespiegelstijging, woestijnvorming, enzovoort), droogte, extreme temperaturen, stormen en overstromingen, en verschuiving van seizoenen. Nu mensen veranderingen in hun gebruikelijke levenspatronen beginnen waar te nemen, nemen zorgen over klimaatverandering en opwarming van de aarde toe. Broeikasgassen zoals CO2, halogeenkoolwaterstoffen, methaan en distikstofoxide zijn geïdentificeerd als een belangrijke oorzaak van de opwarming van de aarde.

Het internationale karakter van grensoverschrijdende vervuiling wijst op de noodzaak voor internationale samenwerking om mondiale temperatuurstijging te beperken tot niveaus waarop het mogelijk is om te overleven. Het internationale karakter van klimaatverandering en grensoverschrijdende vervuiling leiden ertoe dat het in het belang van alle landen is om het groeipad van ontwikkelingslanden te vergroenen. Het geven van ontwikkelingshulp uit milieuoverwegingen is een manier om arme landen op een duurzame manier te helpen groeien zodat "groene groei" mogelijk is.

Dit proefschrift bestaat uit vier hoofdstukken. Hoofdstuk 1 bevat een introductie. In hoofdstuk 2 beargumenteren we dat de huidige praktijk van voorwaardelijke ontwikkelingshulp niet effectief is, en daarom bestuderen we onvoorwaardelijke ontwikkelingshulp. Ons raamwerk is een open-lus Stackelberg evenwicht van een differentiaalspel tussen een ontwikkeld land (leider) en een ontwikkelingsland (volger). De leider kiest de hoeveelheid klimaatmitigatiehulp die het geeft aan de volger. Deze hulp wordt door de volger geconsumeerd of geïnvesteerd in duur niet-vervuilend kapitaal of in goedkoop hoogvervuilend kapitaal. De leider geeft alleen onvoorwaardelijke mitigatiehulp wanneer dit land voldoende welvarend is of voldoende bezorgd over de kwaliteit van het milieu, terwijl de volger in zekere mate bezorgd is over het milieu. Als hulp in de stationaire toestand wordt gegeven, vermindert dit het stationaire niveau van hoogvervuilend kapitaal en kapitaalinvesteringen in het ontvangende landen en de mondiale hoeveelheid milieuvervuiling, maar het heeft geen effect op het niveau van niet-vervuilend kapitaal en niet-vervuilende investeringen.

Overgangshulp vergroot de economische groei van de volger; dit effect is echter kleiner dan wat voorspeld wordt door statische groeitheorie omdat het merendeel van de hulp geconsumeerd wordt. Daarnaast vinden we dat de groeitoename plaatsvindt in de niet-vervuilende sector.

Verschillen in de standpunten ten aanzien van klimaatverandering en in het beleid dat landen implementeren veroorzaakt verstoringen in internationale concurrentieposities, wat ervoor zorgt dat dergelijke maatregelen minder efficient zijn en minder geaccepteerd worden door bedrijven en burgers. Bedrijven in landen die een koolstofbelasting of emissierechten introduceren worden geconfronteerd met additionele productiekosten die niet door hun internationale concurrenten gedragen hoeven worden. De vraag naar hun producten daalt, wat leidt tot een productiedaling en een verlies van winst en marktaandeel. Tegelijkertijd neemt uitstoot toe in landen met een soepel klimaatbeleid, waardoor een zogenaamd koolstoflek (carbon leakage) ontstaat. Corrigerende Grensmaatregelen (CG) worden besproken als mogelijke effectieve instrumenten om het koolstoflek te beperken en de verstoring in concurrentiepositie tussen handelspartners te limiteren.

In hoofdstuk 3 breiden we het Melitz (2003) model uit om het door concurrentievermogen gedreven kanaal van het koolstoflek te onderzoeken en de effecten van unilaterale koolstofbelastingen, Border Tax Adjusmtent (BTA) en Border Carbon Adjustment (BCA), op het koolstoflek, het internationale concurrentievermogen en welvaart te onderzoeken. In het bijzonder analyseren we hoe deze maatregelen bedrijven langs het productiviteitsspectrum beinvloeden. In navolging van Kreickemeier & Richter (2014) benadrukken we het belang van de correlatie tussen productiviteit en uitstootniveaus. Wanneer bedrijfsspecifieke uitstootniveaus zwak afnemen met het productiviteitsniveau vinden we dat een koolstofbelasting in een land de gemiddelde winstgevendheid verlaagt en de kans op succesvolle toetreding van bedrijven verhoogt, wat er paradoxaal genoeg voor zorgt dat minder productieve bedrijven tot de markt toetreden na invoering van de belasting. We concluderen dat beide corrigerende grensaanpassingen effectief zijn in het verminderen van het koolstoflek en het internationale concurrentievermogen gedeeltelijk herstellen. De efficiëntie van de maatregelen hangt echter af van de doelstellingen van het implementerende land. In algemene zin is een BCA een beter instrument om een uitstootlek te voorkomen dan een BTA, omdat een BCA zich direct richt op het koolstofgehalte van de invoer; een BTA vormt echter een meer geloofwaardige dreiging om internationale samenwerking af te dwingen.

Tenslotte voer ik in hoofdstuk 4 een theoretische analyse uit naar het effect van Border Carbon Taxes (BCTs) op groei en welvaart. Ik ontwikkel een handelsmodel met dynamische investeringsbeslissingen op basis van het Ramsey-groeimodel. In elk land kan de overheid investeren in duur niet-vervuilend kapitaal of in goedkoop vervuilend kapitaal. Het model word numeriek opgelost in een open loop Nash evenwicht om verschillende configuraties van BCTs tussen landen te bestuderen. Ik vind dat een unilaterale BCT welvaartsverhogend is voor het land dat het toepast en een effectief instrument is om de groei van het andere land op een groener pad te brengen, zelfs wanneer landen niet bezorgd zijn over het milieu. Resultaten laten zien dat een bilaterale BCT welvaartsverhogend wordt voor beide landen wanneer beide overheden voldoende bezorgd zijn over de milieukwaliteit van hun consumenten. Daarnaast veroorzaakt de asymmetrie in aanvankelijke ontwikkelingsniveaus tussen landen alleen een lagere groei in het aanvankelijk armere land als het andere land rijker is in het vervuilende kapitaal. Bovendien laat het model zien dat vrijhandel geleidelijk moet worden bewerkstelligd naarmate beide landen zich ontwikkelen.

This dissertation consists of four chapters. A general introduction to the problem of carbon leakage and the necessity of sustainable development is furnished in the first chapter. In chapter 2, we investigate the conditions under which a donor country is motivated to give unconditional mitigation aid to a less developedrecipient, and we analyse the effect of such aid on the growth path of the recipient country. In the third chapter, we extend Melitz 2003 trade model to study carbon leakage and the distortion in international competitiveness on the firm level. Furthermore, we analyse the effectiveness of border adjustments to tackle these concerns focusing on the role of the link between firm-specific emission intensity and its productivity level. In the fourth chapter, we theoretically analyse the growth and welfare impacts of Border Carbon Taxes (BCT) between trading countries, along with investigating the effects of initial asymmetry in development levels on the transitional growth paths across countries. Moreover, we investigate how carbon leakage evolve dynamically, and how effective a BCT in tackling it.

Moutaz Altaghlibi (1985) holds a Bachelor degree in Business Administration from Damascus University, MSc degree in Financial Management from The Arab Academy for Banking and Financial Sciences, along with MSc degree in Quantitative Economics from Université Paris 1 Panthéon–Sorbonne and Ca’Foscari University of Venice.
As a PhD student, he joined the European Doctorate in Economics–Erasmus Mundus (EDEEM) program with a mobility between University of Amsterdam and Université Paris 1 Panthéon–Sorbonne. He did his PhD under the co-supervision of Prof. Antoine d’Autume, Prof. Cars Hommes, and Dr. Florian Wagener. His main interest lies in the quantitative and empirical aspects of sustainable development in an international context.